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Simulations for thermodynamic analyses of transcritical carbon dioxide refrigeration cycle and reheat dehumidification air conditioning cycle

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Simulations for Thermodynamic Analyses of Transcritical Carbon Dioxide Refrigeration
Cycle and Reheat Dehumidification Air Conditioning Cycle

by

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A thesis submitted in partial fulfillment
of the requirements for the degree of
Master of Science in Mechanical Engineering
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Table of Contents

List of Tables	iii
List of Figures	iv
Abstract	ix
Chapter 1: Introduction	1
1.1 Background and Overview of Air Conditioning and Refrigeration Cycles and Refrigerants	1
1.2 Background and Overview of Reheat Dehumidification Cycles and Refrigerants	4
1.3 Nomenclature	8
1.3.1 Carbon Dioxide Cycles	8
1.3.2 Reheat Dehumidification Cycles	10
Chapter 2: Thermodynamic Analysis of Transcritical Carbon Dioxide Cycles	11
2.1 Introduction	11
2.2 Thermodynamic Cycle	14
2.3 Model Formulation	16
2.4 Simulations	22
2.5 Discussion	28
2.6 Results and Conclusions	38
Chapter 3: Thermodynamic Analysis of Reheat Dehumidification Air Conditioning Cycles	47
3.1 Introduction	47
3.2 Warm Liquid Refrigerant Cycle	48
3.2.1 Thermodynamic Cycle	48
3.2.2 Model Formulation	50
3.2.3 Simulations	55
3.2.4 Results and Discussion	58
3.3 Sequential Hot Gas Refrigerant Cycle	69
3.3.1 Thermodynamic Cycle	69
3.3.2 Model Formulation	71
3.3.3 Simulations	75
3.3.4 Results and Discussion	78
3.4 Parallel Hot Gas Refrigerant Cycle	87
3.4.1 Thermodynamic Cycle	87

3.4.2 Model Formulation	89
3.4.3 Simulations	93
3.4.4 Results and Discussion	95
3.5 Two-Phase Mixture Refrigerant Cycle	105
3.5.1 Thermodynamic Cycle	105
3.5.2 Model Formulation	108
3.5.3 Simulations	112
3.5.4 Results and Discussion	116
Chapter 4: Conclusions and Recommendations	130
4.1 Summary of Carbon Dioxide Cycles	130
4.2 Summary of Reheat Dehumidification Cycles	132
References	135
Appendices	137
Appendix A: Visual Basic Programs for Carbon Dioxide Simulations	138
Appendix B: Visual Basic Programs for Reheat Dehumidification Simulations	150
Appendix C: Sample Interpolation Equations (R134a)	218

List of Tables

Table 2.1	Comparison of Coefficient of Performance for Carbon Dioxide and Refrigerant 134a Cycles Using Base Case Conditions	44
Table 2.2	Comparison of Coefficient of Performance for Simulation and Experimental Results	46
Table 3.1	Comparison of COPreheat for Different Refrigerants Using the Warm Liquid Refrigerant Cycle	54
Table 3.2	Base Case Conditions for the Warm Liquid Refrigerant Cycle	55
Table 3.3	Base Case Conditions for the Sequential Hot Gas Refrigerant Cycle	75
Table 3.4	Base Case Conditions for the Parallel Hot Gas Refrigerant Cycle	93
Table 3.5	Base Case Conditions for the Two-phase Mixture Refrigerant Cycle	111

List of Figures

Figure 2.1	Schematic for Single-stage Vapor Compression Cycle	20
Figure 2.2	p-h Diagram for Single-stage CO_2 Vapor Compression Cycle	20
Figure 2.3	Schematic for Two-stage Vapor Compression Cycle	21
Figure 2.4	p-h Diagram for Two-stage CO_2 Vapor Compression Cycle with Intercooler Efficiency Equal to 100%	21
Figure 2.5	Example Visual Basic Program; Two-stage CO_2 System with Compressor and Intercooler Efficiencies	26
Figure 2.6	Example Visual Basic Program; Single-stage CO_2 System with Compressor Efficiency	27
Figure 2.7	Schematic for Single-stage CO_2 System with Sample Visual Basic Program Values Corresponding to Figure 2.6	28
Figure 2.8	Coefficient of Performance vs. Discharge Pressure	30
Figure 2.9	COP as a Function of Quality at Point 4 (Single-stage)	30
Figure 2.10	COP vs. Evaporator Pressure	31
Figure 2.11	Coefficient of Performance vs. Compressor Efficiency	31
Figure 2.12	COP vs. Gas Cooler Pressure for Different Compressor Efficiencies	33
Figure 2.13	Coefficient of Performance vs. Evaporator Temperature (T_4 or T_8)	33
Figure 2.14	COP as a Function of Gas Cooler Exit Temperature (T_3 or T_5)	34
Figure 2.15	COP as a Function of Gas Cooler Exit Temperature (T_3 or T_5), High Temperature Range	34

Figure 2.16	COP vs. Intermediate Pressure	36
Figure 2.17	Coefficient of Performance vs. Intermediate Pressure for Different Gas Cooler Exit Temperatures	36
Figure 2.18	Coefficient of Performance vs. Intermediate Pressure for Different Gas Cooler Exit Temperatures (High Temperature Range)	37
Figure 2.19	COP as a Function of Intercooler Efficiency	37
Figure 2.20	COP vs. Intermediate Pressure for Different Intercooler Efficiencies	38
Figure 2.21	COP vs. Intermediate Pressure Using 2 Different Programs	44
Figure 3.1	Schematic for Warm Liquid Refrigerant Cycle	53
Figure 3.2	p-h Diagram for Base Case Warm Liquid Refrigerant Cycle	54
Figure 3.3	Sample Visual Basic Program for Warm Liquid Refrigerant Cycle with Base Case Conditions	58
Figure 3.4	Difference in Mass Flow Rate ($m_{total} - m_{reheat}$), m_{3b} , as a Function of Reheat Factor	60
Figure 3.5	COPreheat vs. Quality at Condenser Exit (x_3)	61
Figure 3.6	COPreheat vs. Quality at Condenser Exit (x_3), High Pressure of 194 psia	62
Figure 3.7	COPreheat vs. Condenser Pressure for Different Qualities at Condenser Exit	63
Figure 3.8	COPreheat vs. Condenser Pressure for Different Qualities at Condenser Exit (High Pressure Range)	64
Figure 3.9	COPreheat as a Function of Evaporator Exit Temperature	65
Figure 3.10	COPreheat vs. Condenser Pressure for Different Compressor Efficiencies	66
Figure 3.11	COPreheat as a Function of Evaporator Pressure for Different Qualities at Condenser Exit	67

Figure 3.12	COPreheat/COP as a Function of Qreheat	68
Figure 3.13	COPreheat as a Function of mreheat/mtotal	69
Figure 3.14	Schematic for Sequential Hot Gas Refrigerant Cycle	74
Figure 3.15	p-h Diagram for Base Case Sequential Hot Gas Refrigerant Cycle	74
Figure 3.16	Sample Visual Basic Program for Sequential Hot Gas Refrigerant Cycle with Base Case Conditions	77
Figure 3.17	COPreheat vs. Quality at Condenser Exit (x_4)	79
Figure 3.18	COPreheat vs. Quality at Condenser Exit (x_4), High Pressure of 194 psia	79
Figure 3.19	COPreheat vs. Condenser Pressure for Different Qualities at Condenser Exit	80
Figure 3.20	COPreheat vs. Condenser Pressure for Different Qualities at Condenser Exit (High Pressure Range)	81
Figure 3.21	COPreheat as a Function of Evaporator Exit Temperature	82
Figure 3.22	COPreheat vs. Condenser Pressure for Different Compressor Efficiencies	83
Figure 3.23	COPreheat as a Function of Reheat Factor for Different Compressor Efficiencies	84
Figure 3.24	COPreheat/COP as a Function of Qreheat	85
Figure 3.25	COPreheat vs. Evaporator Pressure for Different Qualities at Condenser Exit	86
Figure 3.26	COPreheat as a Function of mreheat/mtotal	87
Figure 3.27	Schematic for Parallel Hot Gas Refrigerant Cycle	92
Figure 3.28	p-h Diagram for Base Case Parallel Hot Gas Refrigerant Cycle	92
Figure 3.29	Sample Visual Basic Program for Parallel Hot Gas Refrigerant Cycle with Base Case Conditions	95

Figure 3.30	COPreheat as a Function of Quality at Condenser Exit (x_{3b})	96
Figure 3.31	COPreheat as a Function of Quality at Condenser Exit (x_{3b}), High Pressure of 194 psia	97
Figure 3.32	COPreheat vs. Evaporator Exit Temperature	98
Figure 3.33	COPreheat/COP as a Function of Qreheat	99
Figure 3.34	COPreheat vs. mreheat/motoal	100
Figure 3.35	COPreheat as a Function of Condenser Pressure for Different Qualities at Condenser Exit	101
Figure 3.36	COPreheat as a Function of Condenser Pressure for Different Qualities at Condenser Exit (High Pressure Range)	102
Figure 3.37	COPreheat vs. Condenser Pressure for Different Compressor Efficiencies	103
Figure 3.38	COPreheat as a Function of Evaporator Pressure for Different Qualities at Condenser Exit	104
Figure 3.39	COPreheat as a Function of Reheat Factor for Different Compressor Efficiencies	105
Figure 3.40	Schematic for Two-phase Mixture Refrigerant Cycle	110
Figure 3.41	p-h Diagram for Base Case Two-phase Mixture Refrigerant Cycle	111
Figure 3.42	Sample Visual Basic Program for Parallel Hot Gas Refrigerant Cycle with Base Case Conditions	115
Figure 3.43	Mass Flow Rate Through 4b (Non-reheat Bypass) vs. Percent Mass Flow Rate of 3b Through 3a	117
Figure 3.44	COPreheat as a Function of Quality at Condenser Exit (x_{3b})	118
Figure 3.45	COPreheat as a Function of Quality at Condenser Exit (x_{3b}), High Pressure of 194 psia	119
Figure 3.46	COPreheat as a Function of Evaporator Exit Temperature	120

Figure 3.47	COPreheat vs. mreheat/mtotal	121
Figure 3.48	COPreheat/COP as a Function of Reheat Factor	122
Figure 3.49	COPreheat vs. Condenser Pressure for Different Qualities at Condenser Exit	123
Figure 3.50	COPreheat vs. Condenser Pressure for Different Qualities at Condenser Exit (High Pressure Range)	124
Figure 3.51	COPreheat as a Function of Condenser Pressure for Different Compressor Efficiencies	125
Figure 3.52	COPreheat vs. Evaporator Pressure for Different Qualities at Condenser Exit	126
Figure 3.53	COPreheat vs. Quality at Condenser Exit for Different Refrigerant Cycles	128
Figure 3.54	COPreheat vs. Quality at Condenser Exit for Different Refrigerant Cycles (High Pressure Range)	128
Figure 3.55	COPreheat as a Function of Condenser Pressure for Different Refrigerant Cycles	129
Figure 3.56	COPreheat as a Function of Condenser Pressure for Different Refrigerant Cycles (High Pressure Range)	129
Figure A.1	Form for One-Stage Cycle Sample Program	140
Figure A.2	Form for Two-Stage Cycle Sample Program	144
Figure A.3	Form for Two-Stage Cycle with Intercooler Program	149
Figure B.1	Form for Warm Liquid Refrigerant Cycle Program	166
Figure B.2	Form for Sequential Hot Gas Refrigerant Cycle Program	183
Figure B.3	Form for Parallel Hot Gas Refrigerant Cycle Program	200
Figure B.4	Form for Two-Phase Mixture Refrigerant Cycle Program	217
Figure C.1	Temperature and Enthalpy vs. Pressure Equations for R134a	218
Figure C.2	Enthalpy and Entropy vs. Temperature Equations for R134a	219

Simulations for Thermodynamic Analyses of Transcritical Carbon Dioxide
Refrigeration Cycle and Reheat Dehumidification Air Conditioning Cycle

Mark Brown

ABSTRACT

Carbon dioxide is a natural refrigerant that has been considered for certain refrigeration and air conditioning applications. The coefficient of performance (COP) of carbon dioxide cycles is low compared to classical vapor compression cycles. The aim of this portion of the thesis is to present a thermodynamic analysis of carbon dioxide cycles in order to evaluate the potential performance of a refrigeration cycle using carbon dioxide. A thermodynamic model for the cycle is proposed which can simulate the operation of a carbon dioxide refrigeration cycle. This model takes into account the practical effects of the thermo-physical properties of carbon dioxide as a refrigerant in a trans-critical cycle. One and two-stage compression processes were considered for comparison purposes. A sensitivity analysis has been conducted so that cycle performance can be estimated. The effect of cycle components on system capacity and cycle performance was investigated.

The second portion of the thesis deals with the concept of reheat air conditioning, and looks at the performance of different reheat cycles. The thesis looks at reheat systems that utilize different placements of the reheat coil. The overall performance of

these reheat systems is then calculated. These systems require no additional electric power to reheat the air after it is cooled and dehumidified in the evaporator. Instead, they use heat from the condenser heat exchanger to reheat the air during partial load conditions. Four different reheat configurations are discussed and analyzed to determine performance levels. Visual Basic programs were written for each of the four cycles to simulate the different configurations and to evaluate key performance parameters. Graphs were developed based on these programs, where critical variables were changed to monitor trends in coefficient of performance. The thermodynamic cycle of each reheat configuration is developed, with equations presented with figures depicting the cycles. Refrigerant 134a was used in the programs throughout the reheat section of the thesis. The reheat coefficient of performance is used as the basis for cycle comparison. The relative performance of the four cycles is illustrated in the figures and explained in the Results and Discussion section at the end of chapter 3.

Chapter 1

Introduction

1.1 Background and Overview of Air Conditioning and Refrigeration Cycles and Refrigerants

The applications of air conditioning and refrigeration are apparent and exploited by people in business and in everyday life. Refrigeration systems are used in the preparation, storage, and distribution of many different types of food and beverages. Refrigeration is also used in the chemical and process industries, as thermodynamic change of phase processes are carried out. The medical industry as well as the field of engineering use refrigeration to develop new technologies. Likewise, air conditioning is used both in industry and in personal comfort. Maintaining a specified temperature is needed in the testing of products as well as in manufacturing equipment. The most common use of air conditioning systems is to maintain comfortable surroundings for people, which creates a high need for environmentally safe and efficient refrigerants.

The desirable properties of refrigerants used in the applications discussed above include wide availability, environmentally safe, stability, and low cost. There are many different types of refrigerants, of which only a few of the most commonly used ones will be presented here. Stoecker [1] discusses, among others, three groups of refrigerants that

are widely used. They are the inorganic compounds, halocarbon compounds, and hydrocarbons (HC). Refrigerant 12 and Refrigerant 22 were two popular refrigerants used in the past, both being non-toxic. They both reside in the halocarbon group, and exhibited distinct advantages and disadvantages. According to Stoecker [1] Refrigerant 12 was found in household refrigeration systems and in industrial and commercial air conditioning applications. From the inorganic compound group, Ammonia is used mainly in industrial and low-temperature applications. Its high toxicity limits its use to non-populated venues. Some natural refrigerants are also inorganic compounds and are used in select applications, including air in aircraft refrigeration cycles and water in absorption refrigeration units. In the automobile industry, different chlorofluorocarbon (CFC) and hydrofluorocarbon (HFC) refrigerants are used abroad, including CFC-12 and HFC-134a. However, the global warming potential of these refrigerants is high and brings rise to possible replacements for these refrigerants. Two naturally occurring flammable substances have also been explored in the past, HC-290 (propane) and HFC-152a. Many factors must be evaluated in order to select the best refrigerant for each particular application. According to Stoecker [1], three main categories exist that contain the most important parameters. Under the thermodynamic category, coefficient of performance and the pressures at the evaporating and condensing temperatures are among the important parameters. The volume flow per ton of refrigerant dictates the size of the compressor which is important in mobile applications. The category containing the chemical properties lists toxicity and flammability as highly influential parameters. The physical nature of the refrigerant is quantified by its tendency to leak, its thermal conductivity and viscosity, and its cost.

The use of Carbon Dioxide as a refrigerant for air conditioning systems and refrigeration systems is motivated by its natural properties and occurrence in the environment. Because the properties of CO_2 are well-known, and it occurs naturally, uncertainties regarding unknown health risks and unsafe environmental impact are limited. Pettersen [2] proposed using CO_2 as a refrigerant in automobile air-conditioning systems, and listed several advantages it has over currently used refrigerants. These advantages include its low cost, wide availability, and compact system requirements. There is no need to recover or recycle excess CO_2 . By building and testing a laboratory prototype, Pettersen [2] found that a CO_2 vapor compression system is very competitive in performance with currently used CFC-12 and HFC-134a units, with regards to refrigerating capacity, cost, coefficient of performance, size, and weight. Pettersen [2] and Bodinus [3] both suggest that CO_2 was used as far back as the first decades of the 20th century, while according to Bodinus [3], reaching its maximum usage in the 1920's. Bodinus [3] goes on to explain how R-12 replaced CO_2 as the safer refrigerant for comfort cooling systems during the time of the depression. Pettersen [2] talks in more detail about the benefits of using CO_2 as a refrigerant. He describes the value of the ozone-depletion potential (ODP) and the effective global warming potential (GWP) for CO_2 to be zero. Carbon Dioxide is also nontoxic and noncombustible. Because of the high working pressure of CO_2 , systems using it as a refrigerant require more compact compressors and corresponding tubing. The thickness of the tubing would also have to be increased to account for the high working pressures. Pettersen [2] indicates possible disadvantages of CO_2 are a lower value of coefficient of performance

(COP) along with a loss of capacity at elevated gas cooling temperatures. The heat transfer in the gas cooler (upper heat exchanger) occurs without taking advantage of the phase change process for CO_2 systems. This is due to the fact that this heat transfer takes place above the critical pressure of Carbon Dioxide. According to Little [4], mobile air conditioning systems operating with CO_2 as the refrigerant present two possible health hazards. The reaction of a system operating at high pressures to a puncture or rupture could be severe. In addition, a rupture in the evaporator of a CO_2 unit could produce dangerously high concentrations of CO_2 in the vehicle. According to Bodinus [3], CO_2 systems are still in use today, operating in a cascade system with an additional refrigerant. Sawalha [5] explains how Carbon Dioxide is currently being used in supermarket refrigeration systems in Europe. He presents 3 different types of systems in which Carbon Dioxide is being used. It is used as a secondary refrigerant in indirect systems, and recently it is being used in cascade and multi-stage systems for supermarket refrigeration. He concludes that CO_2 is comparable in performance with synthetic refrigerants for certain applications, and provides promise for widespread refrigeration in supermarkets.

1.2 Background and Overview of Reheat Dehumidification Cycles and Refrigerants

The second part of the thesis deals with different concepts of reheat. The concept of reheat is used in air conditioning systems to heat the air after it exits the evaporator and before it enters the conditioned space. The behavior of outdoor conditions has been studied for over 20 years for a vast number of locations across the globe. These

environmental conditions govern the operating conditions of air conditioning units. These air conditioning systems are designed to meet maximum load conditions, which consist of two different parameters. These two parameters are the maximum outside air temperature and the maximum number of people occupying the room being cooled. When these conditions exist, the air conditioner runs at full level, maintaining a consistent air temperature and humidity level in the room. At these maximum conditions, the reheat coil heats the air exiting the evaporator to a comfortable temperature for the room. When one or both of these conditions is not at its maximum design level, the air conditioning system is operating for a partial load. When this is the case, which is the majority of the time, the air conditioning system cools the room to the specified temperature on the thermostat, then is tricked to continue to run based on the input of heat from the reheat coil into the cooled room. The amount of heating at the reheat coil is controlled by the mass flow rate of the refrigerant through the reheat coil. This additional heat from the reheat coil fools the system and triggers the compressor to keep running, thus continually dehumidifying and cooling the air. In the past, an electric reheat coil was used to reheat the air before it entered the room. This remains a very inefficient approach, as additional energy from electric power is introduced into the system. To improve the efficiency of the system, it was recognized that some heat from the heated outdoor air (from the condenser heat exchanger) could be used to reheat the air. Using this approach, no additional energy is required in the system. To execute this, part of the refrigerant from the condenser and part of the area of the condenser are used in the reheat coil. This provides the additional reheat needed to heat the air that exits the evaporator in order to produce comfortable conditions in the room. By using this method, part of the

potential of the refrigerant in the condenser is being used at another location in the system. The amount of refrigerant that passes through the reheat coil is controlled by the humidistat, which maintains a comfortable humidity level inside the room.

The importance of removing humidity from the outside and recirculating air is critical due to the partial load condition, which exists the majority of the time. Several papers have been written recently dealing with the issue of dehumidifying the air. Mazzei [6] attacks this problem by using both mechanical and chemical means. A compression refrigeration system is used to cool the air and a desiccant is utilized to remove humidity from the air. The compression refrigeration system is the mechanical part of the unit while the desiccant is the chemical portion. A mechanical dehumidifying system is represented by an air handling unit, which controls the humidity level and temperature of the outside air, and a simple cooling coil, which controls the humidity and temperature of the recirculating air. He looks at hybrid systems that utilize both the desiccant approach as well as the mechanical approach in theatres and supermarkets, and notices reduction of costs, reduction of electric power requirements, and better control of humidity levels for these types of systems. Using desiccants, whether liquid or solid, to dehumidify the air is researched in several papers recently. Ghaddar [7] presents a model where a liquid desiccant is utilized for air dehumidification. He presents this approach as a method to reduce the latent heat load on the HVAC system and increase efficiency. He considers the performance of the model for actual ambient conditions experienced in Beirut city. The proposed system can replace vapor compression systems for low latent heat applications, and is combined with a vapor compression system to form a hybrid system in high latent heat environments. The cost reduction for this type of

dehumidification system is significant since the need for reheat in the vapor compression refrigeration system is eliminated. Subramanyam [8] also looks at desiccant assisted air conditioning systems. He analyzes the effects of different operating parameters on the performance of these types of systems. Among his reported findings, he suggests that the energy efficiency ratio of desiccant assisted air conditioning systems is higher than that of air conditioning systems with reheat, bypass control, and variable speed fans at low sensible heat ratios. Desiccant systems have the same capabilities as reheat systems, controlling the temperature and humidity of the air, while maintaining low electrical energy requirements. Nautica [9] presents a reliable and energy efficient indoor air dehumidification system. This system pre-cools the air before it enters the cooling coil, thus reducing energy consumption by up to 50%. Rudd [10] looked at developing a cost effective and energy efficient approach to provide humidity control and controlled mechanical ventilation in hot and humid environments for residential homes. They performed a study on several homes, installing different dehumidification and controlled mechanical ventilation systems into these homes. They monitored the temperature and humidity levels inside the homes, and found that the most effective system utilized a standard dehumidifier located in a particular location within the home with proper fan ventilation. The refrigerant-side also does not require complicated controls that traditional dehumidifying systems require when routing hot gas to the reheat coil. The following papers link the conventional reheat HVAC systems with different, possibly more efficient methods of temperature and humidity control. In all systems, the final goal is to have good quality control of the temperature and humidity levels as well as use the least amount of additional energy and cost to support the system requirements.

The following portion of the thesis looks at reheat systems that utilize different placements of the reheat coil, and their overall performance. These systems require no additional electric power to reheat the air. Instead, they use heat from the condenser heat exchanger to heat the air to comfortable conditions and to keep the compressor running for dehumidification purposes. The four cycles discussed in this section are slight variations of the more efficient design concept discussed previously above. The placement of the reheat coil as well as the amount of refrigerant that is passed through the condenser is changed for the different cycles. The name of each cycle indicates the phase of the refrigerant that is passed through the reheat coil. The Warm Liquid Refrigerant Cycle has liquid refrigerant passing through the reheat coil, while the two hot gas cycles have hot gas from the compressor passing through the reheat coil. The reheat coil is placed in sequence before the condenser in the Sequential Hot Gas Refrigerant Cycle whereas the reheat coil is placed in parallel with the condenser in the Parallel Hot Gas Refrigerant Cycle. The refrigerant is made up of a mixture of liquid and gas as it passes through the reheat coil in the Two-phase Mixture Refrigerant Cycle. The reheat coil is placed after the condenser in the Warm Liquid and Two-phase Mixture Refrigerant Cycles.

1.3 Nomenclature

1.3.1 Carbon Dioxide Cycles

- m Mass flow rate in one-stage cycle, kg/s
- m1 Mass flow rate in lower portion of two-stage cycle, kg/s
- m2 Mass flow rate in upper portion of two-stage cycle, kg/s

h	Enthalpy, kJ/kg
W	Power, kW
Q	Heat Transfer rate, kW
COP	Coefficient of Performance
P	Pressure, Mpa
T	Temperature, K
x	Quality of refrigerant
s	Entropy, kJ/kg*K

Greek Symbols

η	Efficiency, %
--------	---------------

Subscripts

1-2	Compression process from state 1 to 2
2-3	Heat loss process in one-stage cycle from state 2 to 3
4-1	Evaporation process in one-stage cycle from state 4 to 1
3-4	Compression process in two-stage cycle from state 3 to 4
4-5	Heat loss process in two-stage cycle from state 4 to 5
8-1	Evaporation process in two-stage cycle from state 8 to 1
f	Saturated liquid
g	Saturated vapor
a	Actual enthalpy value(not isentropic)
I	Intermediate pressure
L	Low pressure
H	High pressure

comp	Compressor
HX	Intercooler
discharge	High pressure
cooling	Evaporation process
critical	Critical temperature
int	Intermediate pressure
low	Low pressure

1.3.2 Reheat Dehumidification Cycles

COP	Coefficient of Performance
F	Reheat factor
h	Enthalpy, Btu/lbm
m	mass flow rate, lbm/hr
p	Pressure, psia
Q	Heat Transfer rate, Btu/hr
s	Entropy, Btu/lbm ^{°R}
T	Temperature, °R
W	Power, Btu/hr
x	Quality of refrigerant

Greek Symbols

η	Efficiency, %
--------	---------------

*Subscripts **

* The numbering of the subscripts is different for each of the 4 reheat cycles; therefore, a unique subscript section is provided for each reheat cycle in Chapter 3.

Chapter 2

Thermodynamic Analysis of Transcritical Carbon Dioxide Cycles

2.1 Introduction

Among the important parameters used to evaluate refrigerants are coefficient of performance and the pressures at the evaporating and condensing temperatures. Two naturally occurring flammable substances which have been explored are HC-290 (propane) and HFC-152a. Another promising naturally occurring refrigerant being investigated is carbon dioxide. The following papers developed methods for building and analyzing carbon dioxide systems.

By building and testing a laboratory prototype, Pettersen [2] found that a CO₂ vapor compression system is very competitive in performance with currently used HFC-134a units, with regards to refrigerating capacity, cost, efficiency, size, and weight. Pettersen [2] indicated possible disadvantages of CO₂ are a lower value of coefficient of performance (COP) along with a loss of capacity at an elevated heat rejection temperature.

Several papers have been written recently in regards to using alternate refrigerants, including CO₂, in automobile A/C systems. Hill and Papasavva [11] presented a life cycle analysis rating 6 different refrigerants with respect to their

individual global warming impact. In their model of the R744 (CO₂) system, an additional suction line heat exchanger was used due to the decreasing CO₂ system efficiency at high temperatures. They concluded that R744 systems produce lower CO₂ emissions than conventional HFC-134a systems, except in selected cases. Martin [12] presented a test setup and corresponding simulation data. They also used a suction line heat exchanger for optimal performance. Among their results, they graphed the coefficient of performance and cooling capacity as a function of high pressure. For an ambient temperature of 35°C, the experimental data predicted a maximum COP at approximately 95 bar where as the cooling capacity increased with increasing high side pressure. They concluded that their simulation results showed good agreement with their experimental data, even though some operation points were not predicted exactly.

Brown and Domanski [13] developed a semi-theoretical simulation model to analyze the transcritical CO₂ mobile air conditioning unit. Their simulation used the theoretical vapor-compression refrigeration cycle with 11 refrigerant state points. They included a liquid-line/suction-line heat exchanger in addition to the evaporator and condenser heat exchangers. They provided the option of using different type heat exchangers for the evaporator and condenser. Their program also allowed the user to input the high side pressure or enabled the program to select the high side pressure that maximized the COP. Their simulation results showed relatively good agreement with experimental data, except for higher end conditions. McEnaney [14] described a prototype they built to observe the performance of a transcritical R744 mobile A/C system. They noted that the COP of the transcritical carbon dioxide cycle was much lower than that of the R134a cycle operating at identical conditions. In addition, they

pointed out that the thermophysical properties of R744 provided for more heat transfer, and that the R744 cycle operated at much lower pressure ratios than the R134a system. They indicated, as did the preceding authors, that there was a distinct discharge pressure (high pressure) that gave the highest COP. They discussed how this optimum pressure was a function of gas cooler inlet air temperature, flow rate, and compressor speed. This is investigated in the following thesis by way of Figures. Their graphs illustrated how the maximum COP doesn't occur at the same discharge pressure as does the largest cooling capacity. They concluded that the R744 system provided nearly the same air temperatures as the R134a system. Vaisman [15] presented a COP analysis of a carbon dioxide cycle based on a modified cryogenic approach. Included in his results was a plot of COP versus discharge pressure (high pressure), where the COP increased until it reached a certain discharge pressure and then decreased for higher discharge pressures above that point.

There are three aims of Chapter 2 of the thesis. The first aim presents an analysis of a CO₂ refrigeration cycle based on the one-stage vapor compression system. The second aim involves a similar procedure, where the two-stage vapor compression system is used as a basis for the analysis. The final aim of the thesis presents a sensitivity analysis in which the coefficient of performance is evaluated and plotted as a function of different parameters. The COP values for select conditions important in air conditioning design are presented for the CO₂ cycle and then compared with identical conditions using R-134a as the refrigerant. COP results are then compared with experimental data for common operating conditions.

2.2 Thermodynamic Cycle

As shown in Figure 2.1, the standard single stage vapor-compression cycle consists of 4 processes; compression from 1-2, reversible heat loss at constant pressure from 2-3, irreversible expansion with constant enthalpy from 3-4, and reversible heat gain at constant pressure from 4-1, as shown in Figure 2.1. At state 1 the refrigerant exists as saturated vapor at the evaporator, or low pressure/temperature. At state 2 the refrigerant has properties in the superheated region at the condenser (high) pressure. The efficiency of the compressor dictates the location of point 2 along the high pressure line. At state 3 the refrigerant is saturated liquid at the high pressure. Point 4 is located on the low pressure line and the refrigerant has a quality. The evaporator, process 4-1, is where the cooling load of the cycle is determined. The power input to the system occurs in the compressor from 1-2. The coefficient of performance defines the efficiency of the cycle and is equal to the cooling load divided by the work input. The calculations of the parameters described above are carried out in the analysis section.

A standard two-stage vapor compression system consists of 2 compressors, an evaporator, a condenser, 2 expansion valves, and an intercooler, as depicted in Figure 2.3. The process is similar to the one-stage cycle, with the exception of an intermediate pressure that represents the pressure at the exit of the first compressor and entrance to the second compressor. The purpose of multi-stage compression is to decrease the required work input, therefore increasing the COP of the system. This is accomplished by decreasing the enthalpy at point 2, thus decreasing the difference $(h_2 - h_1)$. The refrigerant at the inlet to the second compressor is saturated vapor for an ideal intercooler, and slightly superheated for an intercooler with an efficiency. The

intercooler is illustrated in Figure 2.3. There are also 2 expansion processes in a two-stage cycle, with the refrigerant exiting the first valve with a quality at the intermediate pressure, point 6, and the refrigerant entering the second valve as a saturated liquid, point 7.

The CO_2 vapor compression cycle is similar to the standard vapor compression cycle, with one significant difference. The evaporator and condenser pressures are higher, resulting in a condenser pressure residing in the transcritical region instead of inside the saturation dome. Therefore; the condenser in a CO_2 system is termed a gas cooler in this analysis, as the gas is not cooled to the saturated liquid state. In cooling the refrigerant, heat is released to the surroundings, forcing the temperature range at the gas cooler to be higher than the ambient temperature. This forces the gas cooler pressure above the critical pressure for CO_2 . For one-stage compression, the quality at point 4 determines the enthalpy and location of point 3, since $h_3 = h_4$. For the two-stage cycle analyzed in this thesis, the intermediate pressure is restricted to be within the saturation dome. All states are described as indicated in the above paragraph relating to the standard two-stage cycle except for points 5 and 6, which refer to the exit of the gas cooler and exit of the expansion valve, respectively. Point 5 is located by the quality at point 6. Vaisman [15] presents a COP analysis of a Carbon Dioxide Cycle based on a modified cryogenic approach. Included in his results is a plot of COP versus Discharge Pressure (high pressure), where the COP increases until it reaches a certain discharge pressure and then decreases for higher discharge pressures above this point.

2.3 Model Formulation

Figures 2.1 and 2.2 depict the single-stage CO_2 vapor compression refrigeration cycle in a schematic and a p-h diagram, respectively. States 1 through 4 are located as indicated in the above CO_2 cycle description. An equation is developed for each process represented in the schematic by executing a mass and energy balance at steady state for control volumes surrounding the evaporator, compressor, condenser, and expansion valve. These equations, after simplification, relate the enthalpies at the entrance and exit states to the heat transfer or work occurring in each particular process. The compression process requires a power input that depends on the difference in entrance and exit enthalpies. The equation is as follows:

$$W_{1-2} = m \times (h_2 - h_1) \quad (2.1)$$

where W_{1-2} is the power and has units of kilowatts and m is the mass flow rate and has units of kg/s. The enthalpies h_1 and h_2 have units of kJ/kg, as do all enthalpies used in the analysis. The gas cooler is where the refrigerant, in this case CO_2 , rejects heat to the surroundings, where the heat loss is calculated by:

$$Q_{2-3} = m \times (h_3 - h_2) \quad (2.2)$$

where Q_{2-3} represents the heat gain from 2 to 3, which is negative since heat is being lost, and has units of kilowatts. Since the expansion process is an adiabatic process with no work, the enthalpies at the entrance and exit are equal as presented formally here:

$$h_3 = h_4 \quad (2.3)$$

The enthalpy at point 4, h_4 , can be dictated by either the quality at point 4 or by the enthalpy at point 3, which depends on the temperature of the refrigerant leaving the gas

cooler. Both methods are used in the analysis depending on which of the 2 variables are varied, x_4 or T_3 . The quality at point 4 is related to the enthalpy at point 4 by the following equation:

$$h_4 = h_{f4} + x_4 \times (h_{g4} - h_{f4}) \quad (2.4)$$

where x_4 is the quality at state 4, h_{f4} is the enthalpy corresponding to the saturated liquid state at the evaporator pressure, and h_{g4} is the enthalpy corresponding to the saturated vapor state at the evaporator pressure. In the evaporator, the refrigerant gains heat and is evaporated to a saturated vapor. This process is described by:

$$Q_{4-1} = m \times (h_1 - h_4) \quad (2.5)$$

where Q_{4-1} is positive since there is a heat addition, and has units of kilowatts. The mass flow rate m is found from equation (2.5) with a given value for Q_{4-1} .

The two-stage CO_2 vapor compression cycle is illustrated in figures 2.3 and 2.4 with its corresponding schematic and p-h diagram, respectively. The first compression process is described in the same manner as the compression process in the single-stage cycle but has a different mass flow rate as seen here:

$$W_{1-2} = m_1 \times (h_2 - h_1) \quad (2.6)$$

where m_1 is the mass flow rate through the lower portion (bottom half) of the two-stage cycle. The second compression process is similar with the only difference lying in the entering and exiting states and the mass flow rate, and follows as:

$$W_{3-4} = m_2 \times (h_4 - h_3) \quad (2.7)$$

where m_2 is the mass flow rate through the upper portion (top half) of the two-stage cycle. The mass flow rate in the top half of the cycle, m_2 , is found from an energy balance about the intercooler. Looking at a control volume surrounding the intercooler:

$$m_2 \times h_6 + m_1 \times h_2 = m_2 \times h_3 + m_1 \times h_7 \quad (2.8)$$

Rearranging and solving for m_2 :

$$m_2 = m_1 \times ((h_7 - h_2)/(h_6 - h_3)) \quad (2.9)$$

where h_7 is the saturated liquid enthalpy at the intermediate pressure and h_6 is the enthalpy at the intermediate pressure equal to the enthalpy at point 5 as described in Figure 2.4. The gas cooler operates between states 4 and 5, and is defined by a similar equation to the single-stage gas cooling process, and reads:

$$Q_{4-5} = m_2 \times (h_5 - h_4) \quad (2.10)$$

and gives a negative value as heat is lost to the atmosphere. The two expansion processes are defined similarly as:

$$h_5 = h_6 \quad (2.11)$$

and

$$h_7 = h_8 \quad (2.12)$$

The evaporator is located in the bottom half of the two-stage cycle and operates according to the equation:

$$Q_{8-1} = m_1 \times (h_1 - h_8) \quad (2.13)$$

where Q_{8-1} is positive since heat is added to the system. The mass flow rate, m_1 , is found from equation (2.13) with a given value for Q_{8-1} . The coefficient of performance is defined for the one-stage cycle to be:

$$COP = Q_{4-1} / W_{1-2} \quad (2.14)$$

and for the two-stage cycle:

$$COP = Q_{8-1} / (W_{1-2} + W_{3-4}) \quad (2.15)$$

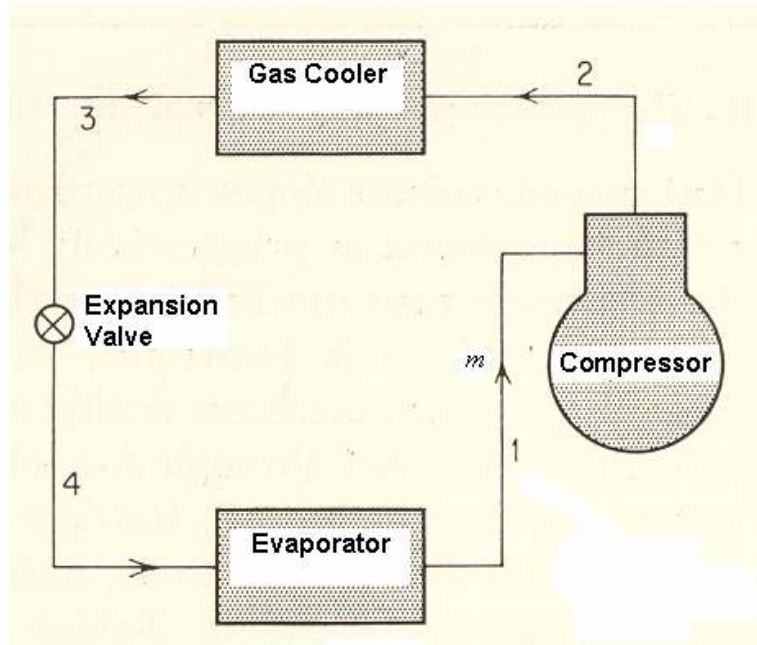


Figure 2.1 Schematic for Single-stage Vapor Compression Cycle

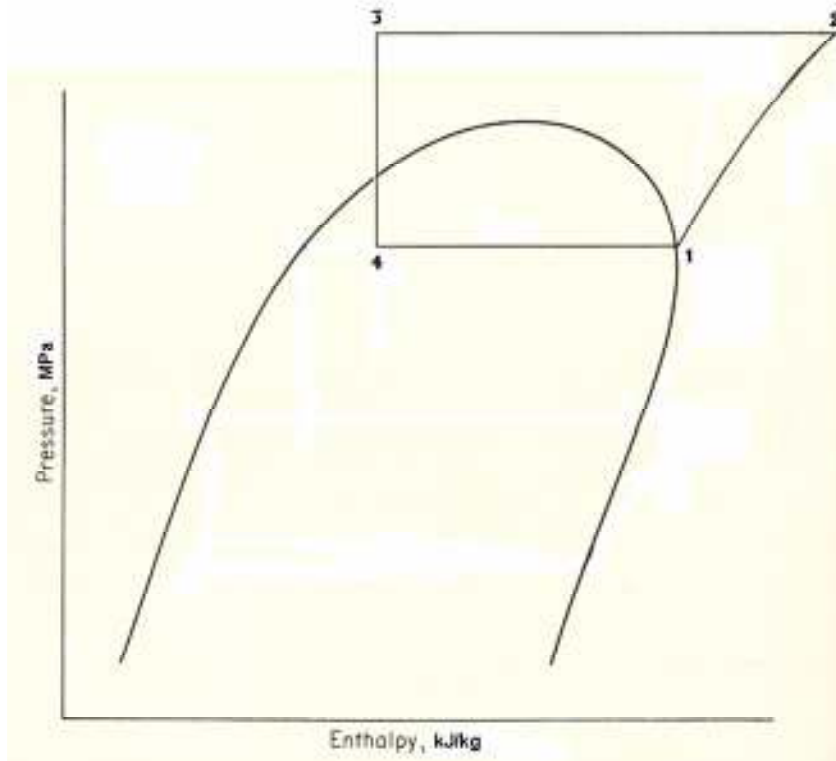


Figure 2.2 p-h Diagram for Single-stage CO₂ Vapor Compression Cycle

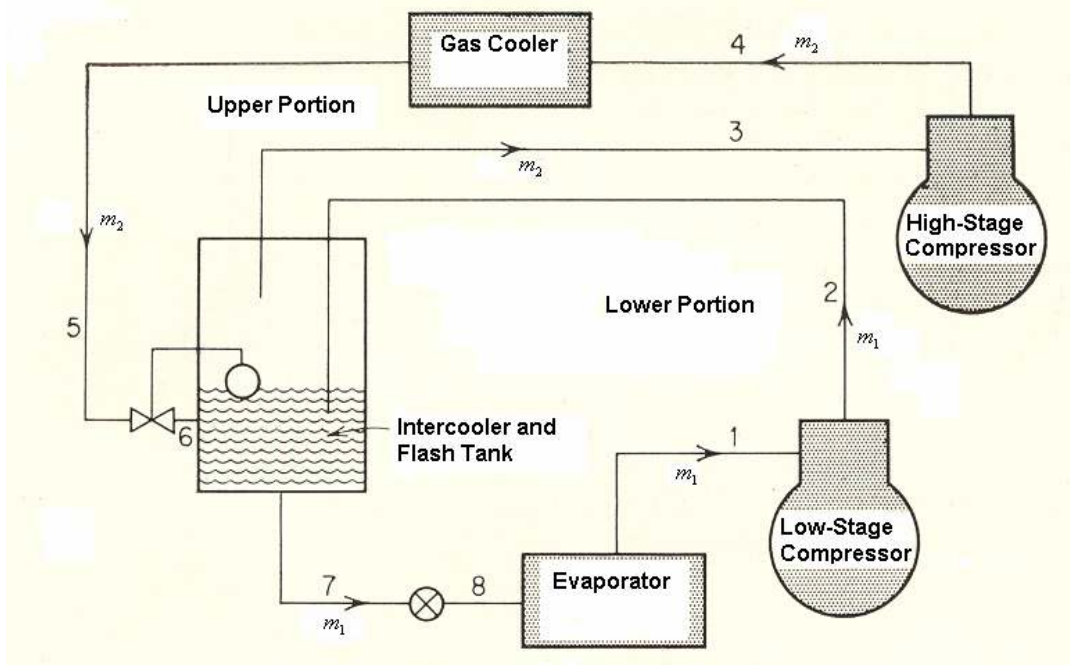


Figure 2.3 Schematic for Two-stage Vapor Compression Cycle

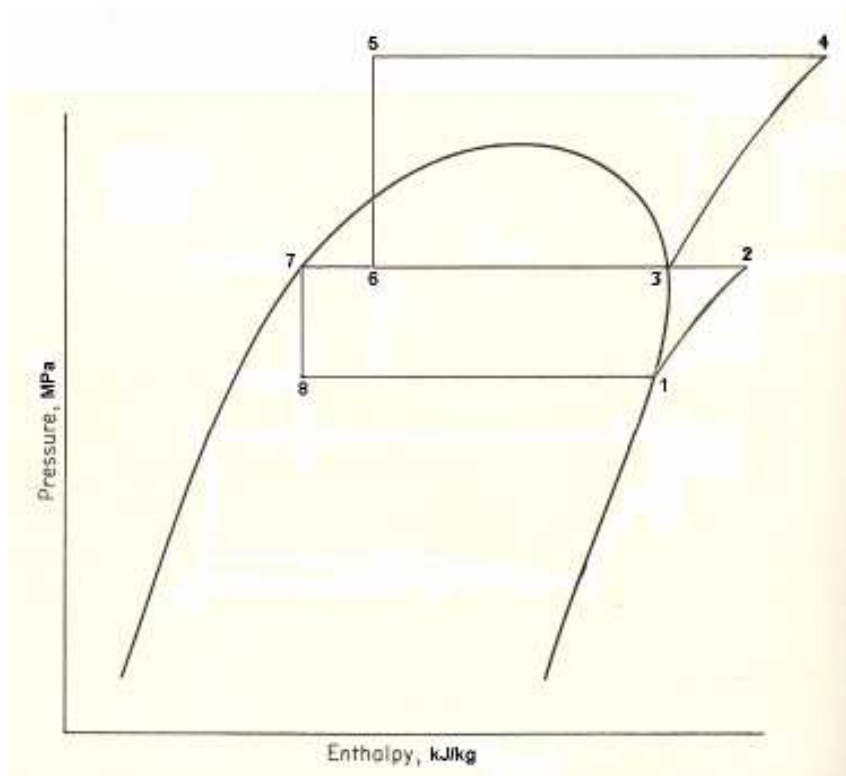


Figure 2.4 p-h Diagram for Two-stage CO_2 Vapor Compression Cycle with Intercooler Efficiency Equal to 100%

2.4 Simulations

Several visual basic programs were written and used to analyze the one and two-stage CO_2 vapor compression cycles. Properties of carbon dioxide were obtained by using interpolation functions for particular regions applicable to refrigeration processes. These interpolation functions were extracted from the property tables provided by the NIST website at <http://webbook.nist.gov/chemistry/fluid/>. Isothermal as well as isobaric properties were obtained and used to develop equations for different CO_2 properties as a function of temperature, pressure, enthalpy, and entropy in excel. For all programs, the high pressure was allowed to range from 10 to 15 Mpa, and the low pressure from 3 to 6 Mpa. For the two-stage CO_2 cycle, the intermediate pressure ranged from 3.1 to 7 Mpa. For the general first case analysis of the single-stage cycle, the high pressure, low pressure, quality at point 4, Q of the evaporator, and compressor efficiency were inputs to the program. The calculated outputs included the mass flow rate, power input to the compressor, Q of the gas cooler, and the coefficient of performance. The enthalpy and entropy at state 1 for all one-stage and two-stage analyses were interpolated from equations giving saturated vapor data as a function of pressure. The ideal location of state 2 is determined by the entropy at point 1, as for an isentropic process:

$$s_1 = s_2 \quad (2.16)$$

From this s_2 value, the corresponding enthalpy is directly interpolated from constant pressure equations relating enthalpy to entropy. Using the efficiency and the isentropic enthalpy at point 2, the actual enthalpy at point 2 was calculated from the relationship:

$$\eta_{comp} = (h_2 - h_1)/(h_{2a} - h_1) \quad (2.17)$$

where h_{2a} is the actual enthalpy at state 2 used in the rest of the calculations. This program involves the input of the quality at 4, utilizing equation (2.4) to obtain the enthalpy at 4, where the saturated liquid and vapor enthalpies at the low pressure are interpolated. Equation (2.3) is applied, thus each state is identified for the calculation phase. The results from this program are presented in Figures 2.8 through 2.12. A similar program involved using the temperature at point 3 as an input for the one-stage cycle instead of the quality at point 4. The quality at 4 was then given as an output. The enthalpy at 3 was interpolated from enthalpy versus temperature equations at each of the 6 high pressures between 10 and 15 Mpa. The enthalpy at 4 was then given by equation (2.3). States 1 and 2 were found the same way as in the first program. The results from this program are seen in Figures 2.14 and 2.15 for 2 different temperature ranges for the temperature at point 3. The third different program for the single-stage cycle had the temperature at point 4 as an input and the low pressure as an output. The low pressure is interpolated directly from the temperature at 4, and the rest of the states are determined in the same manner as above. The results from this program are displayed in Figure 2.13.

For the two-stage cycle, 4 different programs were used to develop the resulting plots. The first basic program had inputs of high pressure, low pressure, intermediate pressure, Q of the evaporator, efficiency of the 2 compressors, and the enthalpy at point 5, which equals h_6 . For comparison purposes, h_5 and h_6 were set equal to enthalpies 3 and 4 from the single-stage analysis, therefore; the two-stage system was solved for a given quality at point 4 of the one-stage cycle. States 1 and 2 were found using the same methods as were used for the one-stage analyses, except for the pressure at point 2, which is the intermediate pressure instead of the high pressure. The equations used to

interpolate the enthalpy at point 2 gave enthalpy as a function of entropy for 5 constant pressures from 3 to 7 Mpa. The enthalpy and entropy at state 3 were found using the equations giving saturated vapor values as a function of pressure at the intermediate pressure, between 3.1 and 7 Mpa. Point 3 was located on the saturated vapor line since there was no efficiency introduced for the intercooler. The enthalpy at state 4 was interpolated using the same enthalpy versus entropy equations at the high pressure as used for state 2 for the one-stage cycle. State 7 was saturated liquid at the intermediate pressure, and the enthalpy at 8 followed from equation (2.12). The enthalpy values at all states were outputted, excluding h_5 and h_6 , along with the mass flow rates for the upper and lower portions of the cycle and the quality at point 6. The remaining outputs were the same as the one-stage cycle above. The results were plotted in Figures 2.8 through 2.12 as well as in Figure 2.16. The second program developed used the temperature at point 5 as an input, instead of the enthalpy at 5 and 6. The enthalpy at point 5 was then interpolated in the same fashion as point 3 in the one-stage cycle discussed above. Enthalpy 6 followed from equation (2.11), and the remaining enthalpies were found as mentioned above. Similarly, enthalpies 1 through 4 were located as described above. The outputs of this program were identical to the previous with the additional $h_5 = h_6$ value. The results are seen in Figures 2.14, 2.15, 2.17 and 2.18. The evaporator temperature, T_8 , along with the enthalpy at point 5 were inputs in the next program. The low pressure was interpolated from the low temperature, T_8 , and the remaining states were calculated using the same procedure as the first two-stage cycle analysis discussed above. The same outputs were computed along with the low pressure. The results are

presented in Figure 2.13. The final program involved using an intercooler efficiency to describe the location of point 3, as:

$$\eta_{HX} = (h_2 - h_3)/(h_2 - h_{gl}) \quad (2.18)$$

where h_{gl} is the enthalpy at the saturated vapor line at the intermediate pressure. The enthalpy at point 3 was calculated using equation (2.18) with a specified intercooler efficiency. The entropy at point 3 was interpolated from entropy versus enthalpy equations for the 5 different pressures within the intermediate pressure range of 3 to 7 Mpa. Point 4 was defined the same as in the previous two-stage programs. All other enthalpies were found according to the first two-stage program discussed above. The results are plotted in Figures 2.19 and 2.20.

Form1

High Pressure 10 - 15 (MPa)	12	Low Pressure 3 - 6 (MPa)	4	$h_6 = h_5$	256.07	Intermediate Pressure (3.1 - 7 MPa)	5.1962
Q_{evap} (kW)	1.45	Efficiency for Compressor 1 and 2	0.8	Efficiency for Intercooler	0.9		
<input type="button" value="Evaluate"/>							
		$s_1 = s_2 = s_{g1}$ (kJ/kg*K)	1.8145			$T_7 = T_6$	289.0513
h_1 (kJ/kg)	427.2433	$T_1 = T_8$ (K)	278.3929			$h_7 = h_8$	242.5729
h_{2a} (kJ/kg)	438.6144	h_2 (kJ/kg)	436.3402			Quality at point 6 x_6	0.0781
s_3	1.7498	h_3 (kJ/kg)	417.5097			h_4	447.3344
s_{g1}	1.7424	h_{g1}	415.4174			h_{4a} (kJ/kg)	454.7906
		Work Input (kW)	0.4447	m_2	0.007852	m_3	0.009535
		$Q_{gas\ cooler}$ (kW)	-1.8947	C.O.P.	3.2603		

Figure 2.5 Example Visual Basic Program; Two-stage CO_2 System with Compressor and Intercooler Efficiencies

Form1

High Pressure 10 - 15 (MPa)	14	Low Pressure 3 - 6 (MPa)	6	Quality at point 4 x4	0.2	Q _{evap} (kW)	1.45
compressor efficiency	0.85						
Evaluate							
s ₁ = s _{gL} (kJ/kg·K)	1.6864	h ₃ = h ₄ (kJ/kg)	290.9348				
T ₁ = T ₄ (K)	295.0254						
h ₁ (kJ/kg)	403.4156						
h ₂ (kJ/kg)	430.8398	h _{2a} (kJ/kg)	435.6794				
Work Input (kW)	0.4159	mevap	0.012891				
Q _{gas cooler} (kW)	-1.8659	C.O.P.	3.4863				

Figure 2.6 Example Visual Basic Program; Single-stage CO_2 System with Compressor Efficiency

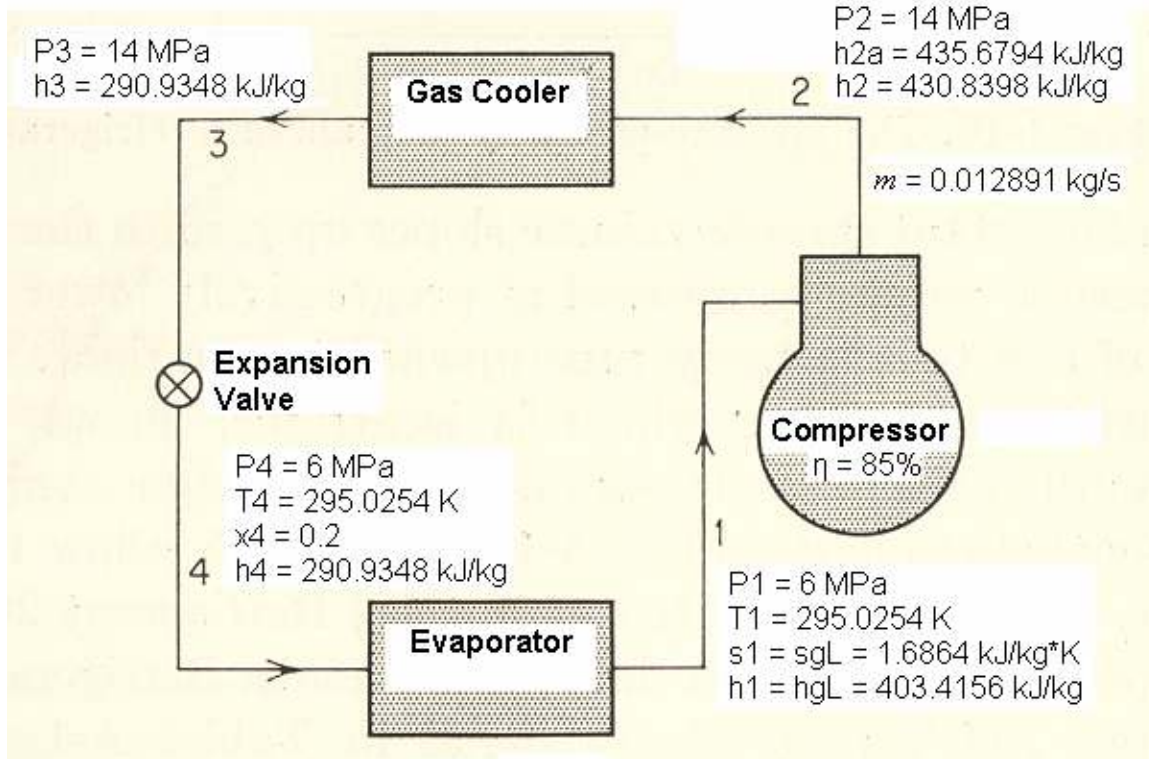


Figure 2.7 Schematic for Single-stage CO_2 System with Sample Visual Basic Program Values Corresponding to Figure 2.6

2.5 Discussion

The results of the visual basic programs are plotted in Figures 2.8 through 2.20, as indicated in the Simulations section. Each plot depicts the coefficient of performance against some particular pressure, quality, temperature, or efficiency. Figure 2.8 shows the COP versus Discharge Pressure (high pressure) where the quality at point 4 for the one-stage cycle is fixed at 0.2, which fixes enthalpies 3 and 4 in the one-stage analysis, and enthalpies 5 and 6 in the two-stage analysis. The low pressure was kept at 4 Mpa, the Q of the evaporator was 1.45kW, and the compressor efficiency was 100% for the ideal analysis. For the two-stage analysis, the intermediate pressure was varied as the discharge pressure varied by:

$$p_I = 0.75 \times \sqrt{p_H \times p_L} \quad (2.19)$$

where p_I is the intermediate pressure, p_H is the high pressure, and p_L is the low pressure. The second figure, Figure 2.9 involved varying the quality at state 4 for the one-stage cycle, which changed the enthalpies at 3 and 4 for the one-stage system, and enthalpies 5 and 6 for the two-stage system. The low pressure remained at 4 Mpa, the high pressure was fixed at 12 Mpa, the Q of the evaporator was 1.45 kW, and the compressor efficiency was 100%. The intermediate pressure for the two-stage cycle was constant from equation (2.19) since neither the high or low pressure changed. Figure 2.10 varied the evaporator pressure while keeping the high pressure constant at 12 Mpa, the quality at point 4 constant at 0.2, Q of the evaporator equal to 1.45 kW, and the compressor efficiency at 100%. The enthalpies at 3 and 4 in the single-stage system varied as did the enthalpies at 5 and 6 in the two-stage system due to the varying low pressure. The intermediate pressure also varied by equation (2.19), as the low pressure changed. Figure 2.11 depicts the COP as a function of compressor efficiency. The only changing parameter is the compressor efficiency. The high pressure is 12 Mpa, the low pressure is 4 Mpa, Q of the evaporator is 1.45 kW, and the quality at point 4 for the one-stage cycle is 0.2. Enthalpies 3 and 4 for the one-stage cycle and 5 and 6 for the two-stage cycle are constant. The intermediate pressure is constant. Figure 2.12 shows the COP as a function of high pressure for different compressor efficiencies. The low pressure was kept constant at 4 Mpa, and the quality at point 4 for the one-stage cycle was pinned at 0.2, which fixed the enthalpies at 3 and 4 for the one-stage analysis and enthalpies 5 and 6 for the two-stage analysis.

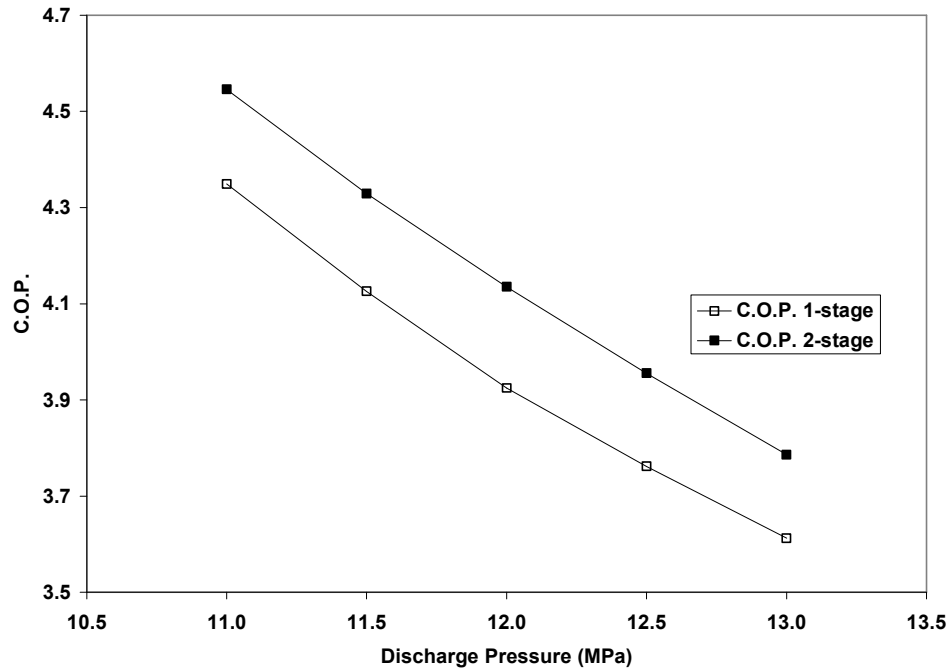


Figure 2.8 Coefficient of Performance vs. Discharge Pressure

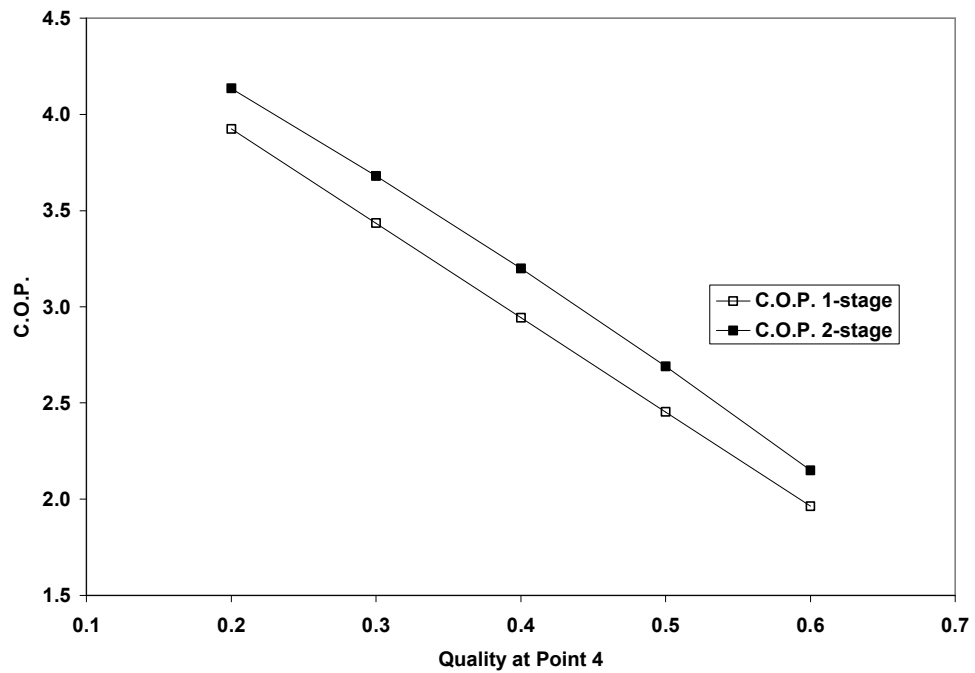


Figure 2.9 COP as a Function of Quality at Point 4 (Single-stage)

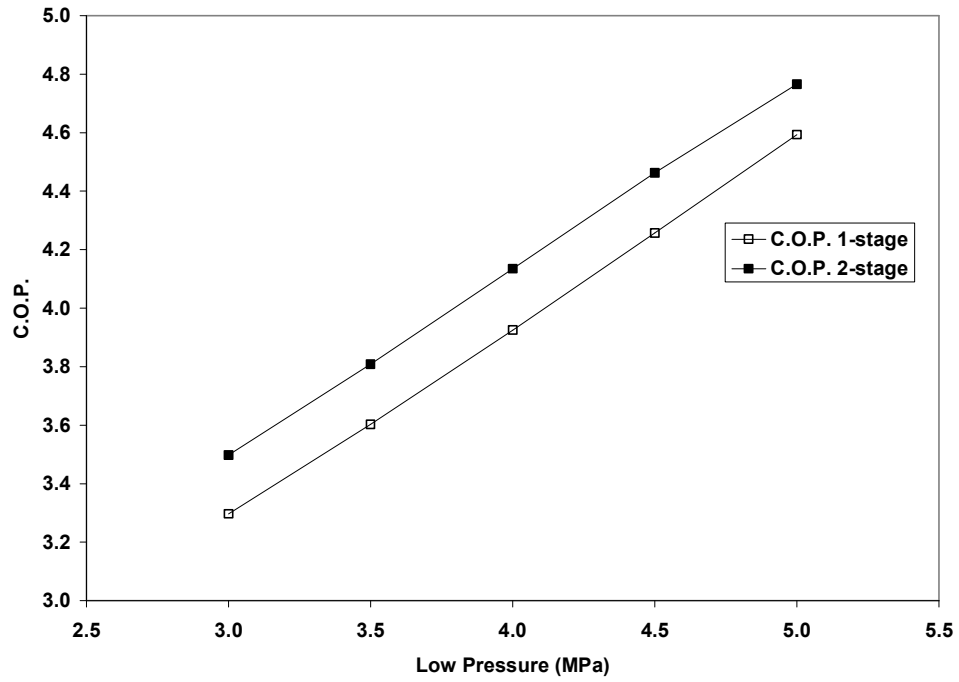


Figure 2.10 COP vs. Evaporator Pressure

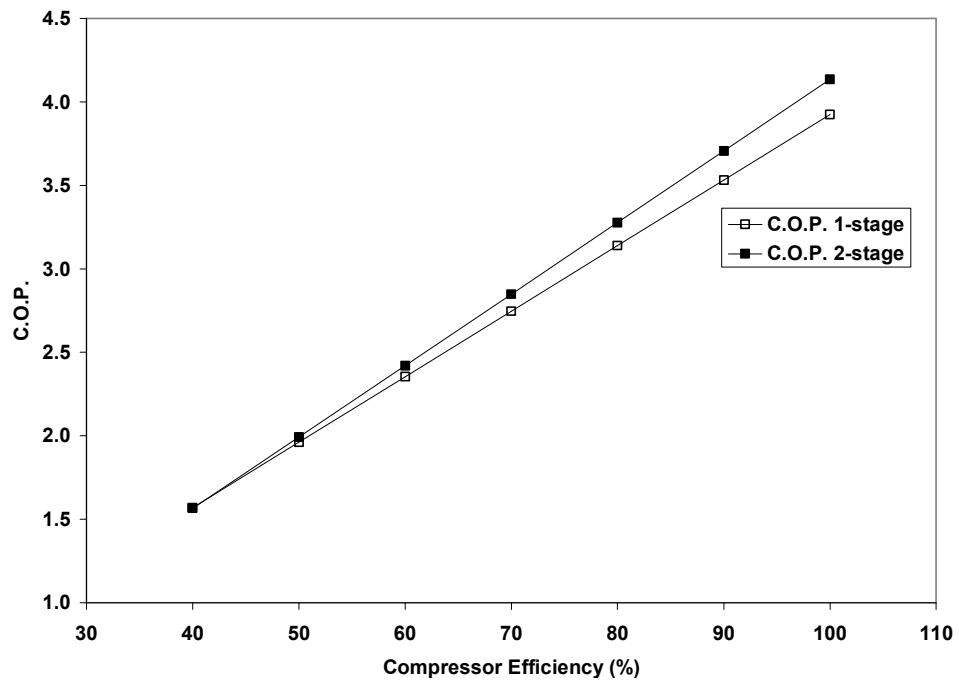


Figure 2.11 Coefficient of Performance vs. Compressor Efficiency

The Q of the evaporator remained constant at 1.45 kW while the intermediate pressure changed from equation (2.19). The coefficient of performance is graphed as the evaporator temperature is varied from 30 to 50 degrees F (-1.11 to 10.00 degrees C) in Figure 2.13. The high pressure is kept at 12 Mpa, the enthalpies at 3 and 4 in the one-stage cycle vary as do the enthalpies 5 and 6 in the two-stage cycle, as the quality at point 4 is constant at 0.2. Q of the evaporator is 1.45 kW and the compressor efficiency is 100%. The intermediate pressure changes from equation (2.19), as the low pressure varies. The COP is plotted as the gas cooler exit temperature varies in Figures 2.14 and 2.15. Two different ranges for the gas cooler exit temperature are used to develop the plots. In Figure 2.14, the gas cooler exit temperature ranges from 25 to 35 degrees C. In Figure 2.15, the gas cooler exit temperature ranges from 43.85 to 53.85 degrees C. The high pressure is kept at 12 Mpa, the low pressure remains at 4 Mpa, Q of the evaporator is 1.45 kW, and the compressor efficiency is 100%. Enthalpies 3 and 4 for the single-stage system vary, along with enthalpies 5 and 6 for the two-stage system. The intermediate pressure remains constant according to equation (2.19) since the high and low pressures are constant. The quality at point 4 in the single stage system and the quality at point 6 in the two-stage system change since the low pressure and intermediate pressure are constant. The remaining 4 figures only apply to the two-stage system. Figure 2.16 shows the coefficient of performance as a function of intermediate pressure. The high and low pressures are maintained at constants of 12Mpa and 4 Mpa, respectively. The enthalpies at points 5 and 6 remain constant at a value equal to the enthalpies 3 and 4 for the one-stage system

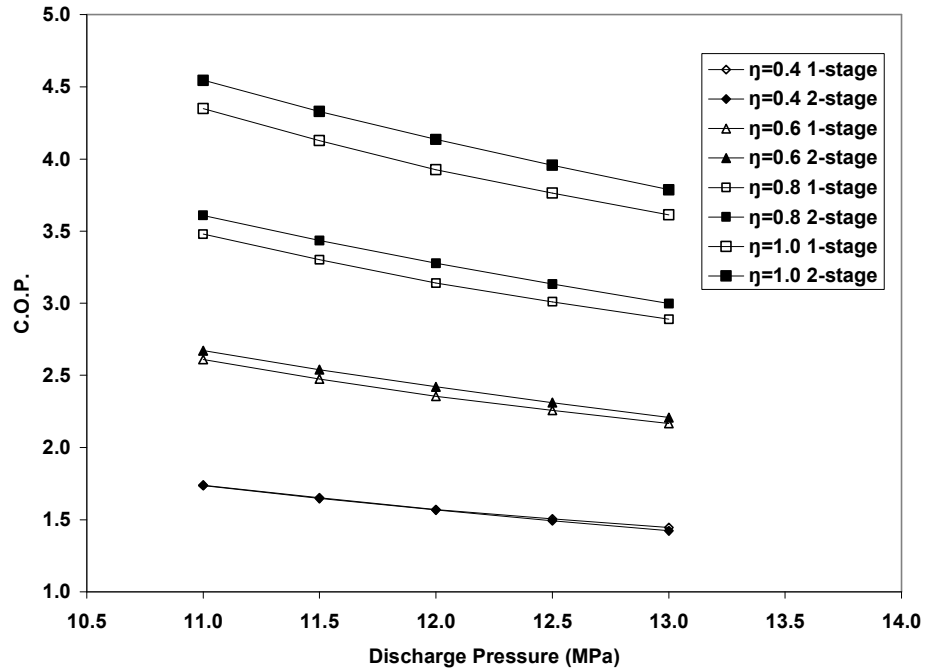


Figure 2.12 COP vs. Gas Cooler Pressure for Different Compressor Efficiencies

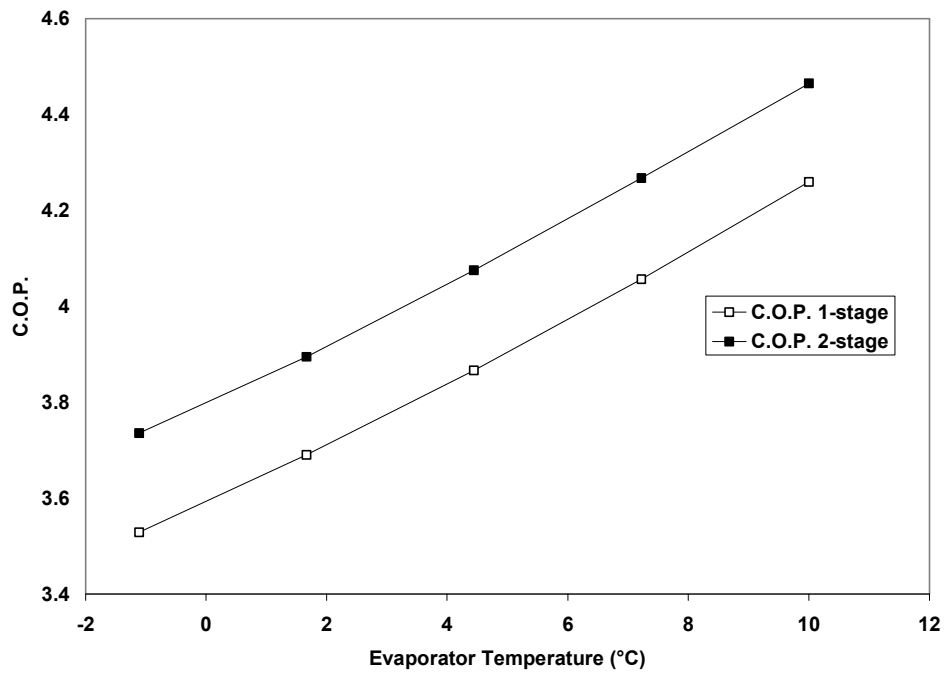


Figure 2.13 Coefficient of Performance vs. Evaporator Temperature (T4 or T8)

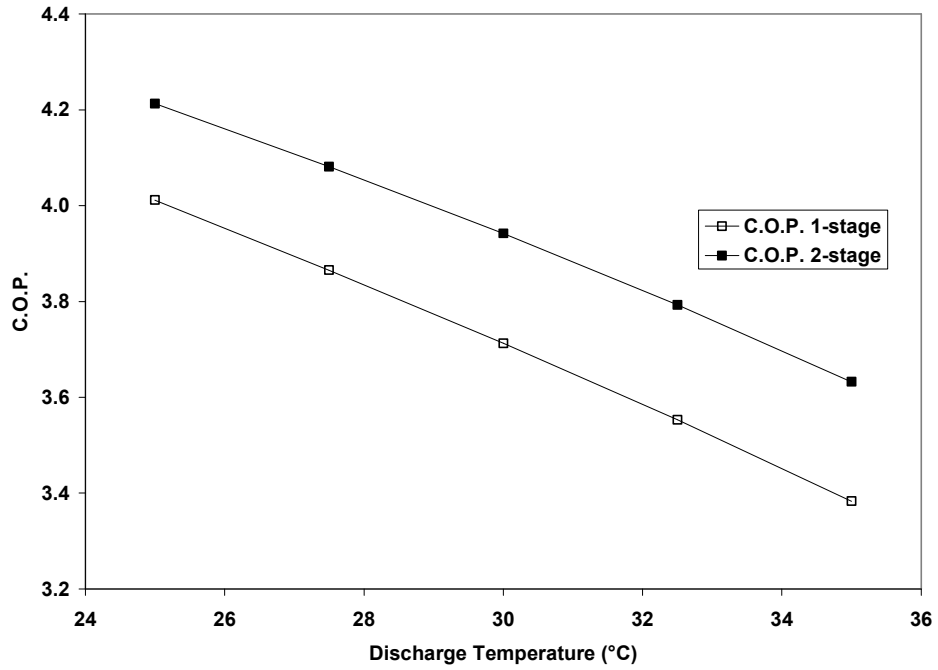


Figure 2.14 COP as a Function of Gas Cooler Exit Temperature (T3 or T5)

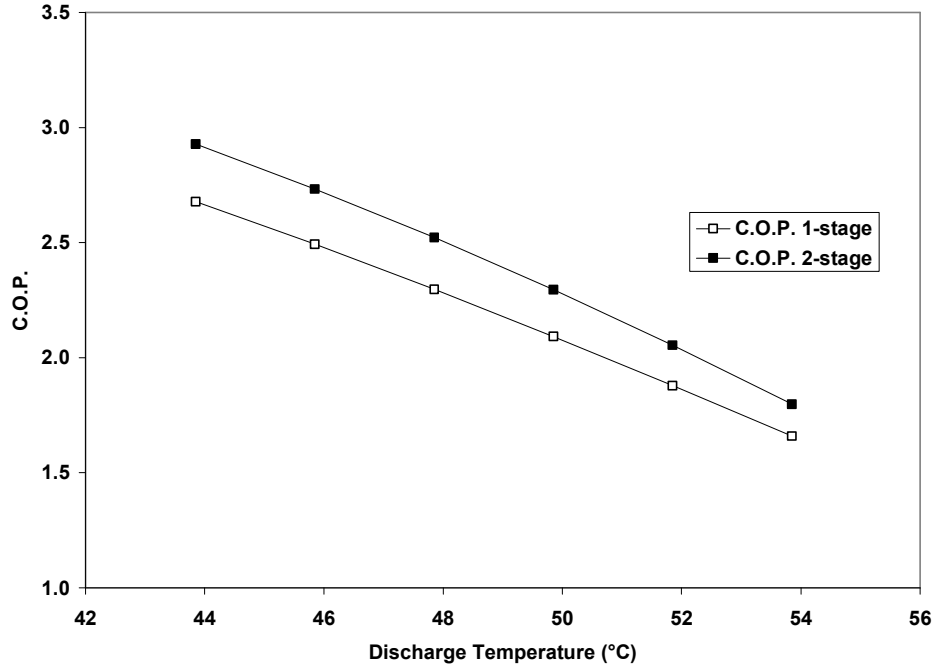


Figure 2.15 COP as a Function of Gas Cooler Exit Temperature (T3 or T5), High Temperature Range

with a quality at point 4 of 0.2. The Q of the evaporator and the compressor efficiency are equal to 1.45 kW and 100%, respectively. In Figures 2.17 and 2.18, the intermediate pressure is varied for 5 different gas cooler exit temperatures. Temperature 5 varies from 25 to 35 degrees C in Figure 2.17 and varies from 43.85 to 53.85 degrees C in Figure 2.18. The high and low pressures are held at 12 and 4 Mpa, respectively. The enthalpies at states 5 and 6 change as a result of varying the temperature at point 5. The Q of the evaporator was 1.45 kW and the compressor efficiency was 100%. Figure 2.19 plots the coefficient of performance versus the intercooler efficiency. The high and low pressures are again set at 12 and 4 Mpa, respectively. The intermediate pressure is constant according to equation (2.19), and the Q of the evaporator and compressor efficiency are held at 1.45 kW and 100%, respectively. The enthalpies at states 5 and 6 are held constant in the same way as described for Figure 2.16 above. Figure 2.20 shows the fluctuation of intermediate pressure for 5 different intercooler efficiencies. The high pressure is again 12 Mpa, and the low pressure is 4 Mpa. The enthalpies at 5 and 6 are the same as indicated in the analysis for Figure 2.16. The Q of the evaporator and the compressor efficiency are again 1.45 kW and 100%.

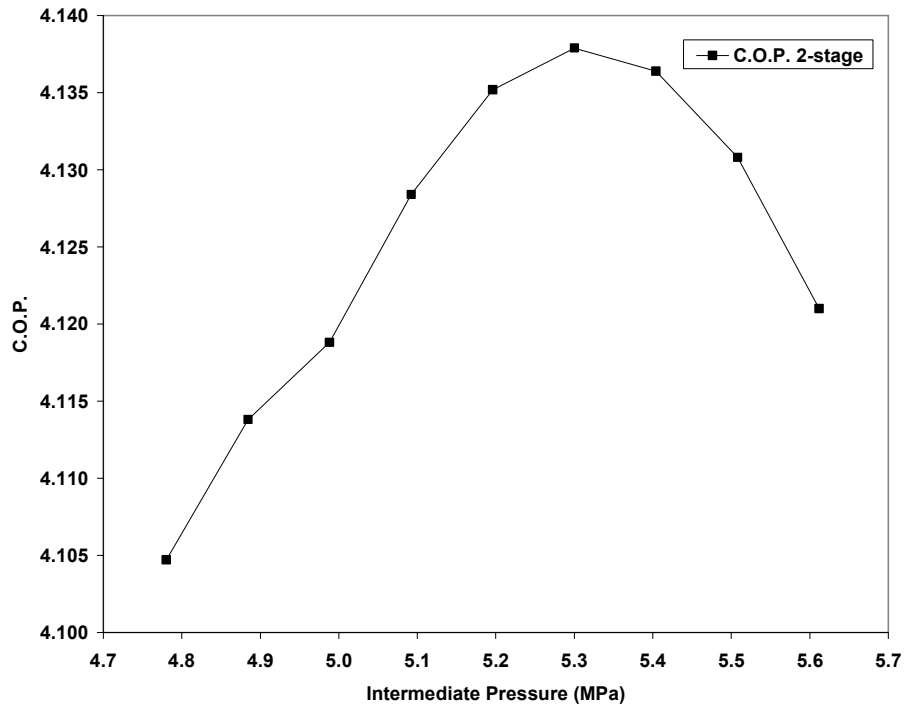


Figure 2.16 COP vs. Intermediate Pressure

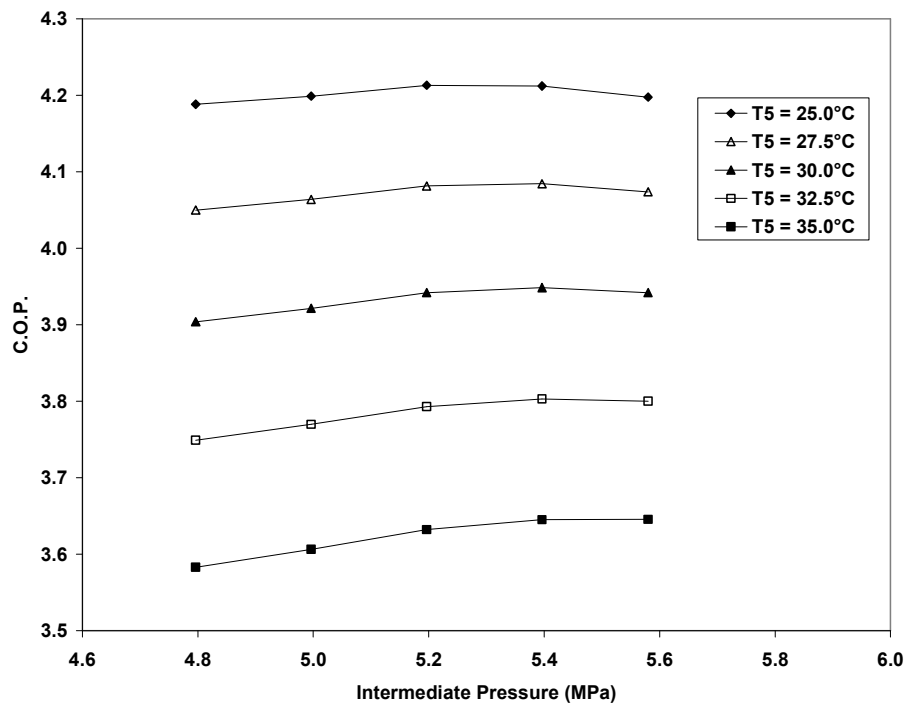


Figure 2.17 Coefficient of Performance vs. Intermediate Pressure for Different Gas Cooler Exit Temperatures

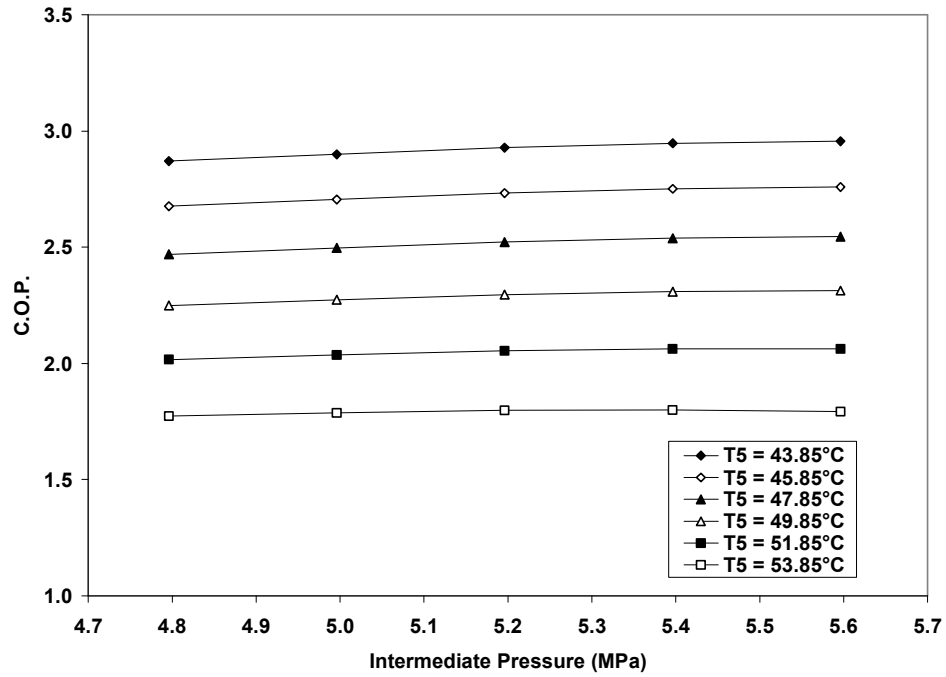


Figure 2.18 Coefficient of Performance vs. Intermediate Pressure for Different Gas Cooler Exit Temperatures (High Temperature Range)

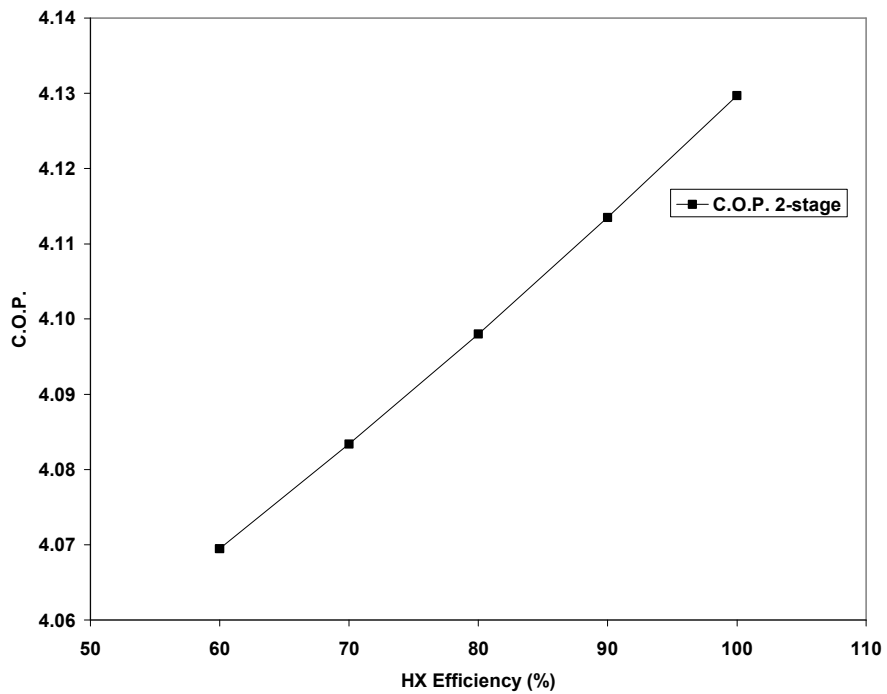


Figure 2.19 COP as a Function of Intercooler Efficiency

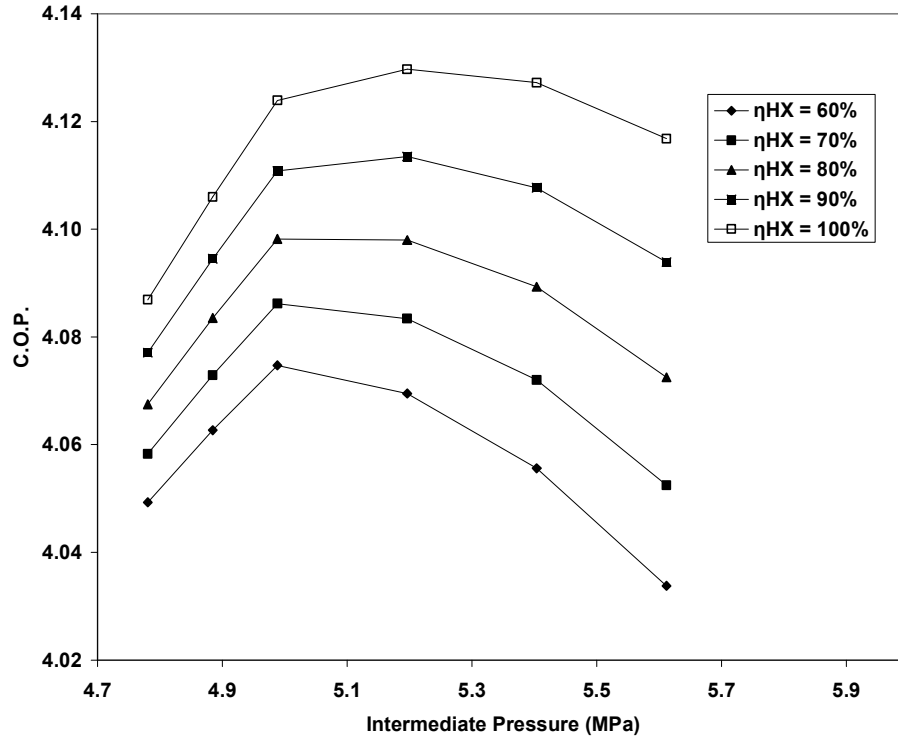


Figure 2.20 COP vs. Intermediate Pressure for Different Intercooler Efficiencies

2.6 Results and Conclusions

The results in Figure 2.8 indicate a decline in coefficient of performance with an increase in discharge pressure. As the high pressure increases, the enthalpy at the entrance to the gas cooler increases, and creates a larger difference $h_2 - h_1$ for the one and two-stage cycles, and a larger difference $h_4 - h_3$ for the two-stage cycle. The work follows from equation (2.1) for the one-stage analysis and equations (2.6) and (2.7) for the two-stage analysis. A larger work decreases the COP according to equations (2.14) and (2.15). Figure 2.9 shows an almost linear decline in coefficient of performance with increasing quality at point 4. This can be illustrated for the one-stage system by looking at equations (2.4), (2.5), and (2.14). As the quality increases, the enthalpy at points 3 and

4 increases, which decreases the difference $h_1 - h_4$. Since Q_{4-1} is constant for this analysis, the mass flow rate increases from equation (2.5), and the COP decreases from equation (2.14). For the two-stage cycle, the mass flow rate through the upper portion of the cycle, m_2 , increases with a rise in enthalpy at point 6, which occurs because of an increase in quality at point 4 for the one-stage cycle. This can be seen in equation (2.9) where the absolute value of the difference $h_6 - h_3$ decreases as h_6 increases. This increases m_2 , which increases the work for the second compressor according to equation (2.7), and decreases the COP. Figure 2.10 shows an increase in coefficient of performance with an increase in low pressure. As the low pressure increases, the difference $h_2 - h_1$ decreases since points one and two become closer on the p-h diagram and the constant entropy lines become more vertical as the pressure increases. This decreases the work input for the one-stage and two-stage cycles according to equations (2.1) and (2.6). The work in the second compressor is also decreased for the two-stage cycle since the mass flow rate in the upper portion of the cycle decreases. This is a result of a smaller enthalpy at point 2, and a smaller difference between the enthalpy at points 7 and 2, which lowers m_2 and W_{3-4} . This can be seen by examining equations (2.9) and (2.7). These lower work values increase the COP from equations (2.14) and (2.15). Figure 2.11 shows a linear relationship between the coefficient of performance and the compressor efficiency. As the compressor efficiency increases, the enthalpy at point 2 moves closer to the isentropic value of h_2 for the one-stage analysis. As h_{2a} decreases, the compressor work decreases, which increases the COP. For the two-stage analysis, both compressor efficiencies are equal, and as they increase, the two compressor works

decrease which increases the COP. The COP appears to increase at a greater rate for the two-stage cycle as opposed to the one-stage cycle. This can be attributed to the two compressor system where the efficiency controls two work values. Figure 2.12 shows how the COP changes with increasing discharge pressure for four different compressor efficiencies. As expected from previous results, the coefficient of performance decreases with increasing discharge pressure. The results plotted in Figure 2.12 indicate that the rate at which the COP decreases tends to increase as the compressor efficiency climbs from 40% to 100%. Figure 2.13 shows that the COP increases as the evaporator temperature increases. This agrees with the results obtained using similar conditions where the COP increased with increasing evaporator pressure in Figure 2.10. The same explanation applies to the results in Figure 2.13 as the gap between the enthalpies at the entrance and exit to the compressor decrease with an increasing low (saturation) temperature. This decreases the work and increases the COP. Figures 2.14 and 2.15 depict the coefficient of performance as a function of increasing gas cooler exit temperature. The COP decreases with increasing gas cooler exit temperature. As the gas cooler exit temperature increases for a constant high pressure, the enthalpy at points 3 and 4 for the one-stage analysis increases, which decreases the difference $h_1 - h_4$. With a constant Q of the evaporator, the mass flow rate increases from equation (2.5). Using equation (2.1), the compressor work increases, decreasing the COP. For the two-stage cycle, the enthalpy at points 5 and 6 increases due to the increasing gas cooler exit temperature. This forces the mass flow rate in the upper portion of the cycle to increase due to equation (2.9). This forces the work to increase and the COP to decrease according to equations (2.7) and (2.15). The purpose of Figure 2.15 is to view the COP

and the COP trend using practical temperatures for the gas cooler exit temperature. The COP is significantly lower for this high temperature range, but the trend for the COP is very similar to that seen in Figure 2.14. Figure 2.16 shows how the COP fluctuates with increasing intermediate pressure. The coefficient of performance increases as the intermediate pressure increases until an inversion point is reached. For intermediate pressures above this inversion point, the COP decreases as p_i increases. This can be explained by examining the p-h diagram for the two-stage CO_2 cycle. The total work input is equal to the work input to compressor 1 plus the work input to compressor 2. These individual works, described by equations (2.6) and (2.7), depend on the location of the intermediate pressure. There is an intermediate pressure, approximately 5.3 Mpa from Figure 2.16, which minimizes the total work. Above and below this particular intermediate pressure, the COP is lower since the work is greater than the minimum value. The mass flow rate in the lower portion of the two-stage cycle, m_1 , increases as the intermediate pressure increases, since the enthalpy at point 8 increases, reducing the difference $h_1 - h_8$. This tends to increase m_1 from equation (2.13). Figure 2.16 is valid for a range of intermediate pressures from approximately 4.8 Mpa to 5.6 Mpa. The trend is likely to change for different ranges of high, low, and intermediate pressures. Figures 2.17 and 2.18 illustrate how the coefficient of performance changes as a function of intermediate pressure for different gas cooler exit temperatures. In Figure 2.17, T_5 ranges from 25 to 35 degrees C. In Figure 2.18, T_5 ranges from 43.85 to 53.85 degrees C. This temperature range represents a more practical range for the gas cooler exit temperature. The COP is significantly lower for the higher gas cooler exit temperature

range, as seen in Figure 2.15. Four of the five trends in Figure 2.17 contain a peak COP value, where the trend for 35°C does not peak for the given intermediate pressure range. The trends for the last 2 temperatures in Figure 2.18 contain a peak COP value whereas the first 4 trends do not reach a maximum COP value in the intermediate pressure range used. The trends mirror the results obtained in Figure 2.16, but appear much flatter because of the range for the COP values on the y-axis. The values for the coefficient of performance are lower for higher gas cooler exit temperatures, but the trends remain very similar. This follows from the relationship between the enthalpy at points 5 and 6 and the gas cooler exit temperature. As the temperature at point 5 increases on a constant pressure line, the enthalpy at points 5 and 6 increases, which drives the mass flow rate in the upper half of the cycle up, equation (2.9), and increases the work. This decreases the COP. Figure 2.19 shows that the COP increases with increasing intercooler efficiency. As the intercooler efficiency increases, point 3 moves closer to the saturated vapor point at the intermediate pressure. The closer point 3 is to the saturated vapor location, the more vertical the constant entropy lines are on the p-h diagram. This results in a minimum value for the enthalpy at point 4 when point 3 is located on the saturated vapor line, since the entropy at point 3 equals the entropy at point 4 for an ideal compressor. A smaller enthalpy at point 4 gives a smaller work for the second compressor, and therefore; reduces the COP. Figure 2.20 illustrates a combination of the results obtained in Figures 2.16 and 2.19. The COP increases until it reaches a maximum value at a certain intermediate pressure, and then decreases for higher intermediate pressures. The trends remain unchanged for 5 different intercooler efficiencies, where the smallest COP values occur for the lowest intercooler efficiencies as expected. The intermediate

pressure corresponding to the inflection point seems to decrease as the intercooler efficiency decreases. At an intercooler efficiency of 100%, the inflection point occurs around 5.2 Mpa, whereas at an intercooler efficiency of 40% the inflection point occurs close to 5 Mpa.

The no HX trace in Figure 2.21 contains data from the visual basic program that does not include an intercooler efficiency calculation. The HX efficiency = 100% trace in Figure 2.21 contains data from the visual basic program that includes an intercooler efficiency calculation. Theoretically, the traces should be exactly on top of one another, but they are significantly different, as seen in Figure 2.21. This is due to the fact that the entropy at point 3 is found from an interpolation function using the intermediate pressure (as s_3 is equal to s_{gI}) for the program not including an intercooler efficiency calculation. Alternatively, the entropy at point 3 is found using an interpolation function involving the enthalpy at point 3 and the intermediate pressure in the program that includes an intercooler efficiency calculation. This extra interpolation function causes s_3 to differ for the two programs.

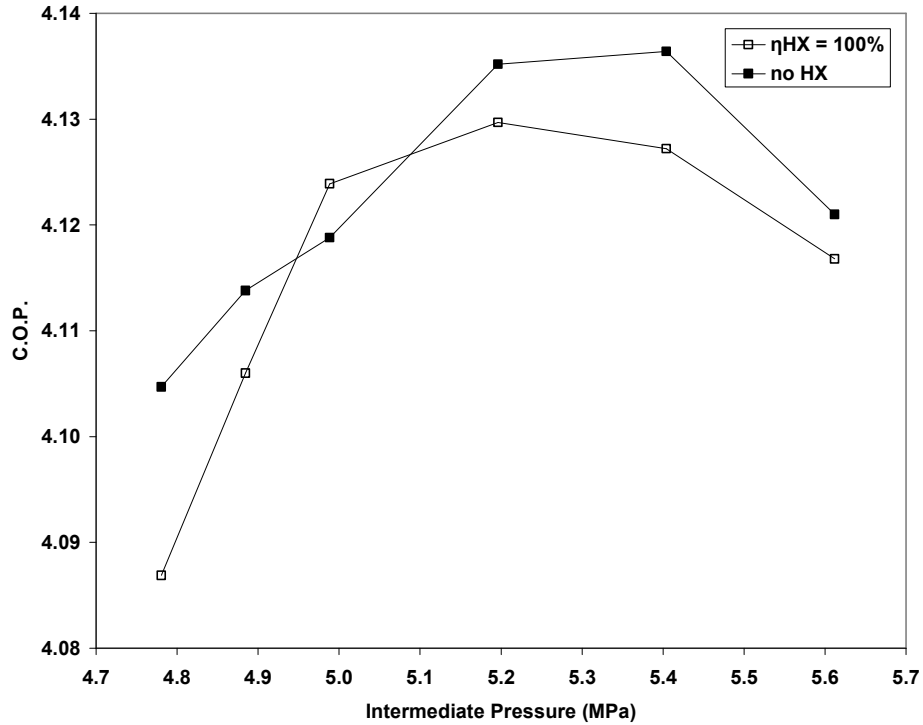


Figure 2.21 COP vs. Intermediate Pressure Using 2 Different Programs

Table 2.1 shows a comparison of COP values for Carbon Dioxide and Refrigerant 134a cycles using base case conditions, as listed below. The COP values for the one and two-stage CO_2 cycles are taken from the visual basic simulations presented above, while the COP value for the R134a one-stage cycle is produced from hand calculations using the equations presented above and properties for R134a taken from a thermal text. The Base case conditions used throughout this portion of the thesis are presented below.

Table 2.1
Comparison of Coefficient of Performance for Carbon Dioxide and Refrigerant 134a Cycles Using Base Case Conditions

COP		
CO_2		R134a
1-stage	2-stage	1-stage
3.9248	4.1352	11.6093

Base case conditions consist of:

- quality at point 4 for one-stage cycle = 0.2
- high pressure = 12 Mpa
- low pressure = 4 Mpa
- intermediate pressure = 5.1962 Mpa
- Q evaporator = 1.45 kW
- h_3 and h_4 for one-stage cycle = 256.07 kJ/kg
- h_5 and h_6 for two-stage cycle = 256.07 kJ/kg
- compressor efficiencies for one and two-stage cycles = 100% *
- intercooler efficiency for two-stage cycle = 100%

* The compressor efficiency is considered to be 100% for the base case since the simulations present an initial analysis for a carbon dioxide transcritical cycle.

Table 2.2 compares results from our model simulation and results presented by Aydin [16] according to ARI Standard [17]. This simulation value corresponds to an intercooler efficiency of 100% (ideal condition) and a compressor efficiency of approximately 60%. The remaining previously listed base case conditions apply except for the compressor efficiency. As expected, simulation model COP shows a higher performance than experimental data. This can be explained by realizing the inefficiencies in a real system. However, our result is in reasonable agreement with experimental data based on the general assumptions made (ideal conditions).

Table 2.2
 Comparison of Coefficient of Performance
 for Simulation and Experimental Results

	COP	
	<i>Simulation</i>	<i>Experimental</i> [6]
CO ₂ 2-stage ARI Standard [7]	2.05	1.76

Chapter 3

Thermodynamic Analysis of Reheat Dehumidification Air Conditioning Cycles

3.1 Introduction

The air conditioning industry is turning to different reheat methods for dehumidification and cooling in hot and humid environments. Reheat is needed to heat the air exiting the evaporator to produce comfortable conditions for the cooled room. In addition, reheat is used to trick the air conditioning system into running constantly to dehumidify the air in the evaporator. Many dehumidifying reheat cycles used in the past do not take advantage of the potential of the refrigerant in the condenser to reheat the air. To utilize this potential, part of the refrigerant from the condenser and part of the area of the condenser are used in the reheat coil. Taras [18] presents four separate mechanical dehumidifying cycles which utilize reheat to obtain the desired conditions. These four cycles fall into two categories of reheat that are currently used. The two basic categories are based on the concepts of using warm liquid refrigerant and hot gas refrigerant schemes. Warm liquid refrigerant passes through the reheat coil in The Warm Liquid Refrigerant Cycle, and hot gas passes through the reheat coil in the two Hot Gas Refrigerant Cycles. A mixture of warm liquid and hot gas flows through the reheat coil in the Two-phase Mixture Refrigerant Cycle. In the process of selecting which

mechanical dehumidification system to use when utilizing primary refrigerants, the application requirements are among the most important issues that need to be addressed.

There are four goals of this section of the thesis. The first goal is to use thermodynamic analysis to simulate four different air conditioning dehumidification cycles using primary refrigerant. This involves writing four different visual basic programs that simulate their respective dehumidification cycle. The second goal is to perform a sensitivity analysis of the four cycles for varying reheat load conditions and application parameters, such as temperatures, pressures, and qualities. The third goal is to compare the performance of different refrigerants in the Warm Liquid Refrigerant Cycle by looking at key parameters such as the reheat coefficient of performance. The final goal is to compare cycle performance among the four cycles by varying the most representative application parameters, which are determined through simulation.

3.2 Warm Liquid Refrigerant Cycle

3.2.1 Thermodynamic Cycle

The Warm Liquid Refrigerant Cycle is the first cycle discussed in the thesis. The cycle is illustrated by a schematic in Figure 3.1 and a p-h diagram in Figure 3.2. At state 1 the refrigerant exists as a saturated vapor or a superheated vapor, with its value depending on the low side pressure and temperature at point 1. This temperature is limited by the indoor air temperature at the inlet to the evaporator. The refrigerant then passes through the compressor where its enthalpy increases and entropy remains the same (for a 100% efficient cycle). The enthalpy at state 2 therefore, represents that of a superheated vapor, with its value depending on the high side pressure. The refrigerant

then passes through the condenser, where its enthalpy decreases at the high side pressure. The enthalpy at state 3 is determined by the quality of the refrigerant at point 3, which depends on the outdoor air temperature and size of the condenser. The refrigerant is separated into two streams at the three-way valve. One stream is routed through the reheat coil, while the other stream bypasses the reheat coil. The enthalpy of the refrigerant as it passes through the bypass is equivalent to the enthalpy at state 3. The enthalpy at the entrance to the reheat coil is identical to that at state 3 while the enthalpy at the exit of the reheat coil is dictated by the temperature at point 4a (exit of the reheat coil). This temperature is limited by the temperature of the indoor air exiting the evaporator and by the size of the reheat coil. State 4 exists at the exit of the mixture between the bypass and reheat coil refrigerant streams. The enthalpy at this point is dependent on the enthalpies and flow rates existing at the mixture location. Next, the refrigerant passes through the expansion valve, where its enthalpy remains constant and its pressure drops to the low side pressure. States 5 and 1 are linked by the evaporator, which operates at the low side pressure. The heat addition to the evaporator is limited by the size of the evaporator and indoor air temperature at the evaporator inlet. Notice the arrangement in this cycle, where the reheat coil is placed after the condenser.

*Subscripts **

- 1-2 Compression process from state 1 to 2
- comp Compressor
- cond Condenser
- evap Evaporator

reheat	Reheat
total	Mass flow rate through evaporator
3b	Mass flow rate through non-reheat bypass
f	Saturated liquid
g	Saturated vapor
1	State at evaporator exit
2	State at compressor exit
3	State at condenser exit
4a	State at reheat exit
4	State at expansion valve inlet
5	State at expansion valve exit/evaporator inlet

3.2.2 Model Formulation

Figures 3.1 and 3.2 illustrate the schematic and p-h diagram for the Warm Liquid Refrigerant Cycle. States 1 through 5 are located in the schematic and described in the p-h diagram. The mass flow rates through the system are illustrated in Figure 3.1 with subscripts representing bypass, reheat, and total refrigerant flow rates. The cycle consists of three heat exchangers, three valves, and one compressor. Energy balances are performed about control volumes surrounding each of these components.

A compression process links states 1 and 2 by including a work input relating enthalpies as follows:

$$W_{1-2} = m_{total} \times (h_2 - h_1) \quad (3.1)$$

where W_{1-2} is the power input and has units of Btu/hr and m_{total} is the total mass flow rate through the system and has units of lbm/hr, as do all the mass flow rates in the analysis. The enthalpies h_1 and h_2 represent the energy per unit mass of the refrigerant at states 1 and 2, respectively, and have units of Btu/lbm, as do all enthalpies in the analysis. The energy balance for the condenser is omitted since it is not used to develop the simulation. State 3 is at the exit of the condenser and h_3 is calculated by the following equation:

$$h_3 = h_f(p_{cond}) + x_3 \times [h_g(p_{cond}) - h_f(p_{cond})] \quad (3.2)$$

where h_3 is the enthalpy at state 3, $h_f(p_{cond})$ is the saturated liquid enthalpy at the condensing pressure, $h_g(p_{cond})$ is the saturated vapor enthalpy at the condensing pressure, and x_3 is the quality of the refrigerant at state 3. Next, a mass balance about the three-way valve results in the following equation:

$$m_{total} = m_{reheat} + m_{3b} \quad (3.3)$$

where m_{reheat} is the mass flow rate through the reheat coil and m_{3b} is the mass flow rate through the non-reheat bypass. An energy balance at the reheat coil results in the following equation linking states 3 and 4a:

$$Q_{reheat} = m_{reheat} \times (h_3 - h_{4a}) \quad (3.4)$$

where Q_{reheat} represents the heat loss by the refrigerant at the reheat coil and h_3 and h_{4a} represent the enthalpies at the entrance and exit to the reheat coil, respectively. Moving through the system, an energy balance performed about the check valve is presented next:

$$m_{total} \times h_4 = m_{reheat} \times h_{4a} + m_{3b} \times h_3 \quad (3.5)$$

where the enthalpy at the mixture exit is h_4 . The energy balance around the expansion valve can be reduced to the following:

$$h_4 = h_5 \quad (3.6)$$

where h_5 is the enthalpy at the exit of the expansion valve and entrance to the evaporator, which is finally described by:

$$Q_{evap} = m_{total} \times (h_1 - h_5) \quad (3.7)$$

where Q_{evap} is the heat addition to the refrigerant in the evaporator. To evaluate the performance of the cycle, a parameter known as the coefficient of performance (COP) is calculated. For a reheat cycle, two different forms of the coefficient of performance can be calculated. The traditional COP is described below as the heat input at the evaporator divided by the work input at the compressor.

$$COP = Q_{evap} / W_{1-2} \quad (3.8)$$

An additional, more representative form of the coefficient of performance for a reheat cycle is shown below in equation (3.8), as presented below.

$$COP_{reheat} = (Q_{evap} - Q_{reheat}) / W_{1-2} \quad (3.9)$$

The heat loss in the reheat coil, Q_{reheat} , is a known parameter in the upcoming simulations, as it is calculated in equation (3.10) below.

$$Q_{reheat} = F_{reheat} \times Q_{evap} \quad (3.10)$$

The reheat factor is listed as F_{reheat} , and is presented in Table 3.2 as a base case variable.

The reheat coefficient of performance, COP_{reheat} , was calculated by hand from the above

equations for four different refrigerants. The results are plotted in Table 3.1. The base case conditions used to develop this table are shown in Table 3.2.

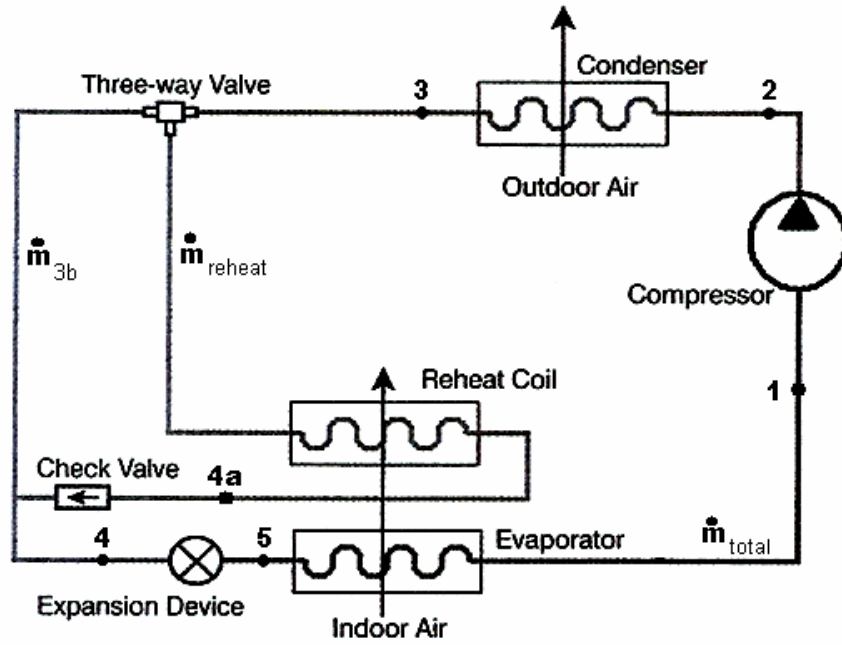


Figure 3.1 Schematic for Warm Liquid Refrigerant Cycle

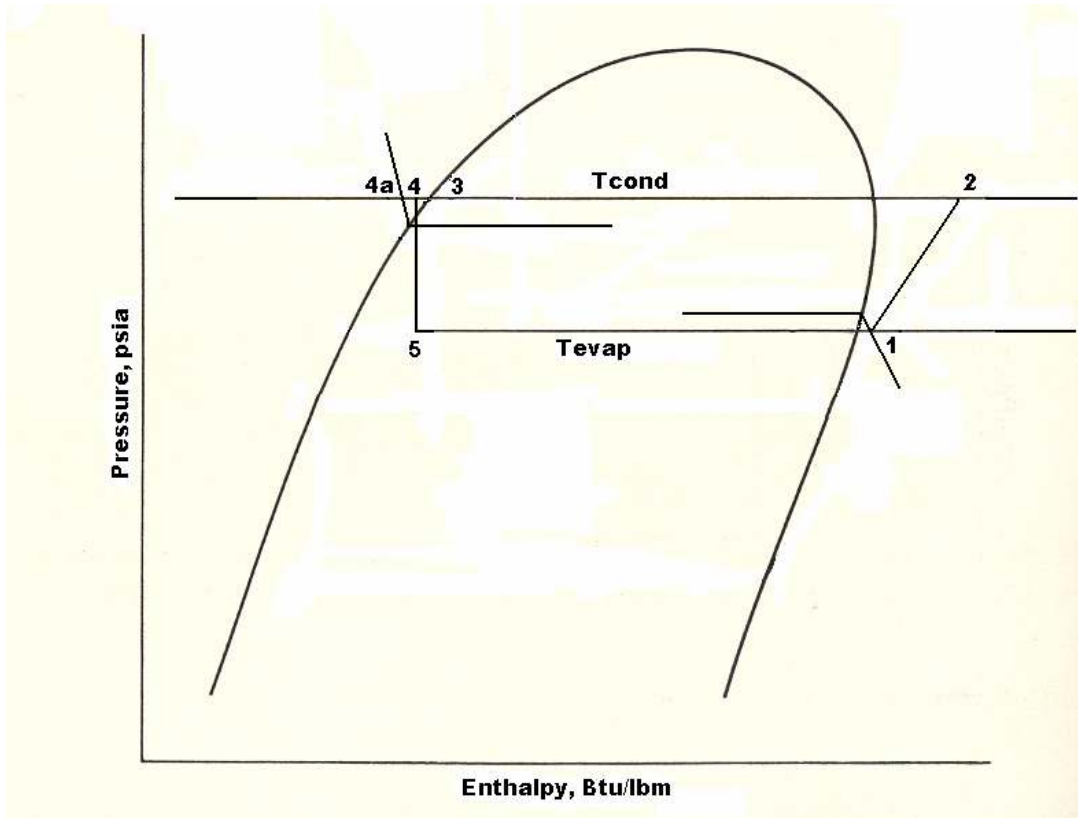


Figure 3.2 p-h Diagram for Base Case Warm Liquid Refrigerant Cycle

Table 3.1
Comparison of COP_{Preheat} for Different
Refrigerants Using the Warm Liquid
Refrigerant Cycle

Warm Liquid Refrigerant Cycle Base Case COP _{Preheat} Comparison	
Refrigerant	COP _{Preheat}
R134a	8.63
R22	8.62
R717 (Ammonia)	8.84
R410a	8.33

Table 3.2
Base Case Conditions for the
Warm Liquid Refrigerant Cycle

Base Case Conditions	
Pevap	49.741 psia
Tevap	40°F
T1	45°F
Pcond	119.01 psia
Tcond	90°F
x3	0
T4a	80°F
Freheat	0.02
Qevap	60016.2398 Btu/hr
η_{comp}	100%

3.2.3 Simulations

A visual basic program was written to simulate the Warm Liquid Refrigerant Cycle using equations (3.1) through (3.10) described above. Thermophysical properties of refrigerant 134a, R134a, were used from the NIST website at <http://webbook.nist.gov/chemistry/fluid/>. Isobaric and saturation properties of R134a were taken for common regions associated with refrigeration applications. This data was input into tables in excel and corresponding equations were developed to interpolate properties. The equations depicted enthalpy versus temperature or enthalpy versus entropy for the different operating regions. The error introduced from these interpolation equations was calculated to be less than 1%.

The base case evaporator temperature is 40°F, which corresponds to an evaporator pressure of 49.741 psia. The evaporator pressure and temperature at the evaporator exit, T_1 , are inputs in the program. The allowed range for the evaporator pressure is between 45 and 55 psia. An enthalpy versus temperature equation exists in the program for the eleven pressures between 45 and 55 psia, at intervals of 1 psia. If the input pressure falls

on one of these pressures, the evaporator exit temperature is limited by the saturation temperature at that pressure and that saturation temperature plus 10°F in the superheated region. If the input pressure falls between two of the pressure values, the evaporator exit temperature is limited by the saturation temperature at the upper bound pressure and the saturation temperature plus 10°F at the lower bound pressure. The upper bound pressure and lower bound pressure refer to the input evaporator pressure rounded up and input evaporator pressure rounded down, respectively. The overall limits on the evaporator exit temperature are the saturation temperature at 45 psia and the saturation temperature at 55 psia. The enthalpy and entropy at point 1 are calculated from the pressure and temperature at that point. The entropy at the compressor exit, point 2, is equal to the entropy at point 1. The enthalpy at point 2 is calculated from enthalpy versus entropy equations at each pressure in the condenser pressure range (upper pressure range). The condenser pressure range is from 100 to 140 psia. An enthalpy versus entropy equation exists for eleven pressure between 100 and 140 psia, at intervals of 4 psia. Interpolation is conducted to calculate the enthalpy at point 2 for pressures not falling on these 4 psia intervals. The base case condensing pressure is 119.01 psia, which corresponds to a 90°F saturation temperature. The range for the enthalpy at point 2 is limited by the saturated vapor enthalpy at the given condenser pressure and the largest entropy occurring at point 1. State 3 is at the exit of the condenser and is calculated from equation (3.2). Equation (3.2) is developed for each of the eleven condensing pressures. The quality at point 3, x_3 , is an input in the program. The enthalpy at point 3 is interpolated if the condensing pressure falls between two of the eleven pressures with a corresponding equation. State 4a occurs at the exit of the reheat coil and at the condensing pressure. If the input

condensing pressure corresponds to one of the pressures with an equation, the temperature at state 4a is limited by the saturation temperature at that pressure and by the saturation temperature minus 30°F. If the input pressure falls between two of the pressures with equations, the temperature at 4a is bounded by the saturation temperature minus 30°F at the high pressure and the saturation temperature at the low pressure. The high and low pressures refer to the input condensing pressure rounded up and the input condensing pressure rounded down, respectively. The enthalpy at point 4a is then calculated by knowing the pressure and temperature at 4a. Enthalpy versus temperature equations are used to interpolate h_{4a} . The enthalpy at point 4, h_4 , is calculated by solving a system of five equations and five unknowns. Equations (3.3), (3.4), (3.5), (3.6), and (3.7) are solved simultaneously to obtain the enthalpy at point 4, which equals the enthalpy at point 5. The total mass flow rate is then found from equation (3.7). The mass flow rate through the reheat coil is calculated from equation (3.4). The mass flow rate through the non-reheat bypass is calculated from equation (3.3). Next, the work input to the compressor is found from equation (3.1). From this value, the reheat coefficient of performance, COP_{reheat} , is computed from equation (3.9), followed by the coefficient of performance, COP , from equation (3.8). Figure 3 illustrates a base case analysis using the visual basic program for the Warm Liquid Refrigerant Cycle. The program contains 7 input variables as listed across the top row of the form.

evap pressure (psia)	Temperature at point 1 (F)	Condenser Pressure (psia)	quality at 3	Temperature at point 4a (F)	reheat factor	Q evaporator (Btu/h)
49.741	45	119.01	0	80	0.02	60016.2398
evap pressure rounded	high pressure (evap exit)	High Saturation Temperature (evap exit)	Eval 1	low pressure (reheat exit)	high pressure (reheat exit)	
50	50	40.267		116	120	
	low pressure (evap exit)	Low Saturation Temperature (evap exit)	Low Saturation Temperature plus 10	Low Saturation Temperature (reheat exit)	High Saturation Temperature (reheat exit)	
	49	39.227	49.227	88.373	90.526	
Evaporator Exit Enthalpy (State 1)	test enthalpy 1 (Btu/lbm)	Evaporator Exit Entropy (State 1)	test entropy 1 (Btu/lbmR)	Reheat Exit Enthalpy (State 4a)	Tsat high minus 30	
173.68305	173.981250827	0.4144	0.41530673694	101.930150462	60.526	
Compressor Exit Enthalpy (State 2)	test enthalpy 2	test entropy 2	mass flow rate (3b)	Enthalpy at State 4	test enthalpy 4a	
181.58567	181.030224108	0.4144	512.527756145	103.980320383	101.929766313	
Condenser Exit Enthalpy (State 3)	test enthalpy 3	mass flow rate through reheat (lbm/h)	mass flow rate of refrigerant (lbm/h)	COP	Q reheat (Btu/h)	
105.374375	102.46	348.503642193	861.031398338	8.82021	1200.3248	
				Work Input (Btu/h)	COP reheat	
				6804.40218109	8.6438	

Figure 3.3 Sample Visual Basic Program for Warm Liquid Refrigerant Cycle with Base Case Conditions

3.2.4 Results and Discussion

Table 3.2 contains the base case data used in the program. When one or more of the parameters are changed, the remaining input variables are equal to the base case values. Through simulation, it was found that there is a unique value for the reheat factor, F_{reheat} , that acts as a transition point for a positive and negative mass flow rate

through the non-reheat bypass, m_{3b} . Values for the reheat factor greater than this number result in a negative non-reheat bypass mass flow rate, whereas values less than this number result in a positive non-reheat bypass mass flow rate. This can be illustrated by examining equations (3.3), (3.4), (3.7), and (3.10). Combining these equations gives the following representative equation:

$$m_{3b} = Q_{evap} / (h_1 - h_4) - (F_{reheat} * Q_{evap}) / (h_3 - h_{4a}) \quad (3.11)$$

where h_3, h_{4a}, Q_{evap} , and h_1 remain constant while h_4 decreases with an increasing F_{reheat} . The first term on the right hand side of the equation decreases with an increasing reheat factor while the second term on the right hand side increases with an increasing reheat factor. When Q_{reheat} is approximately 4.8% of Q_{evap} , m_{3b} is equal to 0. This trend is illustrated in Figure 3.4 below. The mass flow rates are related by equation (3.3).

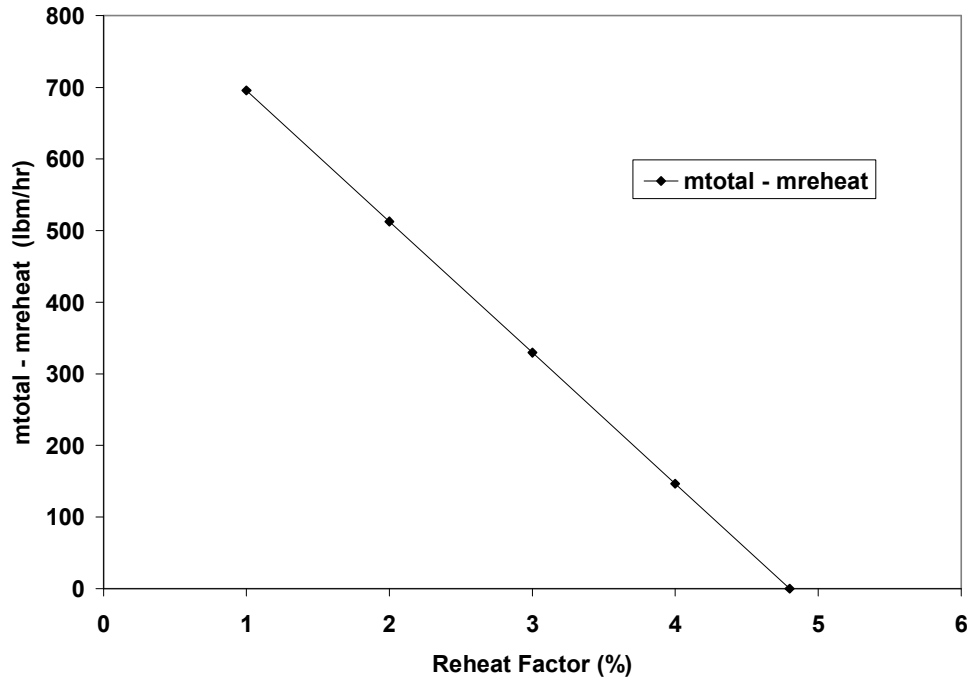


Figure 3.4 Difference in Mass Flow Rate ($m_{total} - m_{reheat}$), m_{3b} , as a Function of Reheat Factor

Figures 3.5 and 3.6 show the reheat coefficient of performance decreasing with an increasing quality at the condenser exit. Figure 3.5 shows results using the base case conditions listed above in Table 3.2. Figure 3.6 shows results based on a more practical condensing pressure and temperature of 194 psia and 123.06°F, respectively. The temperature of the refrigerant at the exit of the reheat coil, T_{4a} , is 113.06°F for Figure 3.6. The values for the remaining variables used in developing Figure 3.6 are identical to those presented in Table 3.2. The 2 plots show similar trends, with the COP values cut by a factor of 2 in Figure 3.6. Both graphs show the COP decreasing linearly with increasing quality at the condenser exit. The following is an explanation of the trend. The enthalpy at state 3 increases with increasing quality at state 3, which in turn moves

the enthalpy at state 4 closer to the saturated liquid value. This can be seen from equation (3.5), where the reheat and non-reheat mass flow rates combine with their respective enthalpies to form the total mass flow rate. The increase in h_4 decreases the difference seen in equation (3.7) since h_4 is equal to h_5 . The corresponding total mass flow rate increases, which decreases the COP_{reheat} from equations (3.1) and (3.9).

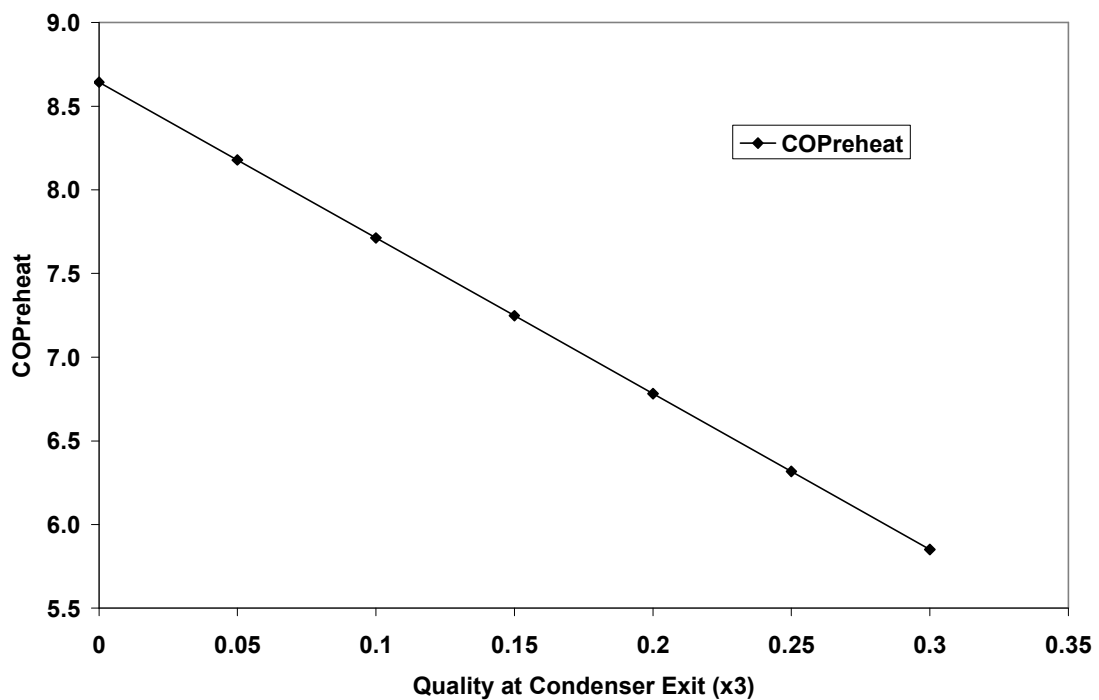


Figure 3.5 COPreheat vs. Quality at Condenser Exit (x_3)

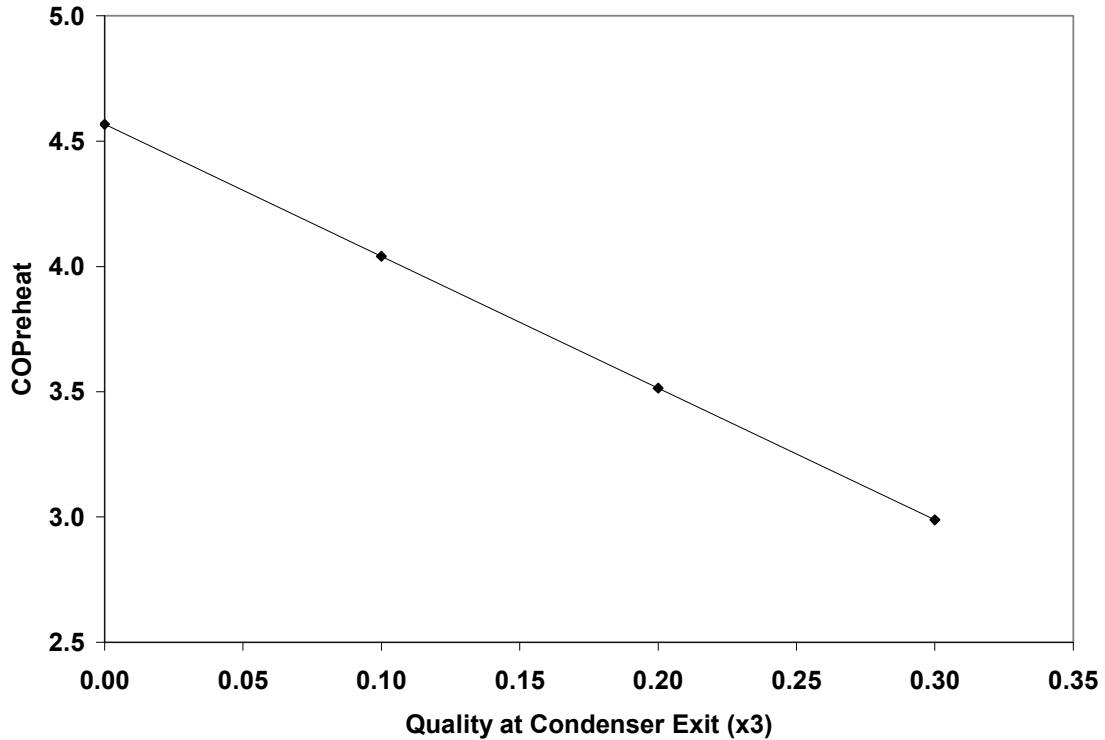


Figure 3.6 COPreheat vs. Quality at Condenser Exit (x_3), High Pressure of 194 psia

Figures 3.7 and 3.8 are shown next and describe the reheat coefficient of performance for an increasing condenser pressure with different qualities at state 3. The input value for the temperature at point 4a was changed as the condenser pressure changed for this analysis. The input temperature at point 4a remained 10°F less than the saturation temperature at the corresponding input condensing pressure. For example, at a p_{cond} of 116 psia a T_{4a} of 78.373°F was used. A more practical condensing pressure range of 174 to 214 psia is used to develop Figure 3.8. The corresponding condensing temperature range is 115.35 to 130.2 degrees F. The reheat COP is nearly cut in half compared to Figure 3.7. Trends in Figure 3.8 seem to flatten out compared to those in Figure 3.7. In both figures, the reheat COP decreases with an increasing condensing

pressure. As the condensing pressure increases, the enthalpy at point 2 increases, which increases the work from equation (3.1). The reheat COP then decreases from equation (3.9).

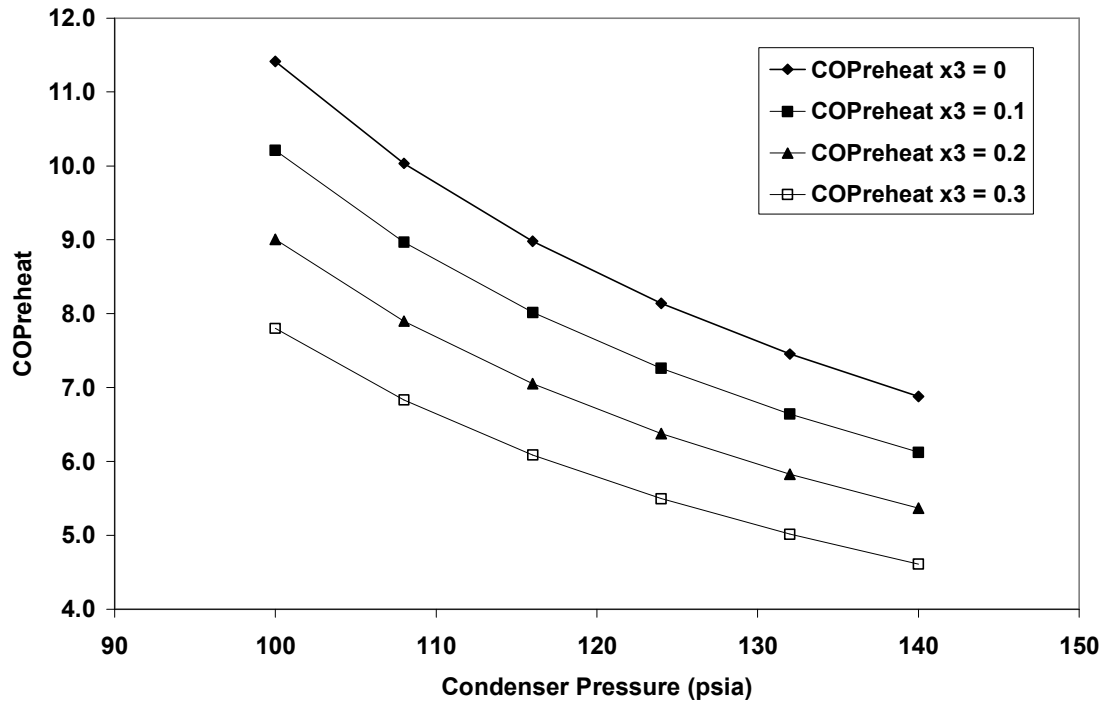


Figure 3.7 COPreheat vs. Condenser Pressure for Different Qualities at Condenser Exit

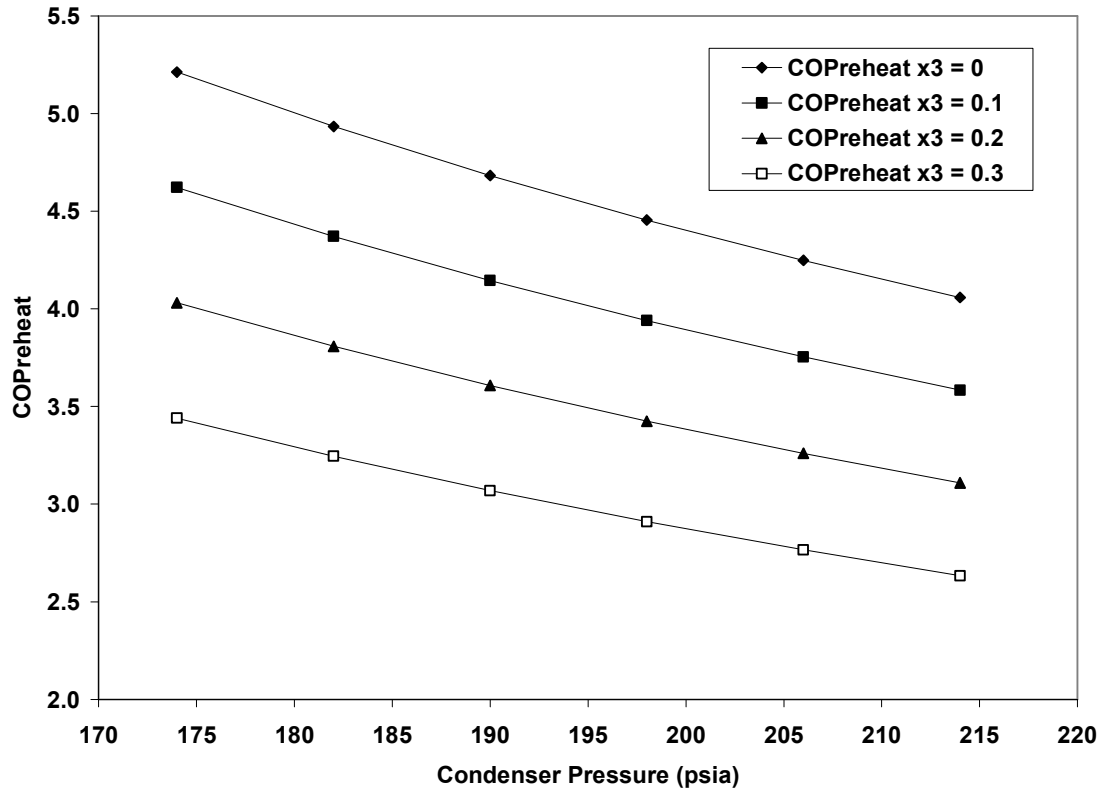


Figure 3.8 COPreheat vs. Condenser Pressure for Different Qualities at Condenser Exit (High Pressure Range)

The reheat coefficient of performance is plotted versus the evaporator exit temperature, T_1 , in Figure 3.9. As T_1 increases, the enthalpy at state 1 increases, and the difference in the enthalpies between states 1 and 5 increases. This is only the case since the enthalpy at state 4 is dictated by the enthalpies at states 3 and 4a, which remain constant from the base case conditions for T_{4a} and x_3 . The enthalpy at state 5 then follows from equation (3.6). This decreases the total mass flow rate from equation (3.7), and therefore, decreases the work input in the compressor from equation (3.1). A smaller work indicates a larger COP_{reheat} from equation (3.9), which is the trend illustrated in Figure 3.7.

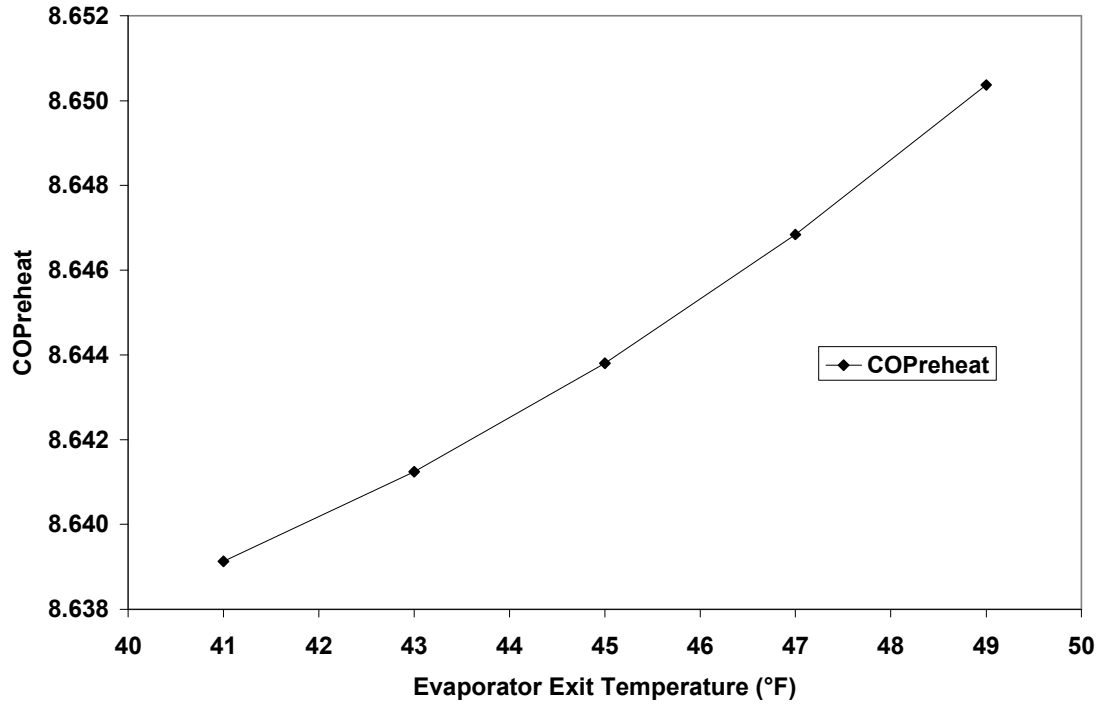


Figure 3.9 COPreheat as a Function of Evaporator Exit Temperature

Figure 3.10 is similar to Figures 3.7 and 3.8 in the trends shown for the reheat COP as a function of condensing pressure. Figure 3.10 shows the COP_{reheat} decreasing with increasing condensing pressure. The explanation for this result is identical to that given for Figures 3.7 and 3.8. The only difference in Figure 3.10 is the added compressor efficiency as a parameter. Decreasing the efficiency of the compressor, increases the work input which decreases the COP_{reheat} , as shown.

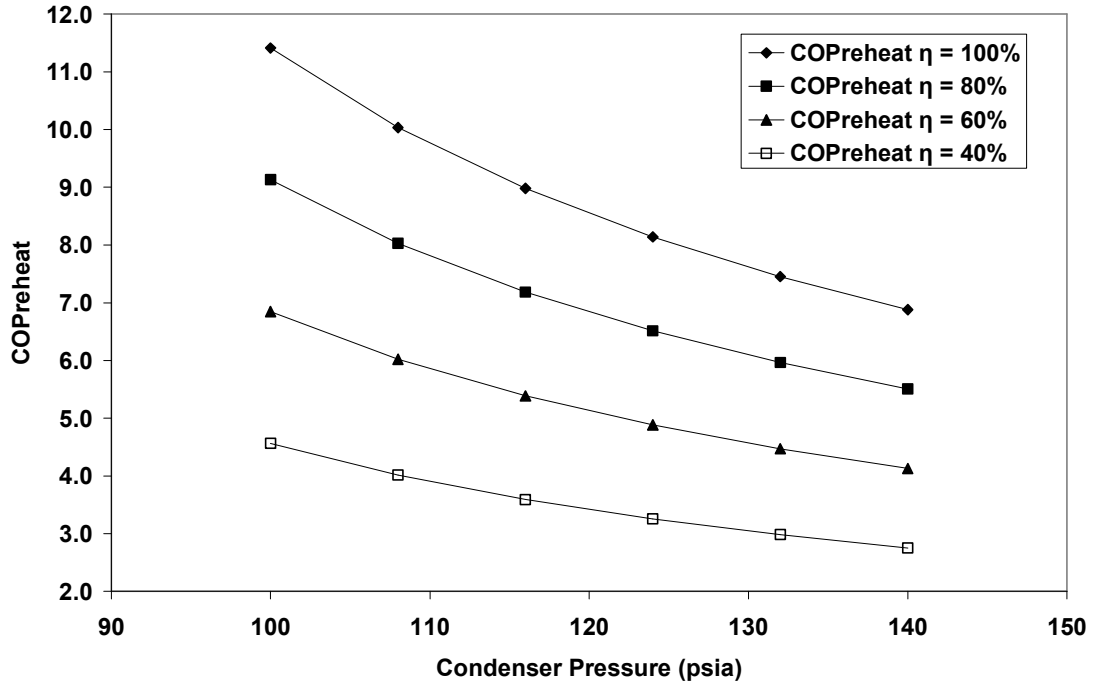


Figure 3.10 COPreheat vs. Condenser Pressure for Different Compressor Efficiencies

The reheat coefficient of performance is plotted as a function of the evaporator pressure for different qualities at the condenser exit in Figure 3.11. The input temperature at point 1 changes as the input evaporator pressure changes. The temperature at point 1 is always 5°F greater than the saturation temperature at the evaporator pressure for this analysis. For example, T_1 is 44.227°F at an evaporating pressure of 49 psia. As the evaporating pressure increases, the enthalpy at point 1 increases, which broadens the gap between the enthalpies at points 5 and 1. Point 5 is only dependent on the temperature at state 4a and quality at state 3. The temperature at state 4a is held at the base case value of 80°F, while the quality at state 3 is constant for each trend line. The total mass flow rate decreases from equation (3.7), and the work input decreases from equation (3.1). This drives up the reheat COP from equation (3.9).

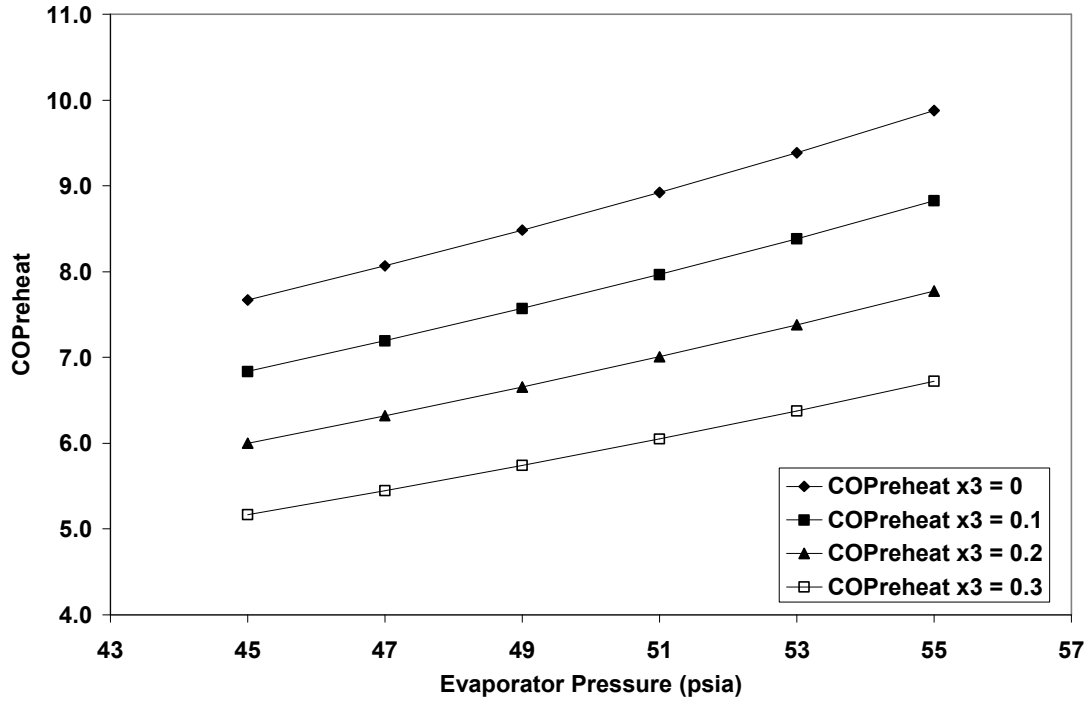


Figure 3.11 COPreheat as a Function of Evaporator Pressure for Different Qualities at Condenser Exit

Figure 3.12 shows how the ratio of reheat COP to COP decreases as Q_{reheat} increases. As more heat leaves the refrigerant at the reheat coil, the coefficient of performance increases. On the other hand, the reheat coefficient of performance remains constant as Q_{reheat} changes. The enthalpy at state 4 decreases with an increasing Q_{reheat} as seen from the following equation:

$$h_4 := \frac{\left[h_3 \cdot Q_{evap} - \left[\frac{(h_3 \cdot h_1 \cdot Q_{reheat})}{(h_3 - h_{4a})} \right] + \left[\frac{(h_{4a} \cdot h_1 \cdot Q_{reheat})}{(h_3 - h_{4a})} \right] \right]}{\left[Q_{evap} - \left[\frac{(h_3 \cdot Q_{reheat})}{(h_3 - h_{4a})} \right] + \left[\frac{(h_{4a} \cdot Q_{reheat})}{(h_3 - h_{4a})} \right] \right]}$$

This equation was developed from equations (3.3) through (3.7) presented above. As h_4 decreases, m_{total} decreases from equation (3.7). The coefficient of performance then

increases by applying equations (3.1) and (3.8). With the reheat COP remaining constant, the ratio COP_{reheat} / COP decreases. The reheat coefficient of performance remains constant from equation (3.9), where W_{1-2} is decreasing at the same rate that Q_{reheat} is increasing.

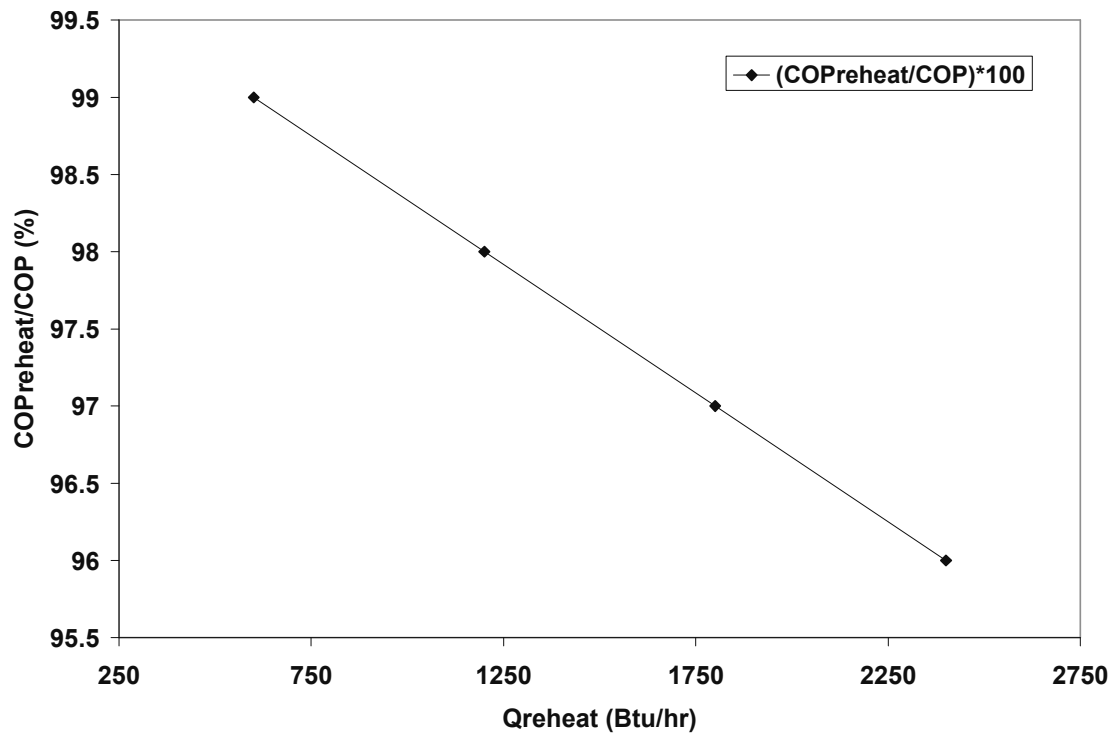


Figure 3.12 COPreheat/COP as a Function of Qreheat

Figure 3.13 shows the reheat COP plotted as a function of the ratio m_{reheat} / m_{total} . The reheat factor is held constant at 0.02 for this analysis, while the mass flow rate through the reheat coil is increased. A simple calculation in excel uses the constant values of h_3 and h_{4a} from the base case program and equation (3.4) to calculate Q_{reheat} , knowing the different values for the mass flow rate of the refrigerant. The total mass

flow rate is held constant at the base case value from the program. The heat loss in the reheat coil increases as the mass flow rate of refrigerant through the reheat coil increases. The work input to the compressor remains constant at the base case value from the program. The reheat COP then decreases from equation (3.9), which is visible in Figure 3.13.

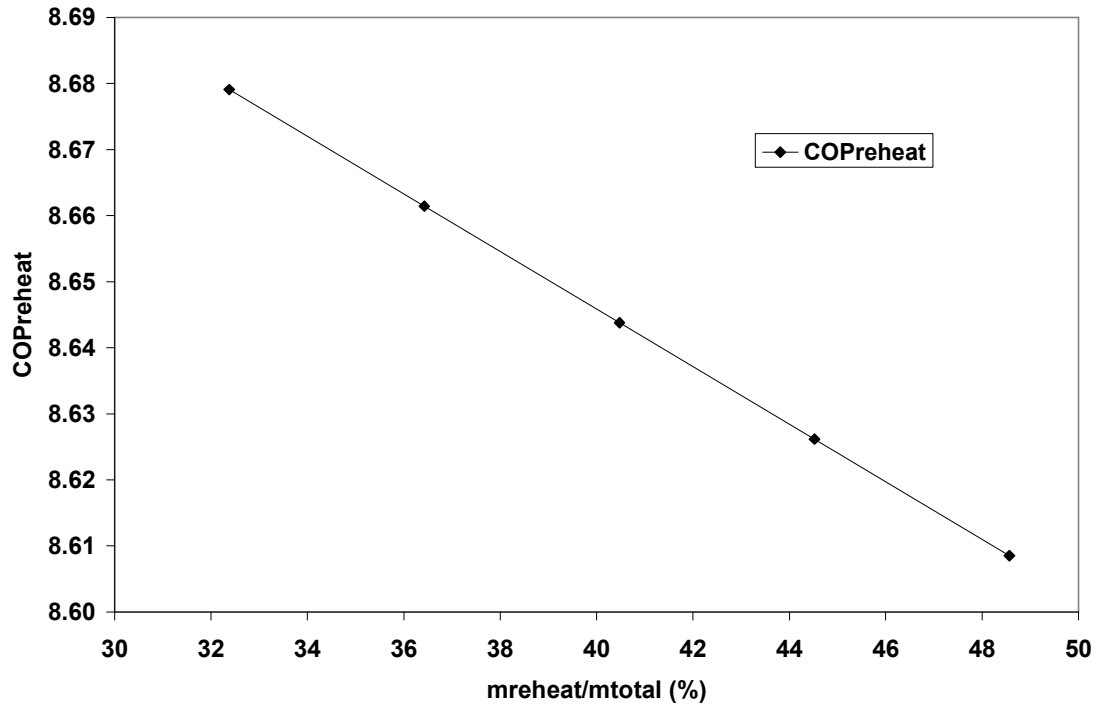


Figure 3.13 COPreheat as a Function of mreheat/mtotal

3.3 Sequential Hot Gas Refrigerant Cycle

3.3.1 Thermodynamic Cycle

The Sequential Hot Gas Refrigerant Cycle is the second cycle discussed in the thesis. The cycle is illustrated by a schematic in Figure 3.14 and a p-h diagram in Figure 3.15. At state 1 the refrigerant exists as a saturated vapor or a superheated vapor, with its value depending on the low side pressure and temperature at point 1. This temperature is

limited by the indoor air temperature at the inlet to the evaporator. The refrigerant then passes through the compressor where its enthalpy increases and entropy remains the same (for a 100% efficient cycle). The enthalpy at state 2; therefore, represents that of a superheated vapor, with its value depending on the high side pressure. Next, the refrigerant is separated into two streams at the three-way valve. One stream is routed through the reheat coil, while the other stream bypasses the reheat coil. The enthalpy of the refrigerant as it passes through the bypass is equivalent to the enthalpy at state 2. The enthalpy at the entrance to the reheat coil is identical to that at state 2 while the enthalpy at the exit of the reheat coil is dictated by the temperature at point 3a (exit of the reheat coil). This temperature is limited by the temperature of the indoor air exiting the evaporator and by the size of the reheat coil. The refrigerant streams unite into one stream at the location of the check valve. The enthalpy at point 3 (entrance to the condenser) is dependent on the enthalpies and flow rates that exist at the mixture location. The refrigerant then passes through the condenser, where its enthalpy decreases at the high side pressure. The enthalpy at state 4 is determined by the quality of the refrigerant at point 4, which depends on the outdoor air temperature and size of the condenser. Next, the refrigerant passes through the expansion valve, where its enthalpy remains constant and its pressure drops to the low side pressure. States 5 and 1 are linked by the evaporator, which operates at the low side pressure. The heat addition to the evaporator is limited by the size of the evaporator and indoor air temperature at the evaporator inlet. Notice the arrangement in this cycle, where the reheat coil is placed before the condenser.

*Subscripts **

1-2	Compression process from state 1 to 2
comp	Compressor
cond	Condenser
evap	Evaporator
reheat	Reheat
total	Mass flow rate through evaporator
3b	Mass flow rate through non-reheat bypass
f	Saturated liquid
g	Saturated vapor
1	State at evaporator exit
2	State at compressor exit
3	State at condenser inlet
3a	State at reheat exit
4	State at expansion valve inlet/condenser exit
5	State at expansion valve exit/evaporator inlet

3.3.2 Model Formulation

Figures 3.14 and 3.15 illustrate the schematic and p-h diagram for the Sequential Hot Gas Refrigerant Cycle. States 1 through 5 are located in the schematic and described in the p-h diagram. The mass flow rates through the system are illustrated in Figure 3.14 with subscripts representing bypass, reheat, and total refrigerant flow rates. The cycle

consists of three heat exchangers, three valves, and one compressor. Energy balances are performed about control volumes surrounding each of these components.

A compression process linking states 1 and 2 is identical to that described for the Warm Liquid Refrigerant Cycle in equation (3.1). The variables in this equation along with the units for enthalpy, heat transfer rate, power, and mass flow rate are the same throughout the analysis for the Sequential Hot Gas Refrigerant Cycle.

Applying a mass balance about the three-way valve results in the following equation, similar to that developed for the Warm Liquid Refrigerant Cycle:

$$m_{total} = m_{reheat} + m_{3b} \quad (3.3)$$

where m_{reheat} is the mass flow rate through the reheat coil and m_{3b} is the mass flow rate through the non-reheat bypass. An energy balance performed at the reheat coil reduces to the following:

$$Q_{reheat} = m_{reheat} \times (h_2 - h_{3a}) \quad (3.4a)$$

where Q_{reheat} represents the heat loss by the refrigerant at the reheat coil and h_2 and h_{3a} represent the enthalpies at the entrance and exit to the reheat coil, respectively. Moving through the cycle, an energy balance at the check valve, where the reheat mass flow rate and non-reheat mass flow rate mix to form the total mass flow rate prior to entry into the condenser results in the following equation:

$$m_{total} \times h_3 = m_{reheat} \times h_{3a} + m_{3b} \times h_2 \quad (3.5a)$$

where the enthalpy at the mixture exit and condenser inlet is h_3 and the enthalpy at the compressor exit is h_2 . Next, the total mass flow rate moves through the condenser. As was the case for the Warm Liquid Refrigerant Cycle, the equation for the condenser is

omitted in the analysis as it is not used to develop the simulation. State 4, at the exit of the condenser, is defined by the condenser pressure and the quality of the refrigerant as follows:

$$h_4 = h_f(p_{cond}) + x_4 \times [h_g(p_{cond}) - h_f(p_{cond})] \quad (3.2a)$$

where h_4 is the enthalpy at state 4, $h_f(p_{cond})$ is the saturated liquid enthalpy at the condensing pressure, $h_g(p_{cond})$ is the saturated vapor enthalpy at the condensing pressure, and x_4 is the quality of the refrigerant at state 4. The energy balance around the expansion valve can be reduced as shown in equation (3.6). Equation (3.7) and its variables describe the energy balance around the evaporator. The coefficient of performance and the reheat coefficient of performance are described by equations (3.8) and (3.9) in the Warm Liquid Refrigerant Cycle section. The heat loss in the reheat coil, Q_{reheat} , is again a known parameter as described previously by equation (3.10). The base case conditions for the Sequential Hot Gas Refrigerant Cycle are listed in Table 3.3. The conditions are identical to those used for the Warm Liquid Refrigerant Cycle, with the exception of the reheat factor. The base case reheat factor for the present cycle is 0.2, whereas it was 0.02 for the previous cycle. The variables in the left column have slightly different subscripts to reflect the correct states on the schematic and p-h diagram.

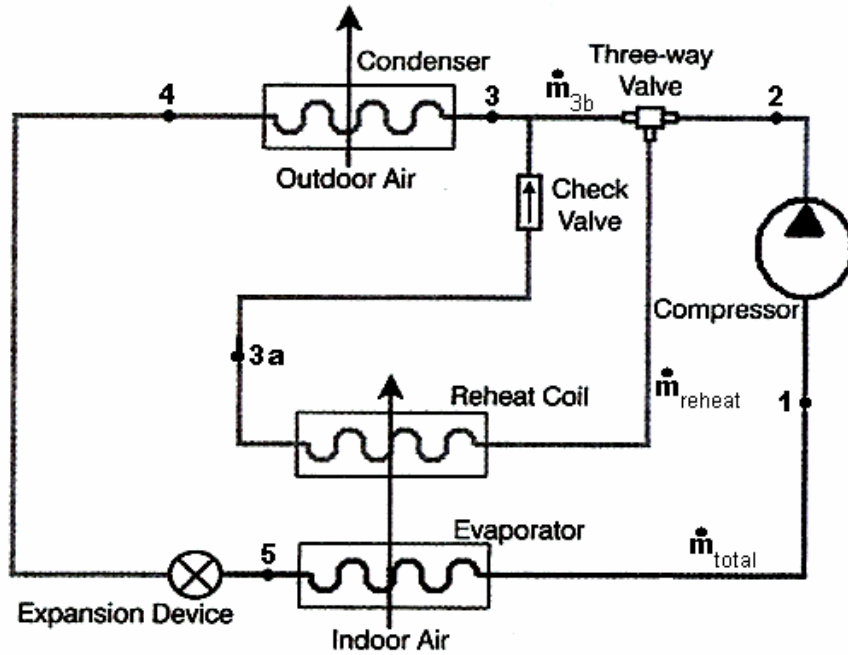


Figure 3.14 Schematic for Sequential Hot Gas Refrigerant Cycle

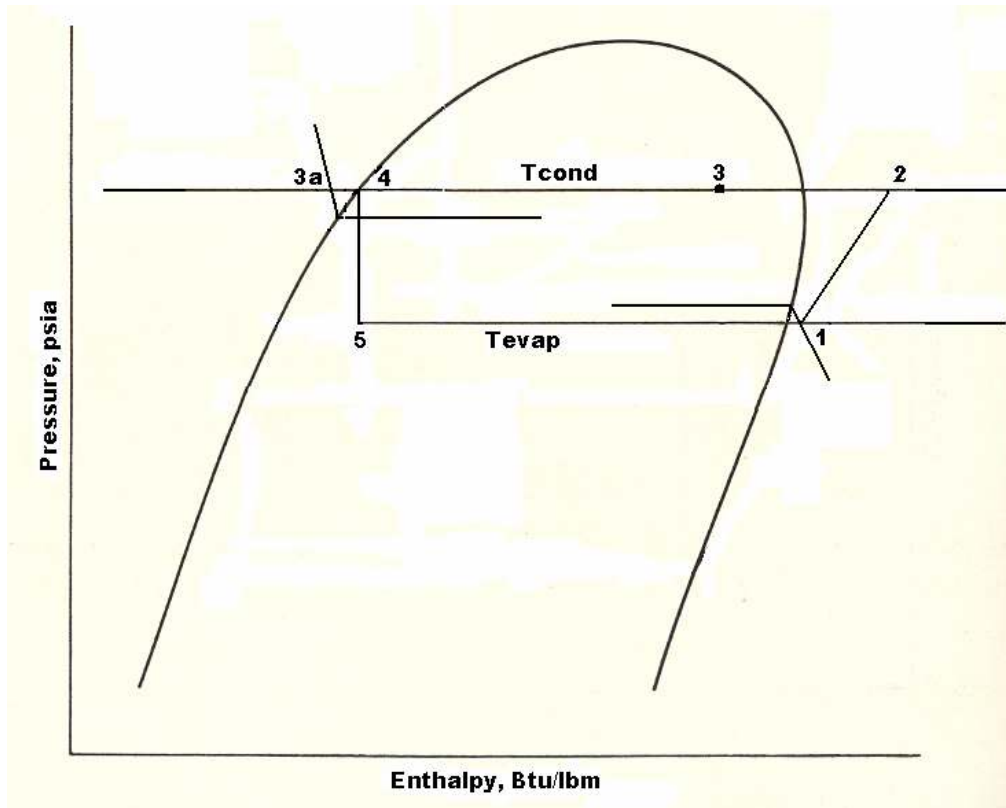


Figure 3.15 p-h Diagram for Base Case Sequential Hot Gas Refrigerant Cycle

Table 3.3
Base Case Conditions for the
Sequential Hot Gas Refrigerant Cycle

Base Case Conditions	
Pevap	49.74 psia
Tevap	40°F
T1	45°F
Pcond	119.01 psia
Tcond	90°F
x4	0
T3a	80°F
Freheat	0.2
Qevap	60016.24 Btu/hr
η_{comp}	100%

3.3.3 Simulations

The same visual basic program written to simulate the Warm Liquid Refrigerant Cycle was used to simulate the Sequential Hot Gas Refrigerant Cycle, with the exception of the renumbering of variables and subscripts to match the appropriate schematic and p-h diagram. The equations used to calculate certain parameters at the end of the program are changed slightly to properly reflect the equations presented for the analysis of this cycle. The program is identical to that described in the previous simulation section, including the type of refrigerant used, ranges on the evaporator and condenser pressures, and interpolation functions. The definitions of states 1 and 2 remain unchanged as well. States 3 through 5 change for the Sequential Hot Gas Refrigerant Cycle based on Figures 3.14 and 3.15. State 3 is at the exit of the check valve mixture and inlet to the condenser. The enthalpy at point 3, h_3 , is calculated by solving a system of five equations and five unknowns. Equations (3.3), (3.4a), (3.5a), (3.6), and (3.7) are solved simultaneously to obtain the enthalpy at point 3. The enthalpy at state 3 is not needed to calculate the critical performance parameters for the system. State 3a occurs at the exit of the reheat

coil and at the condensing pressure. If the input condensing pressure corresponds to one of the pressures with an equation, the temperature at state 3a is limited by the saturation temperature at that pressure and by the saturation temperature minus 30°F. If the input pressure falls between two of the pressures with equations, the temperature at 3a is bounded by the saturation temperature minus 30°F at the high pressure and the saturation temperature at the low pressure. The high and low pressures refer to the input condensing pressure rounded up and the input condensing pressure rounded down, respectively. The enthalpy at point 3a is then calculated by knowing the pressure and temperature at 3a. Enthalpy versus temperature equations are used to interpolate h_{3a} . The total mass flow rate is found from equations (3.6) and (3.7), having found the enthalpy at state 4 from equation (3.2a). Equation (3.2a) is developed for each of the eleven condensing pressures as presented for the Warm Liquid Refrigerant Cycle. The quality at point 4, x_4 , is an input in the program. The enthalpy at point 4 is interpolated if the condensing pressure falls between two of the eleven pressures with a corresponding equation. The mass flow rate through the reheat coil is calculated from equation (3.4a). The mass flow rate through the non-reheat bypass is calculated from equation (3.3). The compressor work, coefficient of performance, and reheat coefficient of performance are then calculated as described for the Warm Liquid Refrigerant Cycle to complete the simulation. Figure 3.16 illustrates a base case analysis using the visual basic program for the Sequential Hot Gas Refrigerant Cycle. The program contains 7 input variables as listed across the top row of the form

evap pressure (psia)	Temperature at point 1 (F)	Condenser Pressure (psia)	quality at 4	Temperature at point 3a (F)	reheat factor	Q evaporator (Btu/h)
49.741	45	119.01	0	80	0.2	60016.2398
evap pressure rounded	high pressure (evap exit)	High Saturation Temperature (evap exit)	Eval 1	low pressure (reheat exit)	high pressure (reheat exit)	
50	50	40.267		116	120	
	low pressure (evap exit)	Low Saturation Temperature (evap exit)	Low Saturation Temperature plus 10	Low Saturation Temperature (reheat exit)	High Saturation Temperature (reheat exit)	
	49	39.227	49.227	88.373	90.526	
Evaporator Exit Enthalpy (State 1)	test enthalpy 1 (Btu/lbm)	Evaporator Exit Entropy (State 1)	test entropy 1 (Btu/lbmR)	Reheat Exit Enthalpy (State 3a)	Tsat high minus 30	
173.68305	173.981250827	0.4144	0.41530673694	101.930150462	60.526	
Compressor Exit Enthalpy (State 2)	test enthalpy 2	test entropy 2		Enthalpy at State 4	test enthalpy 3a	
181.58567	181.030224108	0.4144		105.374375	101.929766313	
Condenser Exit Enthalpy (State 3)		mass flow rate through reheat (lbm/h)	mass flow rate of refrigerant (lbm/h)	COP	Q reheat (Btu/h)	
167.923933922		150.689470802	878.603467692	8.6438	12003.24796	
				Work Input (Btu/h)	COP reheat	
				6943.26753173	6.91504	

Figure 3.16 Sample Visual Basic Program for Sequential Hot Gas Refrigerant Cycle with Base Case Conditions

3.3.4 Results and Discussion

Table 3.3 contains the base case data used in the program. When one or more of the parameters are changed, the remaining input variables are equal to the base case values.

Figures 3.17 and 3.18 are similar to Figures 3.5 and 3.6 described for the Warm Liquid Refrigerant Cycle. The trends for the reheat COP as a function of the quality at the condenser exit are identical to Figures 3.5 and 3.6. Figure 3.17 shows results using the base case conditions listed above in Table 3.3. Figure 3.18 shows results based on a more practical condensing pressure and temperature of 194 psia and 123.06°F, respectively. The temperature of the refrigerant at the exit of the reheat coil, T_{3a} , is 113.06°F for Figure 3.18. The values for the remaining variables used in developing Figure 3.18 are identical to those presented in Table 3.3. The 2 plots show similar trends, with the COP values cut by a factor of 2 in Figure 3.18. Both graphs show the COP decreasing linearly with increasing quality at the condenser exit. The following is an explanation of the trend. The enthalpy at state 4 increases with increasing quality at state 4, which in turn moves the enthalpy at state 4 closer to the enthalpy at state 1. The increase in h_4 decreases the difference seen in equation (3.7) since h_4 is equal to h_5 . The corresponding total mass flow rate increases, which decreases the COP_{reheat} from equations (3.1) and (3.9). One difference is that the values for the COP_{reheat} are less than those for the Warm Liquid Refrigerant Cycle.

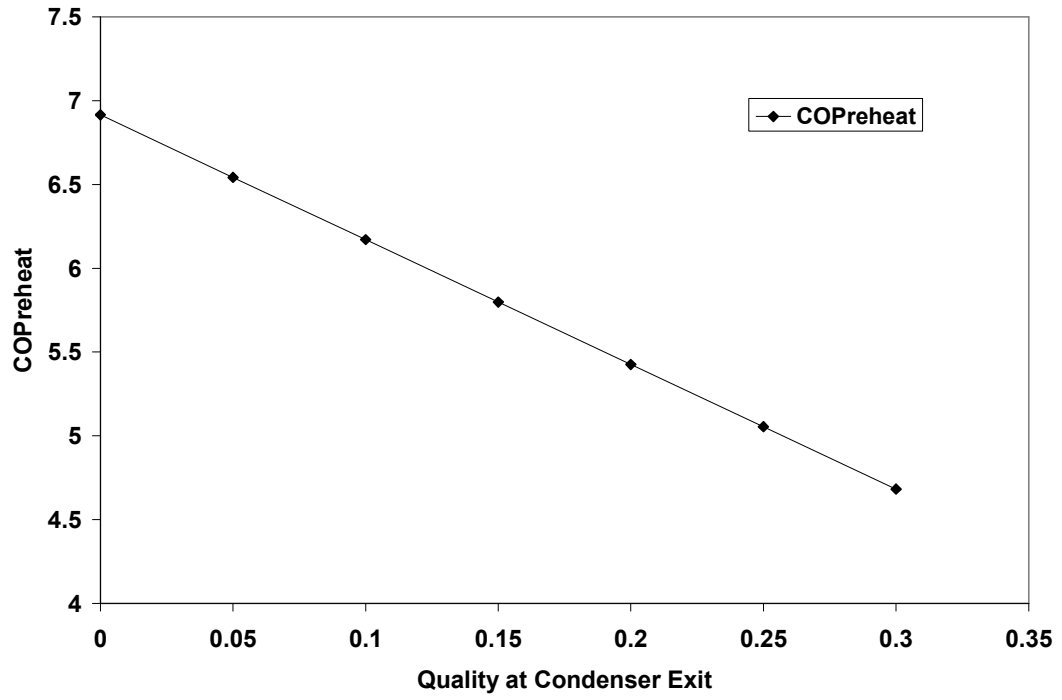


Figure 3.17 COPreheat vs. Quality at Condenser Exit (x_4)

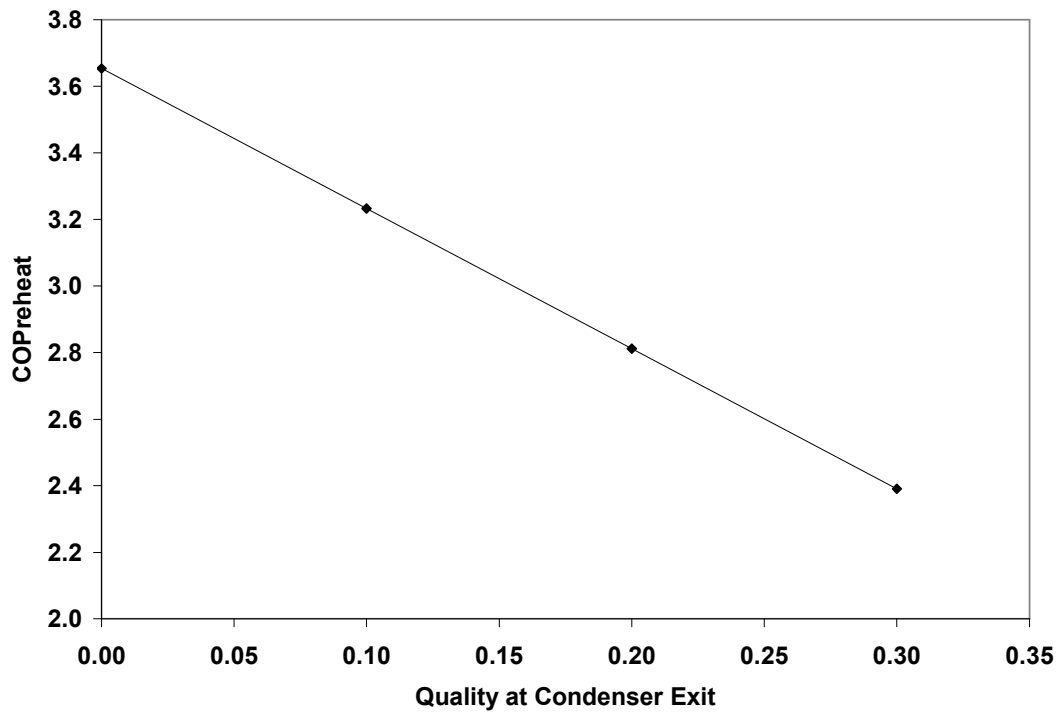


Figure 3.18 COPreheat vs. Quality at Condenser Exit (x_4), High Pressure of 194 psia

The reheat COP is plotted versus the condenser pressure for different qualities at the condenser exit in Figures 3.19 and 3.20. The trends follow similar to those shown in Figures 3.7 and 3.8 for the Warm Liquid Refrigerant Cycle. A more practical condensing pressure range of 174 to 214 psia is used to develop Figure 3.20. The corresponding condensing temperature range is 115.35 to 130.2 degrees F. The reheat COP is nearly cut in half compared to Figure 3.19. Trends in Figure 3.20 seem to flatten out compared to those in Figure 3.19. In both figures, the reheat COP decreases with an increasing condensing pressure. Again, the coefficient of performance values are smaller for the Sequential Hot Gas Refrigerant Cycle. The trend is explained in the summary for Figures 3.7 and 3.8. States 3 and 4a for the Warm Liquid Refrigerant Cycle are replaced by states 4 and 3a for the Sequential Hot Gas Refrigerant Cycle.

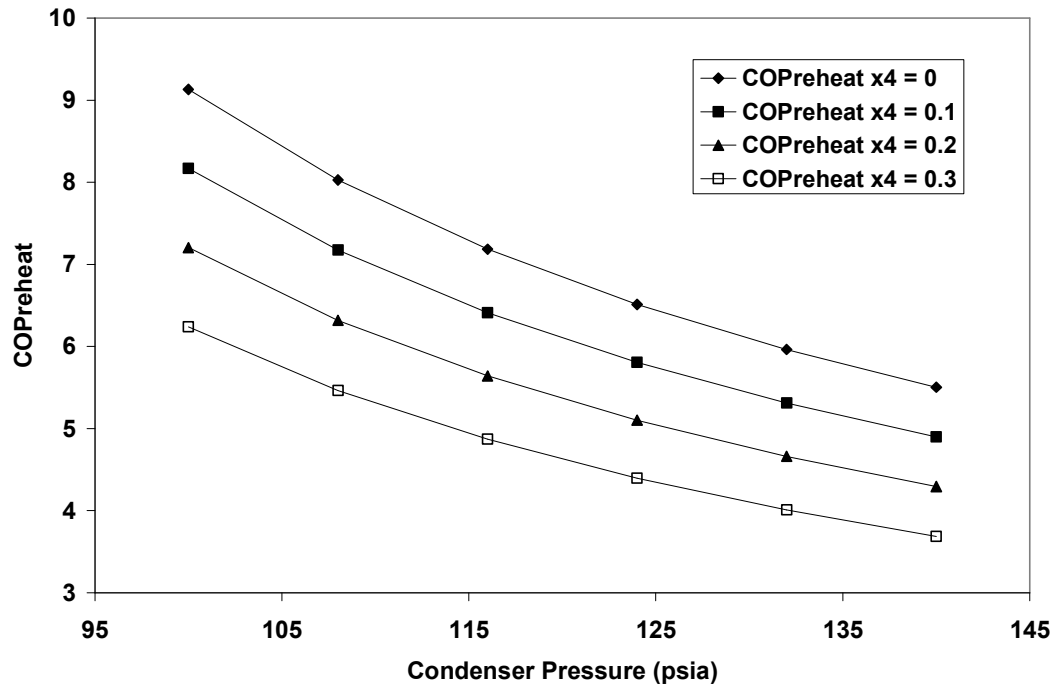


Figure 3.19 COPreheat vs. Condenser Pressure for Different Qualities at Condenser Exit

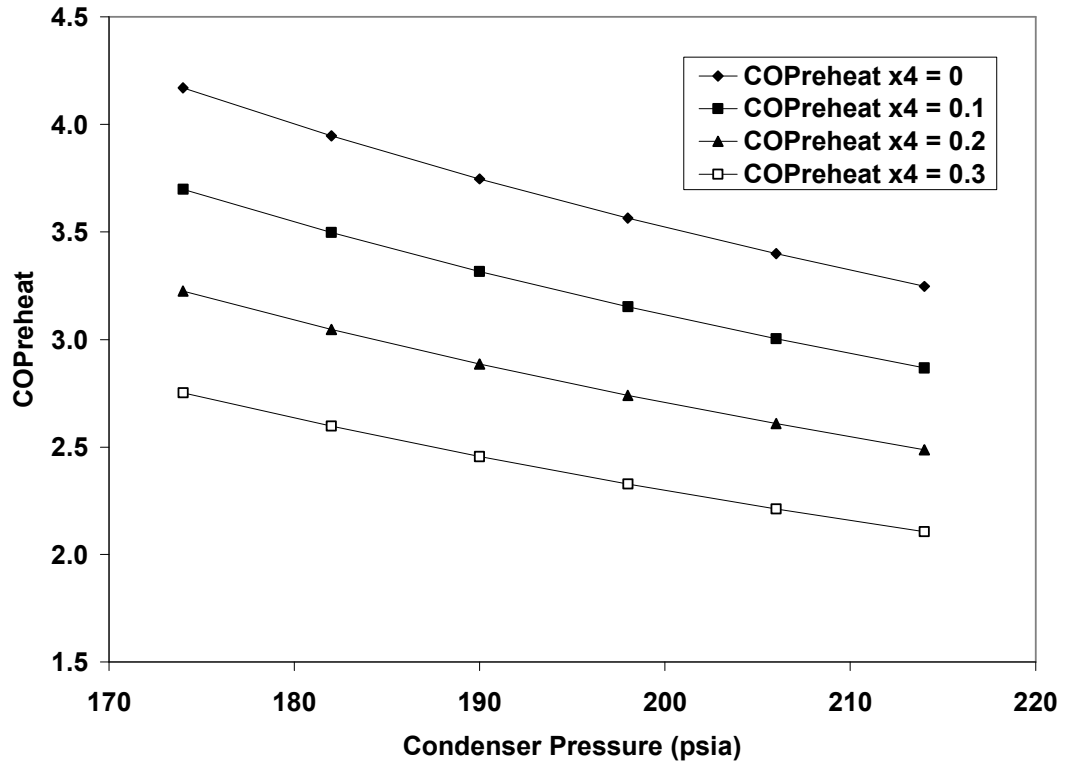


Figure 3.20 COPreheat vs. Condenser Pressure for Different Qualities at Condenser Exit (High Pressure Range)

Figure 3.21 shows the reheat COP plotted versus the evaporator exit temperature, T_1 . The trend followed by the reheat COP is identical to what is seen in Figure 3.9. As T_1 increases, the enthalpy at state 1 increases, and the difference in the enthalpies between states 1 and 5 increases. This is only the case since the enthalpy at state 4 is dictated by the quality at state 4 and condensing pressure, which remain constant. The COP_{reheat} values are lower for the Sequential Hot Gas Refrigerant Cycle than for the Warm Liquid Refrigerant Cycle.

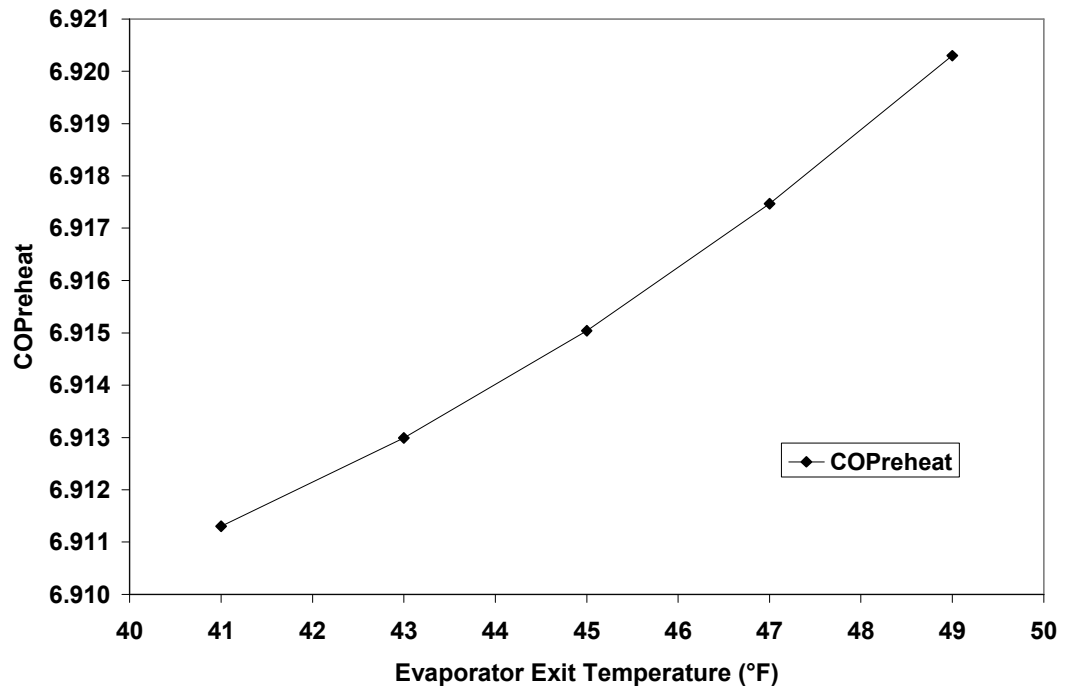


Figure 3.21 COPreheat as a Function of Evaporator Exit Temperature

Figure 3.22 is similar to Figure 3.10 for the Warm Liquid Refrigerant Cycle. The values for the reheat COP are less than those shown in Figure 3.10. This figure is described in the explanation for Figure 3.10. States 3 and 4a in the previous cycle are replaced by states 4 and 3a in the current cycle.

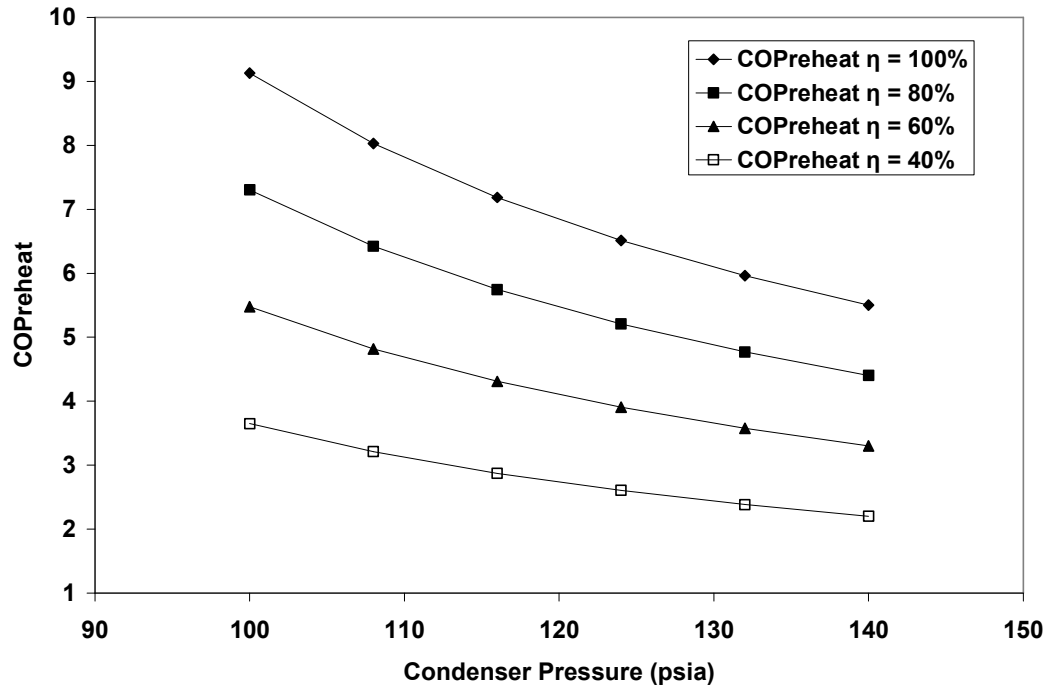


Figure 3.22 COPreheat vs. Condenser Pressure for Different Compressor Efficiencies

Figure 3.23 depicts the reheat COP as a function of the reheat factor for different compressor efficiencies. The reheat COP decreases as the reheat factor increases. This can be seen in equation (3.9), where Q_{reheat} increases as F_{reheat} increases, which decreases the COP_{reheat} . The work input to the compressor and the heat added in the evaporator remain constant. The lower the compressor efficiency, the lower the reheat COP.

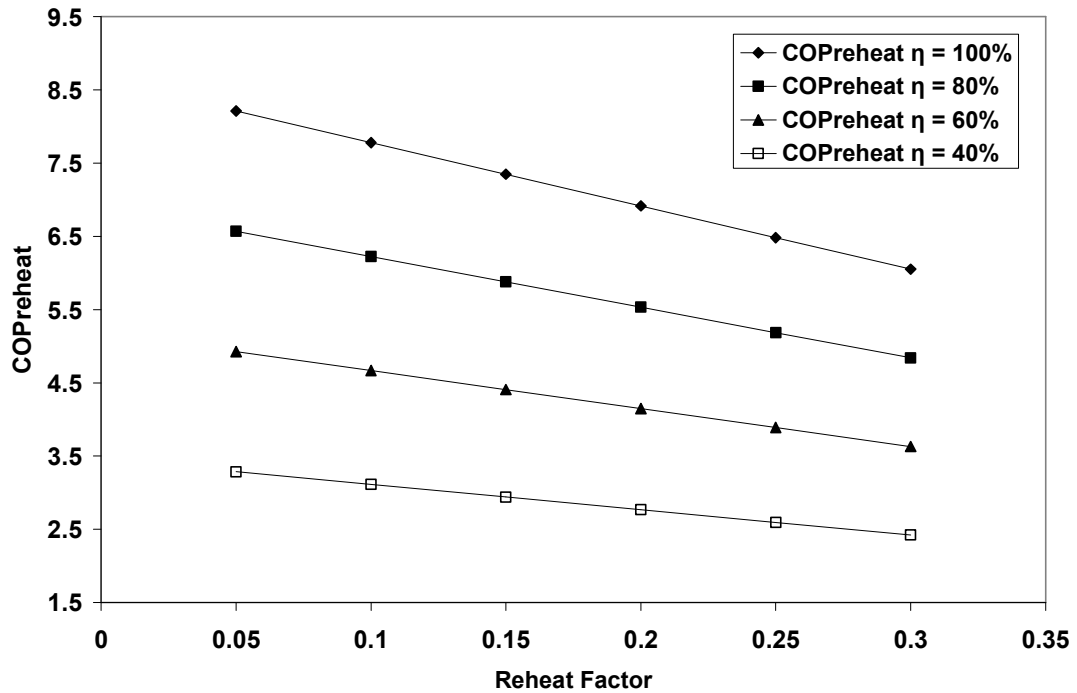


Figure 3.23 COPreheat as a Function of Reheat Factor for Different Compressor Efficiencies

Figure 3.24 shows the ratio COP_{reheat} / COP plotted as a function of Q_{reheat} . The ratio decreases as the heat loss in the reheat coil increases. As the reheat factor increases, the COP remains constant, since the heat added in the evaporator and work input in the compressor stay the same. The reheat COP is reduced by the same reasoning as developed for Figure 3.23. The reheat COP reduces while the COP remains the same, which decreases the coefficient of performance ratio.

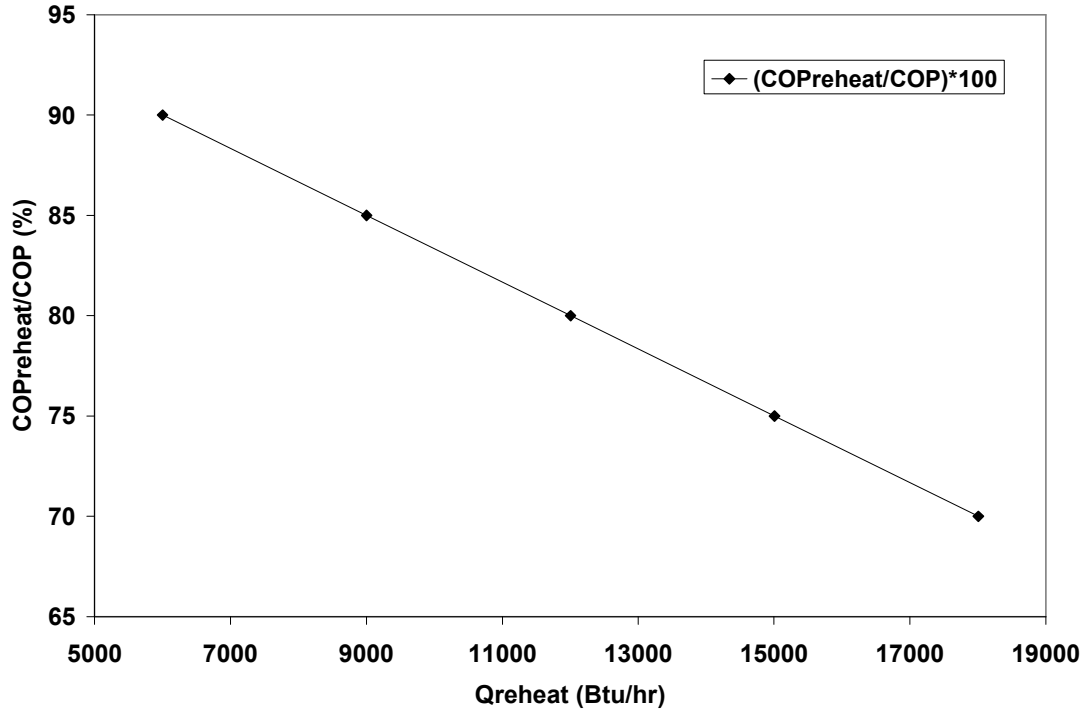


Figure 3.24 COPreheat/COP as a Function of Qreheat

The COP_{reheat} is plotted versus the evaporator pressure for different qualities at the condenser exit in Figure 3.25. The trend followed by the reheat COP is similar to that shown in Figure 3.11 for the Warm Liquid Refrigerant Cycle. The same explanation applies for this cycle. Points 3 and 4a for the previous cycle are replaced with points 4 and 3a for the Sequential Hot Gas Refrigerant Cycle. The values for the reheat COP are again less than those for the previous cycle.

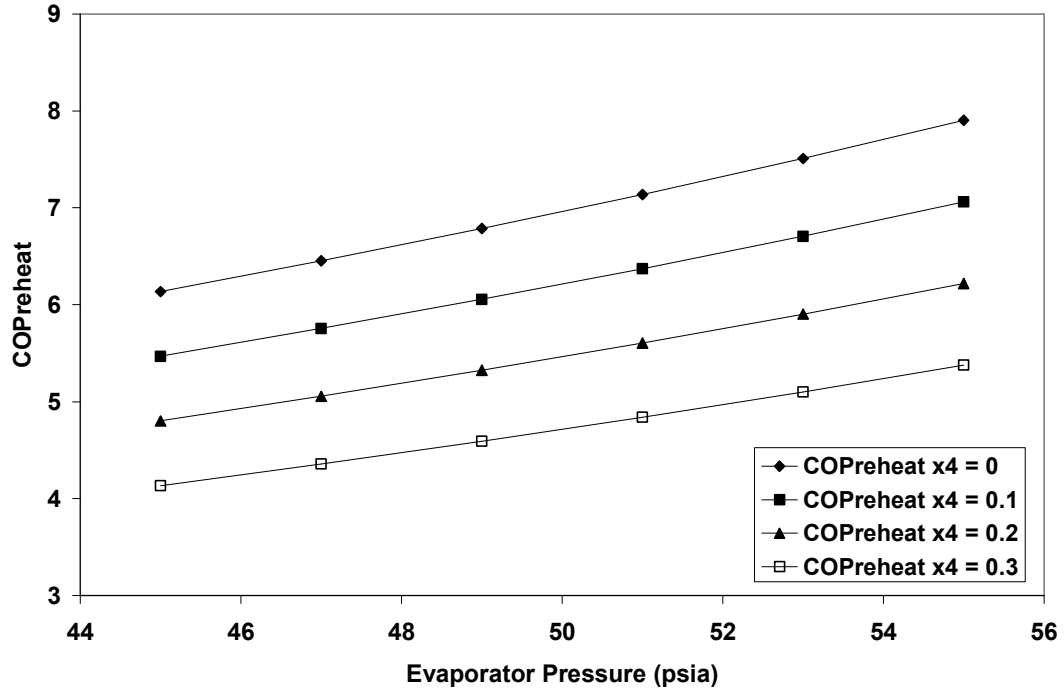


Figure 3.25 COPreheat vs. Evaporator Pressure for Different Qualities at Condenser Exit

Figure 3.26 is similar to Figure 3.13 in that the reheat COP decreases as the ratio of m_{reheat} / m_{total} increases. An explanation is provided for Figure 3.13, and applies to Figure 3.26. The reheat factor is held at 0.2 instead of 0.02 as it was in Figure 3.13. The enthalpies at the entrance and exit to the reheat coil also differ, as they are h_2 and h_{3a} , respectively. A different range for the x-axis is presented in the two figures. The values for the reheat COP for the Sequential Hot Gas Refrigerant Cycle are lower than those for the Warm Liquid Refrigerant Cycle for the same graph.

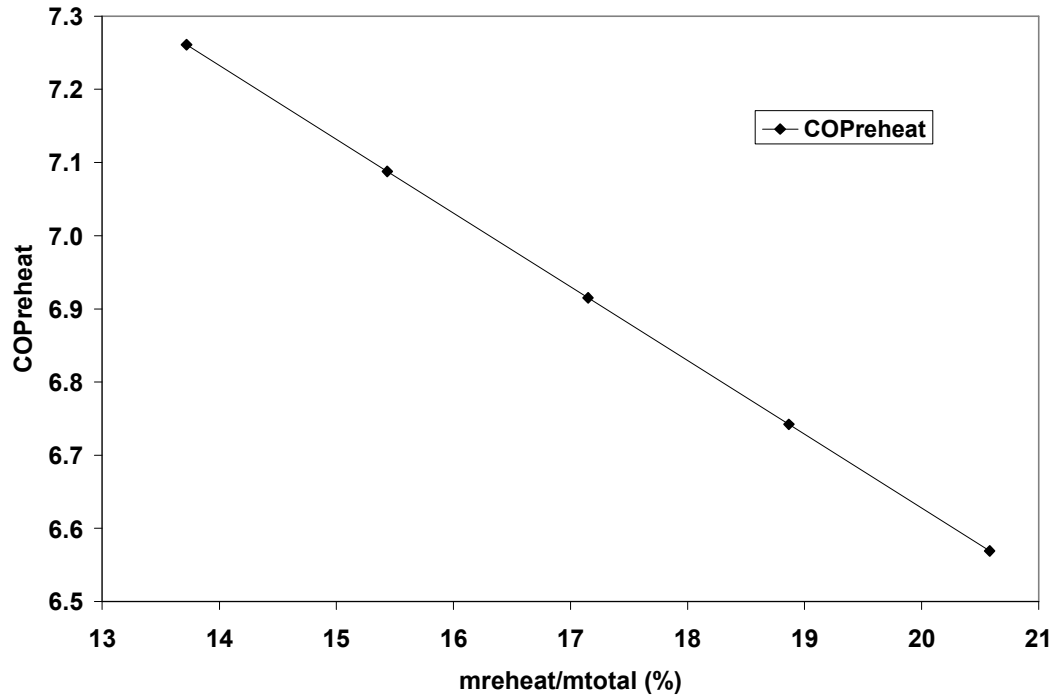


Figure 3.26 COPreheat as a Function of mreheat/mtotal

3.4 Parallel Hot Gas Refrigerant Cycle

3.4.1 Thermodynamic Cycle

The Parallel Hot Gas Refrigerant Cycle is the third cycle discussed in the thesis. The cycle is illustrated by a schematic in Figure 3.27 and a p-h diagram in Figure 3.28. At state 1 the refrigerant exists as a saturated vapor or a superheated vapor, with its value depending on the low side pressure and temperature at point 1. This temperature is limited by the indoor air temperature at the inlet to the evaporator. The refrigerant then passes through the compressor where its enthalpy increases and entropy remains the same (for a 100% efficient cycle). The enthalpy at state 2; therefore, represents that of a superheated vapor, with its value depending on the high side pressure. Next, the refrigerant is separated into two streams at the three-way valve. One stream is routed

through the reheat coil, while the other stream passes through the condenser. As opposed to the previous two cycles, only a portion of the total mass flow rate passes through the condenser. The enthalpy of the refrigerant at the entrance to the reheat coil and entrance to the condenser are equivalent and equal the enthalpy at state 2. The enthalpy at the exit of the reheat coil is dictated by the temperature at point 3a (exit of the reheat coil). This temperature is limited by the temperature of the indoor air exiting the evaporator and by the size of the reheat coil. The enthalpy at the exit of the condenser is determined by the quality at state 3b, which depends on the outdoor air temperature and size of the condenser. The refrigerant streams unite into one stream after the condenser, at the location of the check valve. The enthalpy at this mixture exit (point 3) is dependent on the enthalpies and flow rates that exist at the mixture location. The refrigerant then passes through the expansion valve, where its enthalpy remains constant and its pressure drops to the low side pressure. States 4 and 1 are linked by the evaporator, which operates at the low side pressure. The heat addition to the evaporator is limited by the size of the evaporator and indoor air temperature at the evaporator inlet. Notice the arrangement in this cycle, where the reheat coil is placed in parallel with the condenser.

*Subscripts **

1-2 Compression process from state 1 to 2

comp Compressor

cond Condenser

evap Evaporator

reheat Reheat

total	Mass flow rate through evaporator
3b	Mass flow rate through non-reheat bypass
f	Saturated liquid
g	Saturated vapor
1	State at evaporator exit
2	State at compressor exit
3b	State at condenser exit
3a	State at reheat exit
3	State at expansion valve inlet
4	State at expansion valve exit/evaporator inlet

3.4.2 Model Formulation

Figures 3.27 and 3.28 illustrate the schematic and p-h diagram for the Parallel Hot Gas Refrigerant Cycle. States 1 through 4 are located in the schematic and described in the p-h diagram. The mass flow rates through the system are illustrated in Figure 3.27 with subscripts representing bypass, reheat, and total refrigerant flow rates. The cycle consists of three heat exchangers, three valves, and one compressor. Energy balances are performed about control volumes surrounding each of these components.

A compression process linking states 1 and 2 is identical to that described for the Warm Liquid Refrigerant Cycle in equation (3.1). The variables in this equation along with the units for enthalpy, heat transfer rate, power, and mass flow rate are the same throughout the analysis for the Sequential Hot Gas Refrigerant Cycle

Applying a mass balance about the three-way valve results in the following equation, similar to that developed for the Warm Liquid Refrigerant Cycle:

$$m_{total} = m_{reheat} + m_{3b} \quad (3.3)$$

where m_{reheat} is the mass flow rate through the reheat coil and m_{3b} is the mass flow rate through the non-reheat bypass and condenser. An energy balance at the reheat coil reduces to equation (3.4a), which was developed for the Sequential Hot Gas Refrigerant Cycle. The mass flow rate through the non-reheat bypass now moves through the condenser. As was the case for the previous two cycles, the equation for the condenser is omitted in the analysis as it is not used to develop the simulation. The enthalpy at point 3b is calculated using the following equation:

$$h_{3b} = h_f(p_{cond}) + x_{3b} \times [h_g(p_{cond}) - h_f(p_{cond})] \quad (3.2b)$$

where h_{3b} is the enthalpy at state 3b, $h_f(p_{cond})$ is the saturated liquid enthalpy at the condensing pressure, $h_g(p_{cond})$ is the saturated vapor enthalpy at the condensing pressure, and x_{3b} is the quality of the refrigerant at state 3b. An energy balance is performed at the check valve where the two streams, m_{reheat} and m_{3b} , mix to form the total mass flow rate. The equation is similar to that developed for the Sequential Hot Gas Refrigerant Cycle, except for the enthalpy of the non-reheat bypass stream. The equation is as follows:

$$m_{total} \times h_3 = m_{reheat} \times h_{3a} + m_{3b} \times h_{3b} \quad (3.5b)$$

where h_3 is the enthalpy at the mixture exit and h_{3b} is the enthalpy at the condenser exit.

The equation resulting from an energy balance around the expansion valve contains

different subscripts for the enthalpies than the previous two cycles. The equation follows as below:

$$h_3 = h_4 \quad (3.6b)$$

where h_4 is the enthalpy at the exit of the expansion valve and entrance to the evaporator. The energy balance at the evaporator reduces to an identical form as that seen in the previous two cycles, with the exception of the subscripts on the enthalpies.

$$Q_{evap} = m_{total} \times (h_1 - h_4) \quad (3.7b)$$

The coefficient of performance and the reheat coefficient of performance are described by equations (3.8) and (3.9) in the Warm Liquid Refrigerant Cycle section. The heat loss in the reheat coil, Q_{reheat} , is again a known parameter as described previously by equation (3.10). The base case conditions for the Parallel Hot Gas Refrigerant Cycle are listed in Table 3.4. The conditions are identical to those used for the Sequential Hot Gas Refrigerant Cycle. The variables in the left column have slightly different subscripts to reflect the correct states on the schematic and p-h diagram

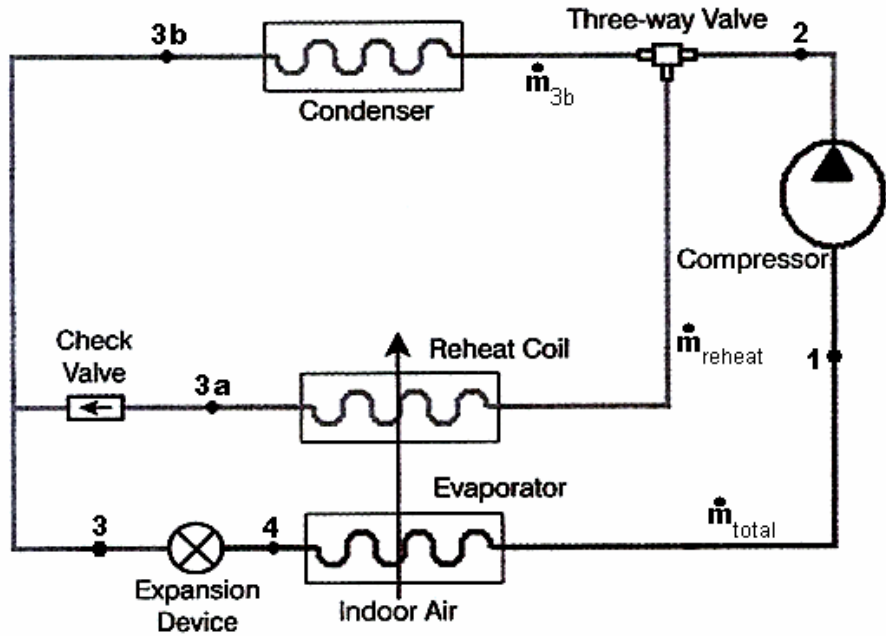


Figure 3.27 Schematic for Parallel Hot Gas Refrigerant Cycle

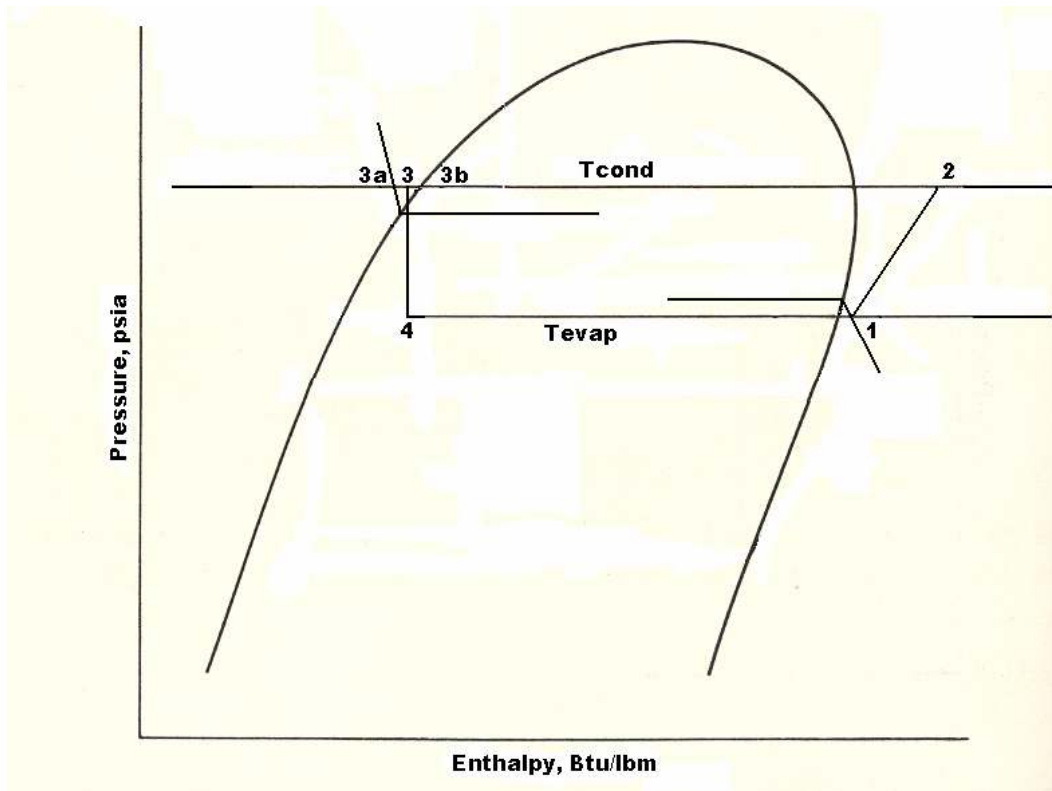


Figure 3.28 p-h Diagram for Base Case Parallel Hot Gas Refrigerant Cycle

Table 3.4
Base Case Conditions for the
Parallel Hot Gas Refrigerant Cycle

Base Case Conditions	
P _{evap}	49.74 psia
T _{evap}	40°F
T ₁	45°F
P _{cond}	119.01 psia
T _{cond}	90°F
x _{3b}	0
T _{3a}	80°F
Fr _{reheat}	0.2
Q _{evap}	60016.24 Btu/hr
η _{comp}	100%

3.4.3 Simulations

The same visual basic program written to simulate the Warm Liquid Refrigerant Cycle and Sequential Hot Gas Refrigerant Cycle was used to simulate the Parallel Hot Gas Refrigerant Cycle, with the exception of the renumbering of variables and subscripts to match the appropriate schematic and p-h diagram. The equations used to calculate certain parameters at the end of the program are changed slightly to properly reflect the equations presented for the analysis of this cycle. The program is identical to that described in the Warm Liquid Refrigerant Cycle simulation section, including the type of refrigerant used, ranges on the evaporator and condenser pressures, and interpolation functions. The definitions of how to locate states 1 and 2 remain unchanged as well.

States 3 through 5 change for the Parallel Hot Gas Refrigerant Cycle based on Figures 3.27 and 3.28. State 3a occurs at the exit of the reheat coil. The enthalpy at state 3a is calculated the same way as presented for the Sequential Hot Gas Refrigerant Cycle. State 3b is at the exit of the condenser and is calculated from equation (3.2b). Equation (3.2b) is developed for each of the eleven condensing pressures. The quality at point 3b,

x_{3b} , is an input in the program. The enthalpy at point 3b is interpolated if the condensing pressure falls between two of the eleven pressures with a corresponding equation. State 3 is at the exit of the check valve mixture and inlet to the expansion valve. The enthalpy at point 3, h_3 , is calculated by solving a system of five equations and five unknowns.

Equations (3.3), (3.4a), (3.5b), (3.6b), and (3.7b) are solved simultaneously to obtain the enthalpy at point 3. The total mass flow rate is found from equations (3.6b) and (3.7b), having found the enthalpy at point 3 above. The mass flow rate through the reheat coil is found from equation (3.4a), having found the enthalpy at point 3a above. The mass flow rate through the non-reheat bypass follows from equation (3.3). The compressor work, coefficient of performance, and reheat coefficient of performance are then calculated as described for the Warm Liquid Refrigerant Cycle to complete the simulation. Figure 3.29 illustrates a base case analysis using the visual basic program for the Parallel Hot Gas Refrigerant Cycle. The program contains 7 input variables as listed across the top row of the form.

evap pressure (psia)	Temperature at point 1 (F)	Condenser Pressure (psia)	quality at 3b	Temperature at point 3a (F)	reheat factor	Q evaporator (Btu/h)
49.741	45	119.01	0	80	0.2	60016.2398
evap pressure rounded	high pressure (evap exit)	High Saturation Temperature (evap exit)	Eval 1	low pressure (reheat exit)	high pressure (reheat exit)	
50	50	40.267		116	120	
	low pressure (evap exit)	Low Saturation Temperature (evap exit)	Low Saturation Temperature plus 10	Low Saturation Temperature (reheat exit)	High Saturation Temperature (reheat exit)	
	49	39.227	49.227	88.373	90.526	
Evaporator Exit Enthalpy (State 1)	test enthalpy 1 (Btu/lbm)	Evaporator Exit Entropy (State 1)	test entropy 1 (Btu/lbmR)	Reheat Exit Enthalpy (State 3a)	Tsat high minus 30	
173.68305	173.981250827	0.4144	0.41530673694	101.930150462	60.526	
Compressor Exit Enthalpy (State 2)	test enthalpy 2	test entropy 2	mass flow rate (3b)	Enthalpy at State 3	test enthalpy 3a	
181.58567	181.030224108	0.4144	720.316010782	104.778502317	101.929766313	
Condenser Exit Enthalpy (State 3b)	test enthalpy 3b	mass flow rate through reheat (lbm/h)	mass flow rate of refrigerant (lbm/h)	COP	Q reheat (Btu/h)	
105.374375	102.46	150.689470802	871.005481585	8.71921	12003.24796	
				Work Input (Btu/h)	COP reheat	
				6883.22355035	6.97536	

Figure 3.29 Sample Visual Basic Program for Parallel Hot Gas Refrigerant Cycle with Base Case Conditions

3.4.4 Results and Discussion

Table 3.4 contains the base case data used in the program. When one or more of the parameters are changed, the remaining input variables are equal to the base case values.

Figures 3.30 and 3.31 show how the reheat COP fluctuates as the quality at the condenser exit increases. The trend is similar to Figures 3.17 and 3.18, and 3.5 and 3.6

from the two previous cycles. Figure 3.30 shows results using the base case conditions listed above in Table 3.4. Figure 3.31 shows results based on a practical condensing pressure and temperature of 194 psia and 123.06°F, respectively. The temperature of the refrigerant at the exit of the reheat coil, T_{3a} , is 113.06°F for Figure 3.31. The values for the remaining variables used in developing Figure 3.31 are identical to those presented in Table 3.4. The 2 plots show similar trends, with the COP values cut by a factor of 2 in Figure 3.31. Both graphs show the COP decreasing linearly with increasing quality at the condenser exit. The same reasoning used to explain Figures 3.5 and 3.6 applies to Figures 3.30 and 3.31. States 3, 4a, and 4 are replaced by states 3b, 3a, and 3, respectively. The values of the reheat COP are closer to the values seen in Figures 3.17 and 3.18 for the Sequential Hot Gas Refrigerant Cycle.

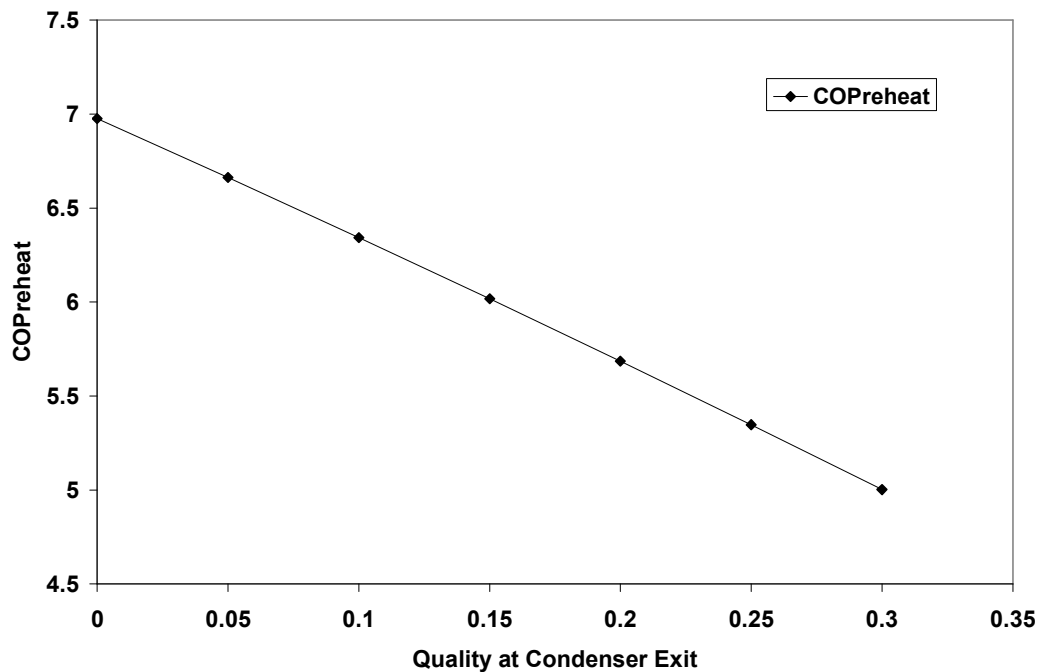


Figure 3.30 COPreheat as a Function of Quality at Condenser Exit (x_{3b})

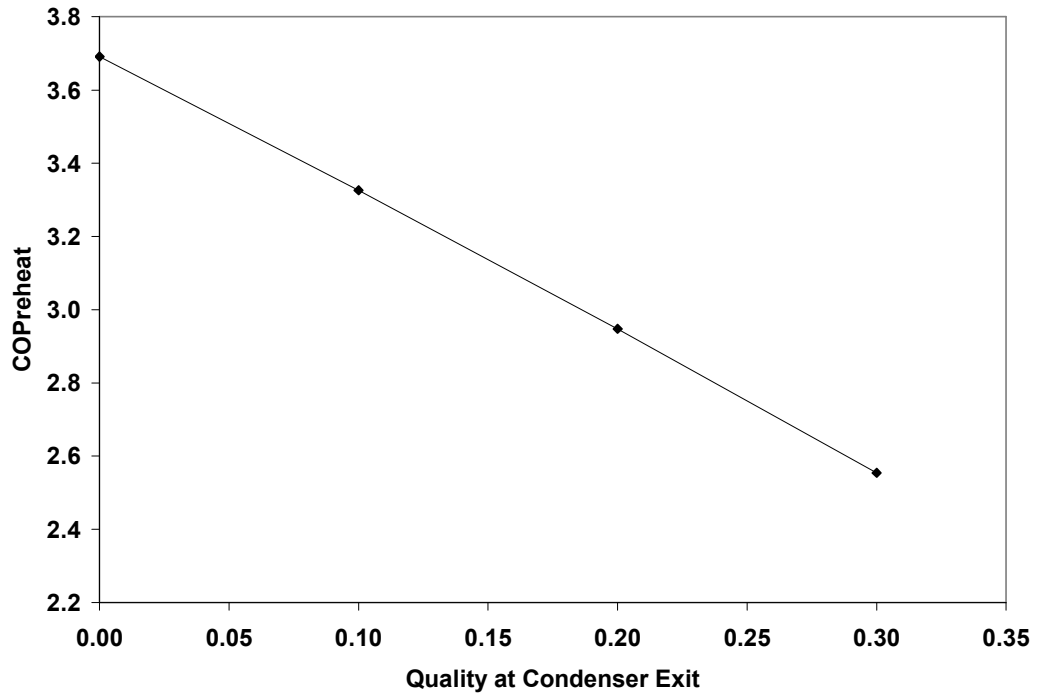


Figure 3.31 COPreheat as a Function of Quality at Condenser Exit (x_{3b}), High Pressure of 194 psia

The reheat coefficient of performance is plotted versus the evaporator exit temperature in Figure 3.32. The trend matches that for the Warm Liquid Refrigerant Cycle plotted in Figure 3.9. States 3, 4a, and 4 are replaced by states 3b, 3a, and 3. The characteristic curve matches closely with the two cycles discussed earlier, with the values for the COP_{reheat} almost equaling those obtained for the Sequential Hot Gas Refrigerant Cycle. The reheat COP values for the Warm Liquid Refrigerant Cycle are considerably larger than those calculated using the two hot gas cycles.

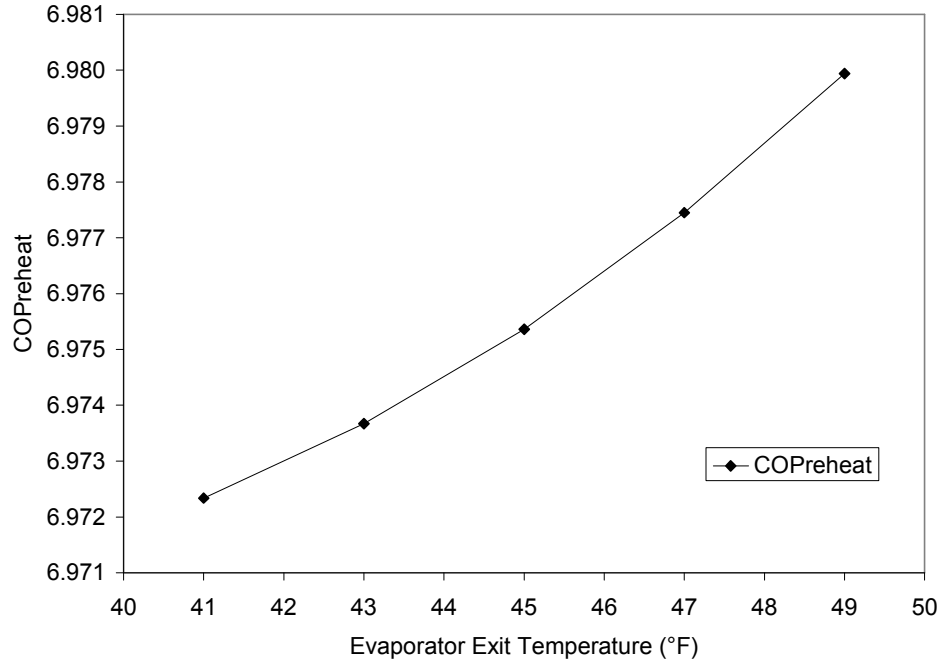


Figure 3.32 COPreheat vs. Evaporator Exit Temperature

Figure 3.33 shows the ratio COP_{reheat} / COP plotted as a function of Q_{reheat} . The ratio decreases as the heat loss in the reheat coil increases. The range for Q_{reheat} on the x-axis is identical to that which appears on Figure 3.24 for the Sequential Hot Gas Refrigerant Cycle. The reheat COP values nearly duplicate those on Figure 3.24, but are much different than those which appear on Figure 3.12 for the Warm Liquid Refrigerant Cycle. The range for Q_{reheat} on the x-axis is different on Figure 3.12 than it is on Figures 3.24 and 3.33. The difference for the Parallel Hot Gas Cycle is that the reheat COP changes as does the COP with an increase in reheat factor. Both coefficients of performance change instead of just one as seen with the previous two cycles. As the reheat factor increases, the compressor work decreases while the reheat heat transfer rate clearly increases. The coefficient of performance increases from equation (3.8) since the

work decreases. However, the work decreases at a slower rate than the reheat transfer rate increases, which causes the numerator of equation (3.9) to dominate the reheat COP equation. This forces the reheat COP to decrease as seen in the program.

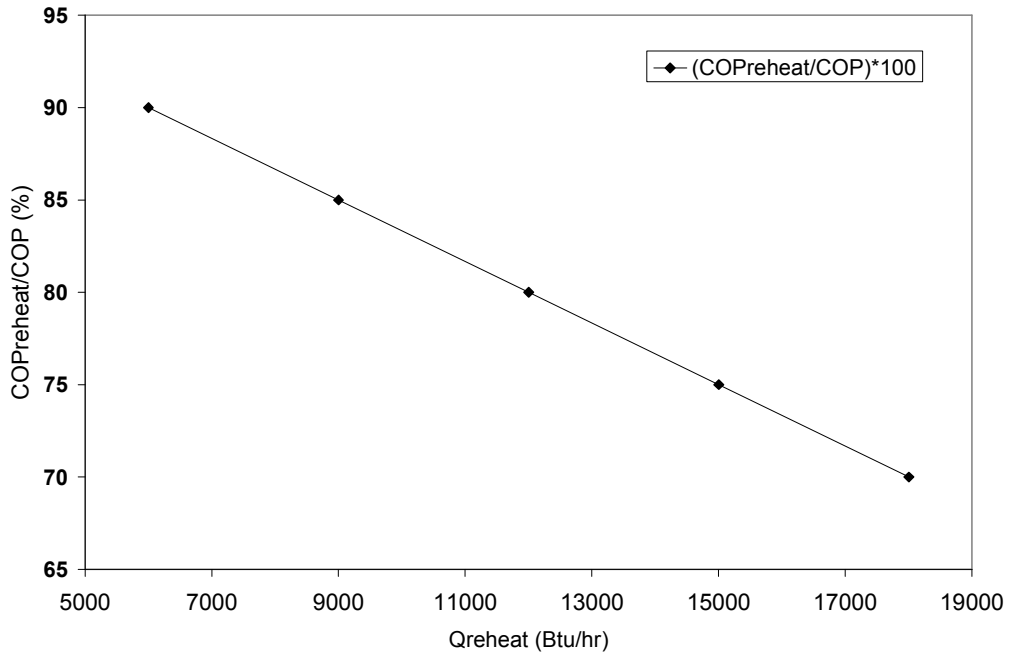


Figure 3.33 COP_{reheat}/COP as a Function of Q_{reheat}

Figure 3.34 shows a graph of how the reheat COP changes with an increase in the ratio m_{reheat} / m_{total} . The background for the trend is explained in the summary of Figure 3.13 for the Warm Liquid Refrigerant Cycle. The reheat factor is held at 0.2 instead of 0.02. The enthalpies at states 2 and 3a, the entrance and exit to the reheat coil, are held constant at the base case conditions as is the total mass flow rate. The lone increasing parameter is the reheat mass flow rate. By examining equation (3.9), it is obvious that the reheat COP decreases with increasing reheat factor.

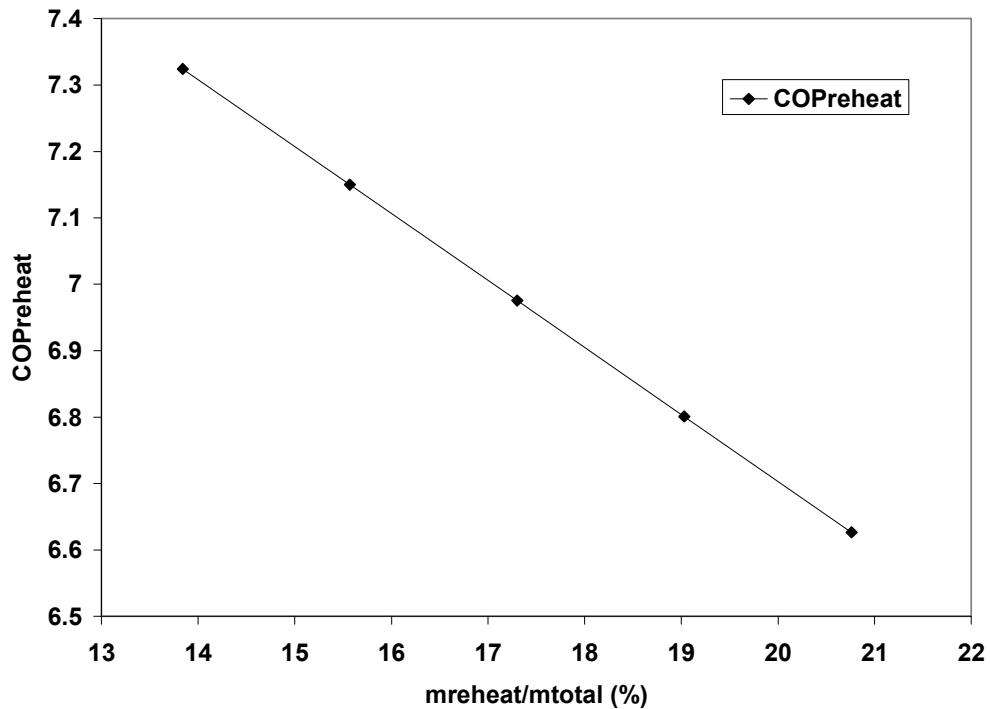


Figure 3.34 COPreheat vs. mreheat/mtotal

Figures 3.35 and 3.36 represent the reheat COP plotted as a function of condensing pressure for different qualities at the condenser exit. The trends for each separate quality at the condenser exit match those presented in Figures 3.19 and 3.20, and 3.7 and 3.8 for the previous two cycles. A more practical condensing pressure range of 174 to 214 psia is used to develop Figure 3.36. The corresponding condensing temperature range is 115.35 to 130.2 degrees F. The reheat COP is nearly cut in half compared to Figure 3.35. Trends in Figure 3.36 seem to flatten out compared to those in Figure 3.35. In both figures, the reheat COP decreases with an increasing condensing pressure. The reheat COP values once again match closely with those obtained for the Sequential Hot Gas Refrigerant Cycle, and are much smaller than those obtained for the Warm Liquid Refrigerant Cycle. The explanation for this graph follows from the

summary of Figures 3.7 and 3.8. States 3 and 4a from the Warm Liquid Refrigerant Cycle are replaced by states 3b and 3a for the Parallel Hot Gas Refrigerant Cycle.

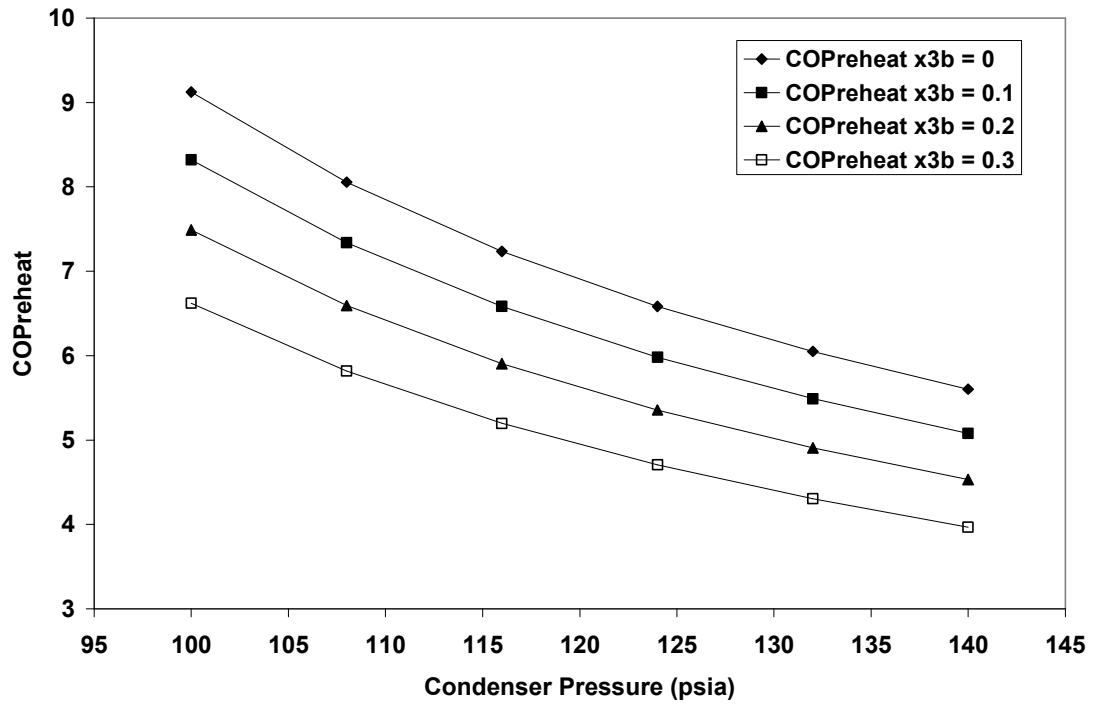


Figure 3.35 COPreheat as a Function of Condenser Pressure for Different Qualities at Condenser Exit

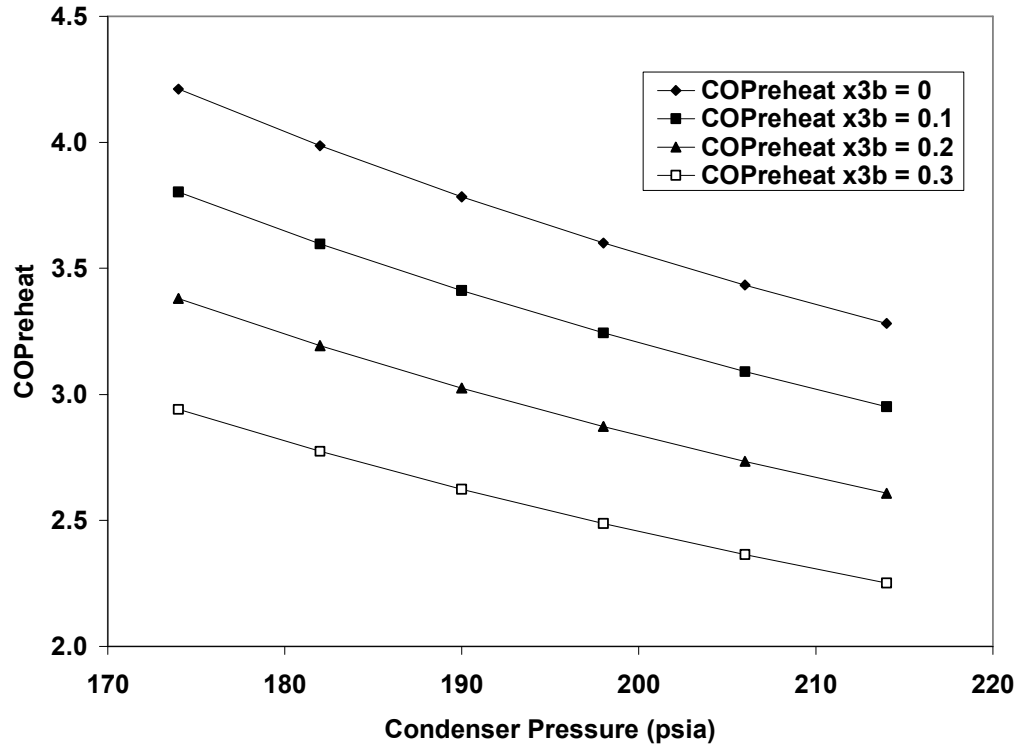


Figure 3.36 COPreheat as a Function of Condenser Pressure for Different Qualities at Condenser Exit (High Pressure Range)

Figure 3.37 matches closely with Figures 3.22 and 3.10 described for the first two cycles. The explanation for these trends follows from the summary for Figure 3.10 for the Warm Liquid Refrigerant Cycle. The inlet and exit states to the reheat coil are 2 and 3a instead of 3 and 4a. The values for the reheat COP match closely those obtained for the Sequential Hot Gas Refrigerant Cycle.

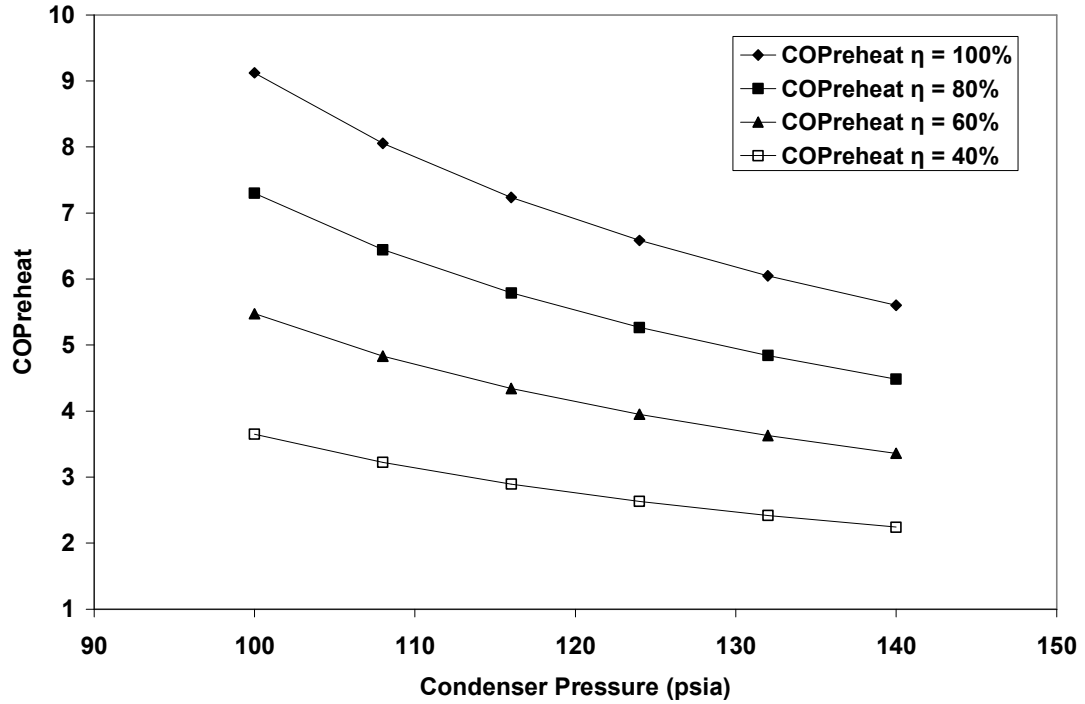


Figure 3.37 COPreheat vs. Condenser Pressure for Different Compressor Efficiencies

Figure 3.38 is similar to Figures 3.25 and 3.11 shown for the previous two cycles. The trend is explained in Figure 3.11, with points 5, 3, and 4a for the Warm Liquid Refrigerant Cycle replaced with points 4, 3b, and 3a for the Parallel Hot Gas Refrigerant Cycle. The values for the reheat COP match those for the Sequential Hot Gas Refrigerant Cycle.

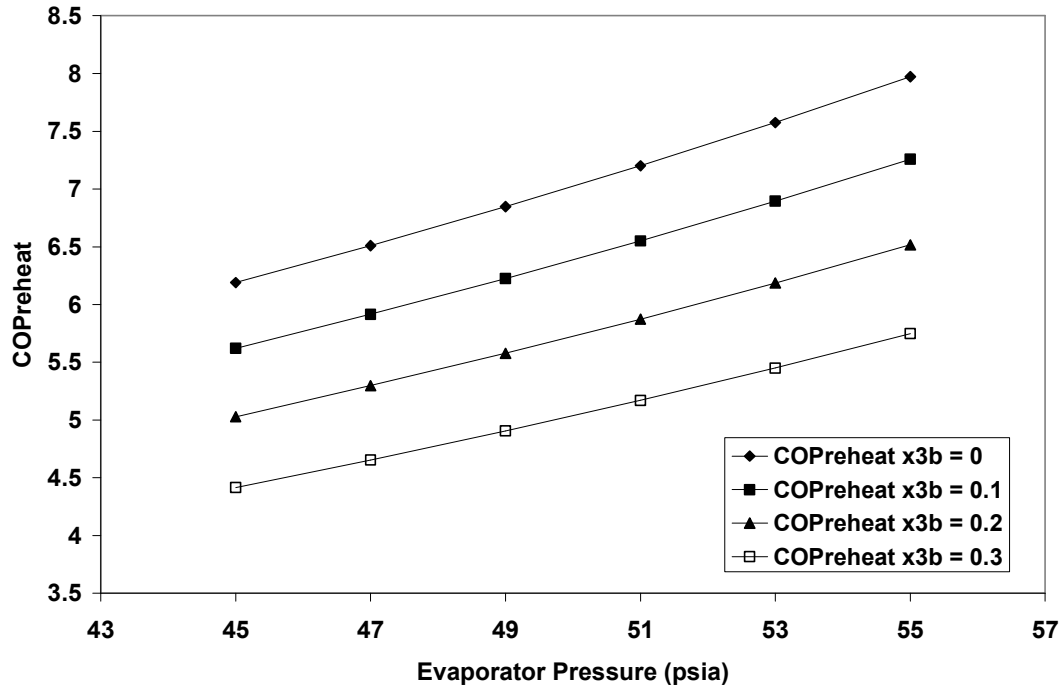


Figure 3.38 COPreheat as a Function of Evaporator Pressure for Different Qualities at Condenser Exit

The COP_{reheat} is plotted against the reheat factor for different compressor efficiencies in Figure 3.39. As the reheat factor increases, the numerator in equation (3.9) decreases. At the same time the denominator decreases, but at a slower rate. Therefore, the COP reheat decreases with increasing reheat factor.

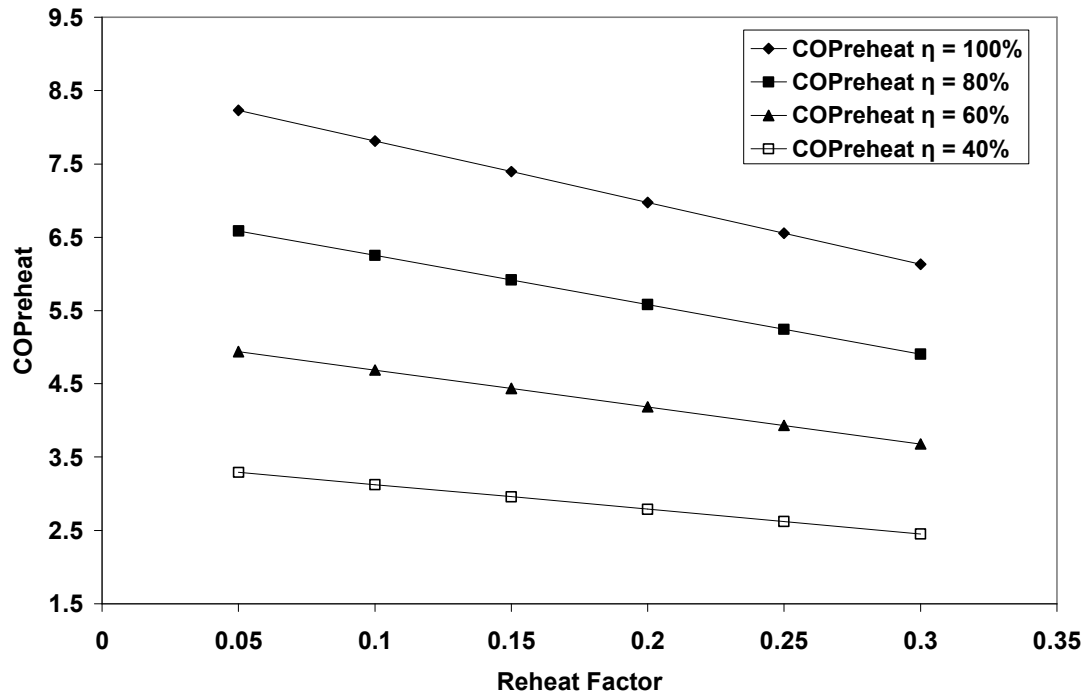


Figure 3.39 COPreheat as a Function of Reheat Factor for Different Compressor Efficiencies

3.5 Two-phase Mixture Refrigerant Cycle

3.5.1 Thermodynamic Cycle

The Two-phase Mixture Refrigerant Cycle is the final cycle discussed in the thesis. The cycle is illustrated by a schematic in Figure 3.40 and a p-h diagram in Figure 3.41. At state 1 the refrigerant exists as a saturated vapor or a superheated vapor, with its value depending on the low side pressure and temperature at point 1. This temperature is limited by the indoor air temperature at the inlet to the evaporator. The refrigerant then passes through the compressor where its enthalpy increases and entropy remains the same (for a 100% efficient cycle). The enthalpy at state 2; therefore, represents that of a superheated vapor, with its value depending on the high side pressure. Next, the

refrigerant is separated into two streams prior to entering the condenser. One stream flows through the condenser, while the other stream passes through the bypass valve. This cycle is similar to the parallel hot gas cycle in that the total mass flow rate does not pass through the condenser. The enthalpy of the refrigerant passing through the bypass valve and at the entrance to the condenser are identical and equal to that at state 2. The two streams combine after the condenser and at the inlet to the three-way valve. The enthalpy at the exit of the condenser is determined by the quality at state 3b, which depends on the outdoor air temperature and size of the condenser. The enthalpy at the exit of this mixture location (state 3) depends on the enthalpies at states 3a and 3b, where h_{3a} and h_2 are equal, and the mass flow rates through the condenser and bypass valve. The refrigerant, with enthalpy 3, is then split into two streams again at the three-way valve. One stream is routed through the reheat coil, while the other stream bypasses the reheat coil. The enthalpy at the inlet to the reheat coil and enthalpy of the refrigerant bypassing the reheat coil are identical and equal to h_3 . The enthalpy at the exit of the reheat coil is dictated by the temperature at point 4a (exit of the reheat coil). This temperature is limited by the temperature of the indoor air exiting the evaporator and by the size of the reheat coil. The refrigerant streams then unite into one stream at the location of the check valve. The enthalpy at this mixture exit (point 4) is dependent on the enthalpies and flow rates that exist at the mixture location. The refrigerant then passes through the expansion valve, where its enthalpy remains constant and its pressure drops to the low side pressure. States 5 and 1 are linked by the evaporator, which operates at the low side pressure. The heat addition to the evaporator is limited by the

size of the evaporator and indoor air temperature at the evaporator inlet. Notice the arrangement in this cycle, where the reheat coil is placed after the condenser.

*Subscripts **

- 1-2 Compression process from state 1 to 2
- comp Compressor
- cond Condenser
- evap Evaporator
- reheat Reheat
- total Mass flow rate through evaporator
- 3a Mass flow rate through non-condenser bypass valve
- 3b Mass flow rate through condenser
- 4a Mass flow rate through reheat
- 4b Mass flow rate through non-reheat bypass
- f Saturated liquid
- g Saturated vapor
- 1 State at evaporator exit
- 2 State at compressor exit
- 3 State at 3a and 3b mixture exit/three-way valve inlet
- 4 State at expansion valve inlet
- 5 State at expansion valve exit/evaporator inlet

3.5.2 Model Formulation

Figures 3.40 and 3.41 illustrate the schematic and p-h diagram for the Two-phase Mixture Refrigerant Cycle. States 1 through 5 are located in the schematic and described in the p-h diagram. The mass flow rates through the system are illustrated in Figure 3.40 with subscripts representing bypass, reheat, and total refrigerant flow rates. The cycle consists of three heat exchangers, four valves, and one compressor. Energy balances are performed about control volumes surrounding each of these components.

A compression process linking states 1 and 2 is identical to that described for the Warm Liquid Refrigerant Cycle in equation (3.1). The variables in this equation along with the units for enthalpy, heat transfer rate, power, and mass flow rate are the same throughout the analysis for the Two-phase Mixture Refrigerant Cycle. As was the case for the previous three cycles, the equation for the condenser is omitted in the analysis as it is not used to develop the simulation. The enthalpy at state 3b is defined by equation (3.2b). Performing a mass balance at the mixture location after the condenser results in the following equation:

$$m_{total} = m_{3a} + m_{3b} \quad (3.12)$$

where m_{3a} is the mass flow rate through the bypass valve, and m_{3b} is the mass flow rate through the condenser. A corresponding energy balance performed at the exact location results in the following equation:

$$m_{total} \times h_3 = m_{3a} \times h_2 + m_{3b} \times h_{3b} \quad (3.13)$$

where h_3 is the enthalpy at the entrance to the three-way valve, h_2 is the enthalpy of the fluid passing through the bypass valve, and h_{3b} is the enthalpy at the condenser exit. A mass balance at the three-way valve results in the following:

$$m_{total} = m_{reheat} + m_{4b} \quad (3.3c)$$

where m_{reheat} is the mass flow rate through the reheat coil and m_{4b} is the mass flow rate through the non-reheat bypass. Equation (3.4) describes an energy balance around the reheat coil. An energy balance is performed at the check valve mixture, and results in the following:

$$m_{total} \times h_4 = m_{reheat} \times h_{4a} + m_{4b} \times h_3 \quad (3.5c)$$

where h_4 is the enthalpy at the check valve mixture exit, h_{4a} is the enthalpy at the reheat coil exit, and h_3 is the enthalpy of the fluid passing through the non-reheat bypass.

Energy balances performed at the expansion valve and evaporator result in equations (3.6) and (3.7). The coefficient of performance and the reheat coefficient of performance are described by equations (3.8) and (3.9) in the Warm Liquid Refrigerant Cycle section.

The heat loss in the reheat coil, Q_{reheat} , is again a known parameter as described previously by equation (3.10). The base case conditions for the Two-phase Mixture Refrigerant Cycle are listed in Table 3.5. The conditions are identical to those used for the Sequential Hot Gas Refrigerant Cycle and Parallel Hot Gas Refrigerant Cycle. The variables in the left column have slightly different subscripts to reflect the correct states on the schematic and p-h diagram. One additional parameter is listed to indicate the amount of mass flow rate passing through the bypass valve. This parameter is described in the following equation:

$$m_{3a} = n_{3a} \times m_{3b} \quad (3.14)$$

where n_{3a} relates the mass flow rate through the bypass valve with the mass flow rate through the condenser. The base case value for n_{3a} is 0.2. The effects of varying this parameter are discussed in the results and discussion section

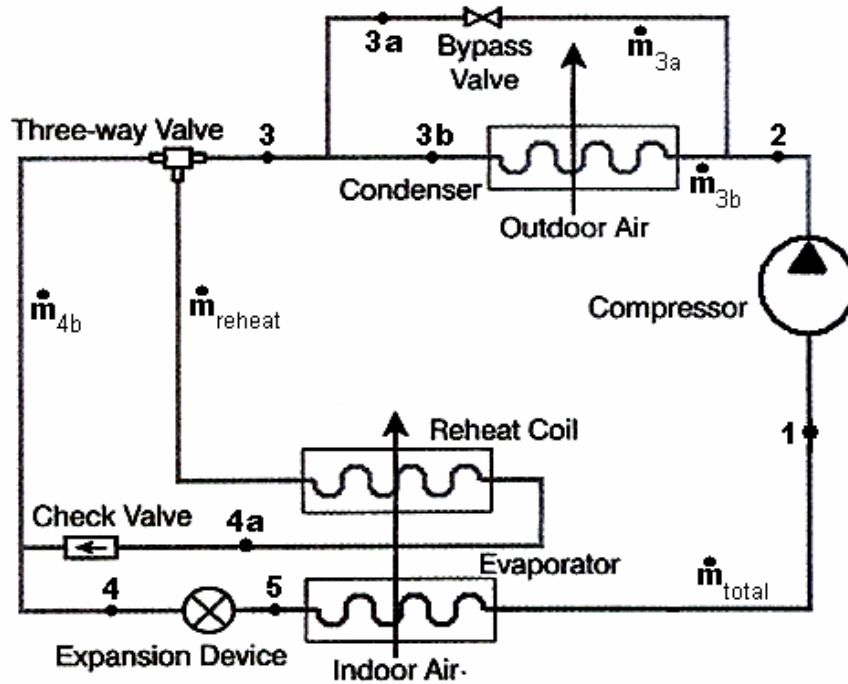


Figure 3.40 Schematic for Two-phase Mixture Refrigerant Cycle

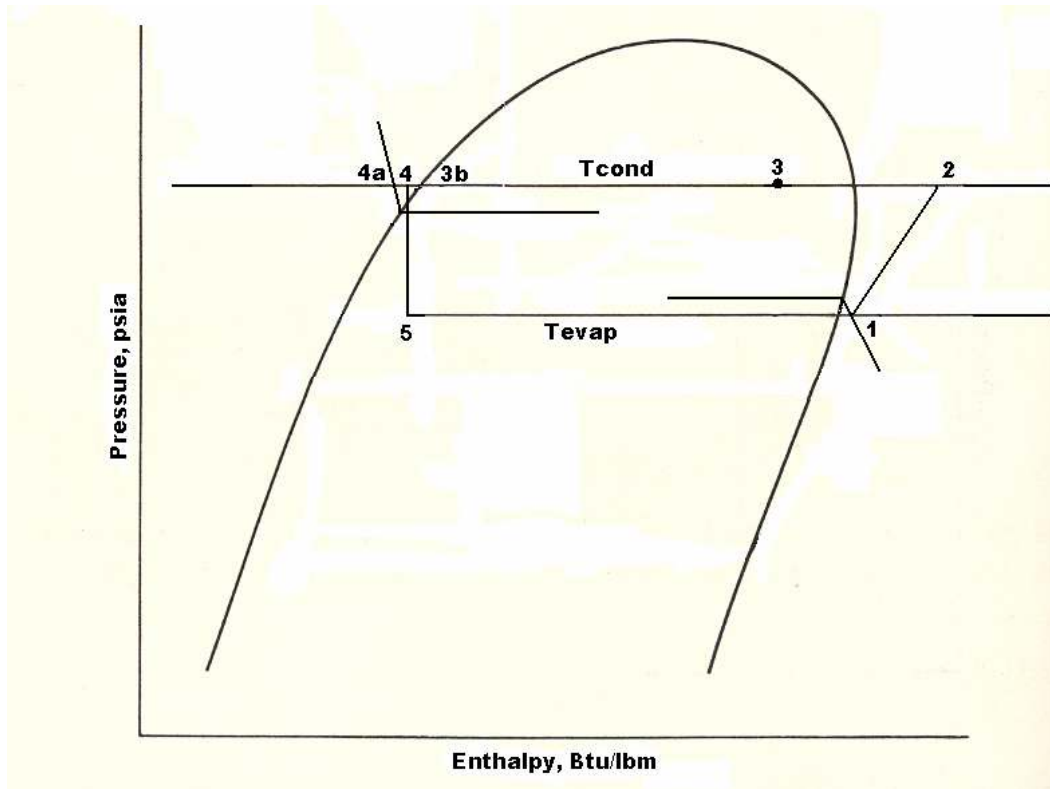


Figure 3.41 p-h Diagram for Base Case Two-phase Mixture Refrigerant Cycle

Table 3.5
Base Case Conditions for the
Two-phase Mixture Refrigerant Cycle

Base Case Conditions	
Pevap	49.74 psia
Tevap	40°F
T1	45°F
Pcond	119.01 psia
Tcond	90°F
x3b	0
T4a	80°F
Freheat	0.2
Qevap	60016.24 Btu/hr
η_{comp}	100%
n3a	0.2

3.5.3 Simulations

The same visual basic program written to simulate the previous three cycles was used to simulate the Two-phase Mixture Refrigerant Cycle, with the exception of the renumbering of variables and subscripts to match the appropriate schematic and p-h diagram. The equations used to calculate certain parameters at the end of the program are changed slightly to properly reflect the equations presented for the analysis of this cycle. The program is identical to that described in the Warm Liquid Refrigerant Cycle simulation section, including the type of refrigerant used, ranges on the evaporator and condenser pressures, and interpolation functions. The definitions of how to locate states 1 and 2 remain unchanged as well.

States 3 through 5 change for the Two-phase Mixture Refrigerant Cycle based on Figures 3.40 and 3.41. The component n_{3a} is an additional input added to the program, to make a total of 8 inputs for this program. The first equation used in the program was developed from equations (3.4), (3.12), (3.13), and (3.14) discussed above. The mass flow rate through the reheat coil is solved for as shown here:

$$m_{\text{reheat}} := \frac{Q_{\text{reheat}}}{\left[\frac{(h_2 \cdot n + h_{3b})}{(n + 1)} \right] - h_{4a}} \quad (3.15)$$

where n is equal to n_{3a} . Using equations (3.4) and (3.15), the enthalpy at state 3 can be solved for:

$$h_3 := \frac{(h_2 \cdot n + h_{3b})}{(n + 1)} \quad (3.16)$$

Manipulating equations (3.3c), (3.5c), (3.6), and (3.7), the mass flow rate through the non-reheat bypass can be solved for:

$$m_{4b} := \frac{(h_{4a} \cdot m_{\text{reheat}} + Q_{\text{evap}} - h_1 \cdot m_{\text{reheat}})}{(h_1 - h_3)} \quad (3.17)$$

From the same set of equations, the enthalpy at point 4 is solved for:

$$h_4 := h_1 - \frac{Q_{\text{evap}}}{(m_{\text{reheat}} + m_{4b})} \quad (3.18)$$

The total mass flow rate is then calculated from equations (3.6) and (3.7). Finally, the mass flow rate through the condenser is equal to:

$$m_{3b} := \frac{m_{\text{total}}}{(n + 1)} \quad (3.19)$$

from equations (3.12) and (3.14). State 3b used in the above equations is at the exit of the condenser and is calculated from equation (3.2b). Equation (3.2b) is developed for each of the eleven condensing pressures. The quality at point 3b, x_{3b} , is an input in the program. The enthalpy at point 3b is interpolated if the condensing pressure falls between two of the eleven pressures with a corresponding equation. State 4a used above occurs at the exit of the reheat coil and at the condensing pressure. If the input condensing pressure corresponds to one of the pressures with an equation, the temperature at state 4a is limited by the saturation temperature at that pressure and by the saturation temperature minus 30°F. If the input pressure falls between two of the pressures with equations, the temperature at 4a is bounded by the saturation temperature minus 30°F at the high pressure and the saturation temperature at the low pressure. The high and low pressures refer to the input condensing pressure rounded up and the input condensing pressure rounded down, respectively. The enthalpy at point 4a is then calculated by knowing the pressure and temperature at 4a. Enthalpy versus temperature equations are used to interpolate h_{4a} . The compressor work, coefficient of performance,

and reheat coefficient of performance are then calculated as described for the Warm Liquid Refrigerant Cycle to complete the simulation. Figure 3.42 illustrates a base case analysis using the visual basic program for the Two-phase Mixture Refrigerant Cycle. The program contains 8 input variables as listed across the top row of the form, with the final variable located to the far left on the second row of the form.

evap pressure (psia)	Temperature at point 1 (F)	Condenser Pressure (psia)	quality at 3b	Temperature at point 4a (F)	reheat factor	Q evaporator (Btu/h)
49.741	45	119.01	0	80	0.2	60016.2398
percent mass flow rate through 3a (not a percent)	high pressure (evap exit)	High Saturation Temperature (evap exit)	Eval 1	low pressure (reheat exit)	high pressure (reheat exit)	
0.2	50	40.267		116	120	
evap pressure rounded	low pressure (evap exit)	Low Saturation Temperature (evap exit)	Low Saturation Temperature plus 10	Low Saturation Temperature (reheat exit)	High Saturation Temperature (reheat exit)	
50	49	39.227	49.227	88.373	90.526	
Evaporator Exit Enthalpy (State 1)	test enthalpy 1 (Btu/lbm)	Evaporator Exit Entropy (State 1)	test entropy 1 (Btu/lbmR)	Reheat Exit Enthalpy (State 4a)	Tsat high minus 30	
173.68305	173.981250827	0.4144	0.41530673694	101.930150462	60.526	
Compressor Exit Enthalpy (State 2)	test enthalpy 2	test entropy 2	mass flow rate (3b)	Enthalpy at State 4	test enthalpy 4a	
181.58567	181.030224108	0.4144	719.531261505	104.174558896	101.929766313	
Condenser Exit Enthalpy (State 3b)	test enthalpy 3b	mass flow rate through reheat (lbm/h)	mass flow rate of refrigerant (lbm/h)	COP	Q reheat (Btu/h)	
105.374375	102.46	743.414374444	863.437513807	8.79563	12003.24796	
Enthalpy at State 3	mass flow rate (4b)	mass flow rate (3a)		Work Input (Btu/h)	COP reheat	
118.076257361	120.02314	143.906252301		6823.41679237	7.0365	

Figure 3.42 Sample Visual Basic Program for Two-phase Mixture Refrigerant Cycle with Base Case Conditions

3.5.4 Results and Discussion

Table 3.5 contains the base case data used in the program. When one or more of the parameters are changed, the remaining input variables are equal to the base case values.

Through simulation, it was discovered that a unique value exists for the component of mass flow rate through the bypass valve, where values greater than this value produce a positive mass flow rate through the non-reheat bypass and values less than this value produce a negative mass flow rate through the non-reheat bypass. The results from several simulations using different values for n_{3a} are plotted in Figure 3.43. It is evident that the transition point occurs when m_{3a} is approximately 16.70% of m_{3b} .

This was verified with a mathcad analysis, where equations (3.15) and (3.16) were substituted into equation (3.17) as follows:

$$m_{4b} := \frac{\left[h_{4a} \cdot \left[\frac{Q_{reheat}}{\left(\frac{h_2 \cdot n_{3a} + h_{3b}}{n_{3a} + 1} \right) - h_{4a}} \right] + Q_{evap} - h_1 \cdot \left[\frac{Q_{reheat}}{\left(\frac{h_2 \cdot n_{3a} + h_{3b}}{n_{3a} + 1} \right) - h_{4a}} \right] \right]}{\left[h_1 - \frac{(h_2 \cdot n_{3a} + h_{3b})}{(n_{3a} + 1)} \right]} = 0 \quad (3.20)$$

where n and n_{3a} are interchangeable. Solving equation (3.20) for n_{3a} yields 0.1670.

Again there is a unique value for the reheat factor that separates positive and negative non-reheat mass flow rates, as was the case for the Warm Liquid Refrigerant Cycle. The exact number was not calculated in this analysis, but can be found through simulations with the program for the Two-phase Mixture Refrigerant Cycle

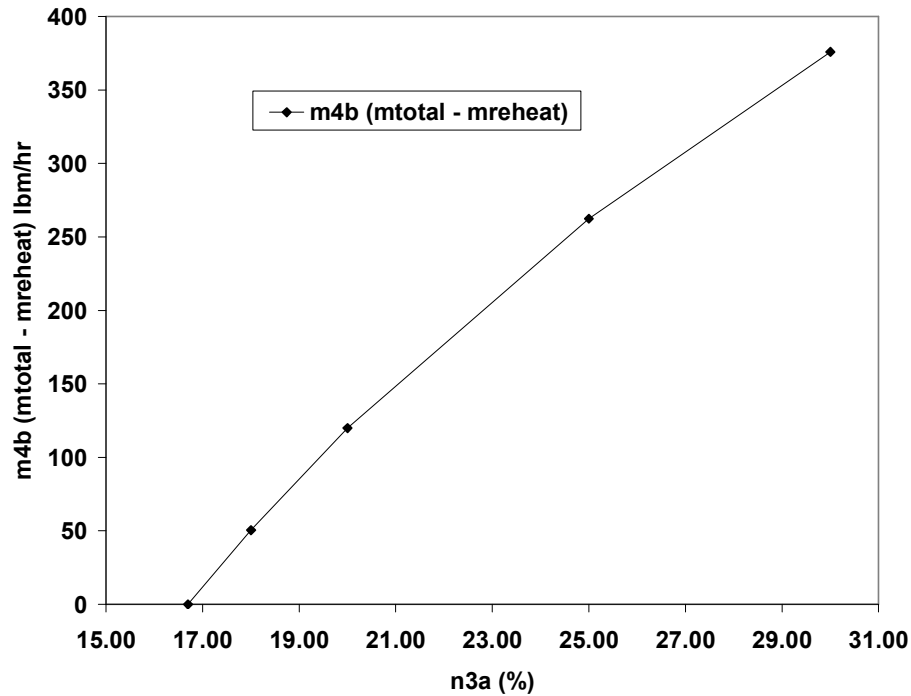


Figure 3.43 Mass Flow Rate Through 4b (Non-reheat Bypass) vs. Percent Mass Flow Rate of 3b Through 3a

Figures 3.44 and 3.45 follow closely to figures 3.30 and 3.31, 3.17 and 3.18, and 3.5 and 3.6 for the previously explained three cycles. Figures 3.44 and 3.45 show how the reheat COP fluctuates as the quality at the condenser exit increases. Figure 3.44 shows results using the base case conditions listed above in Table 3.5. Figure 3.45 shows results based on a practical condensing pressure and temperature of 194 psia and 123.06°F, respectively. The temperature of the refrigerant at the exit of the reheat coil, T_{4a} , is 113.06°F for Figure 3.45. The values for the remaining variables used in developing Figure 3.45 are identical to those presented in Table 3.5. The 2 plots show similar trends, with the COP values cut by a factor of 2 in Figure 3.45. Both graphs show the COP decreasing linearly with increasing quality at the condenser exit. The same

reasoning for the decline in reheat COP applied to Figures 3.5 and 3.6 applies to Figures 3.44 and 3.45. State 3 in the Warm Liquid Refrigerant Cycle is equivalent to state 3b in the Two-phase Mixture Refrigerant Cycle. The values of the reheat COP are closer to the values seen in Figures 3.30 and 3.31, and 3.17 and 3.18 for the Parallel Hot Gas Refrigerant Cycle and the Sequential Hot Gas Refrigerant Cycle.

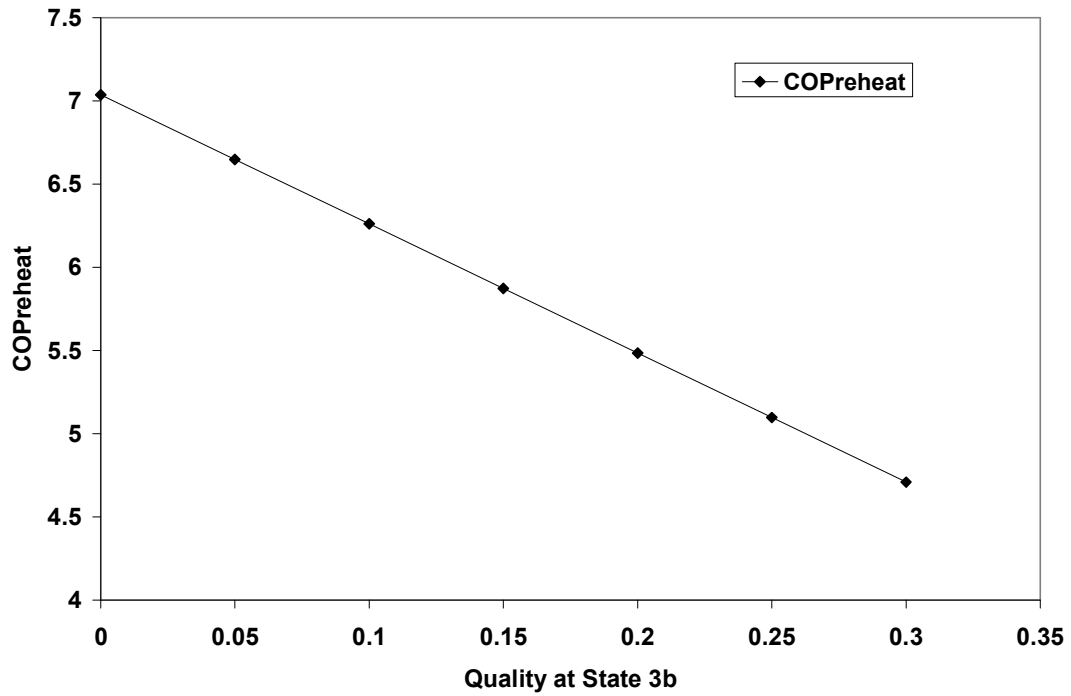


Figure 3.44 COPreheat as a Function of Quality at Condenser Exit (x_{3b})

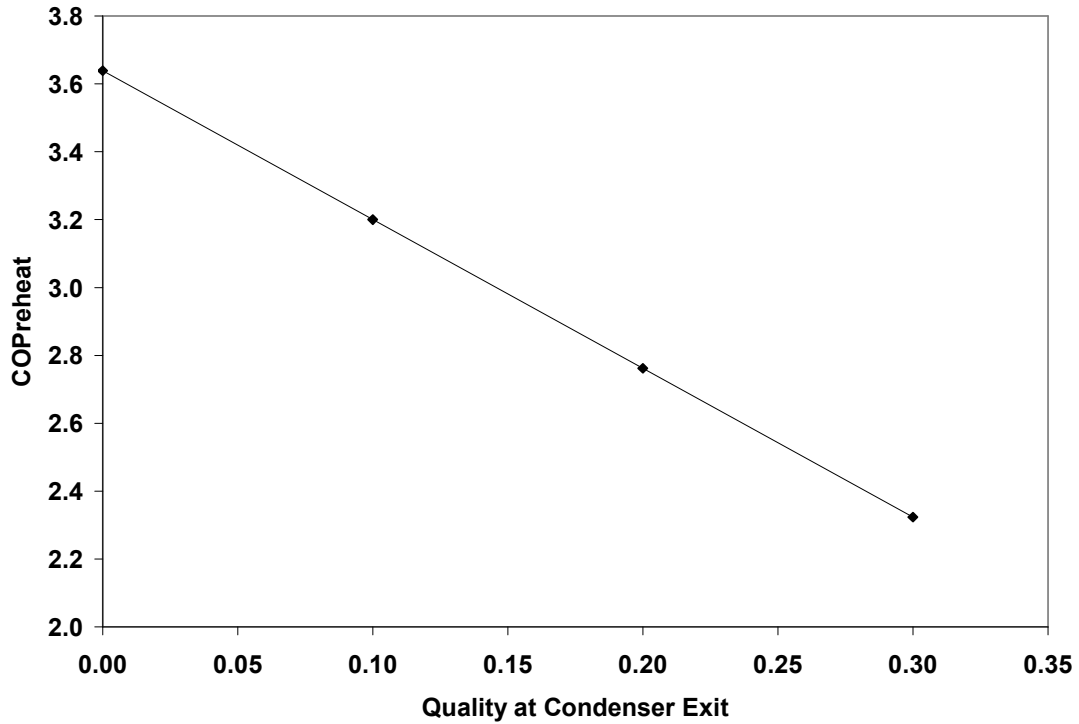


Figure 3.45 COPreheat as a Function of Quality at Condenser Exit (x_{3b}), High Pressure of 194 psia

Figure 3.46 shows how the reheat COP increases as the evaporator exit temperature increases. The trend matches the trends seen for the other three cycles. As T_1 increases, the enthalpy at state 1 increases, and the difference in the enthalpies between states 1 and 5 increases. The enthalpy at point 3 increases as well since the enthalpy at point 2 increases. This increase in h_3 tends to increase h_4 , which tends to lower the reheat COP. This effect has a smaller impact than the actual increase in h_1 , which drives up the reheat COP by the following process. The enthalpy at state 5 then follows from equation (3.6). This decreases the total mass flow rate from equation (3.7), and therefore, decreases the work input in the compressor from equation (3.1). A smaller work indicates a larger COP_{reheat} from equation (3.9), which is the trend illustrated in

Figure 3.46. The reheat COP values for the Warm Liquid Refrigerant Cycle are considerably larger than those calculated using the three latest cycles.

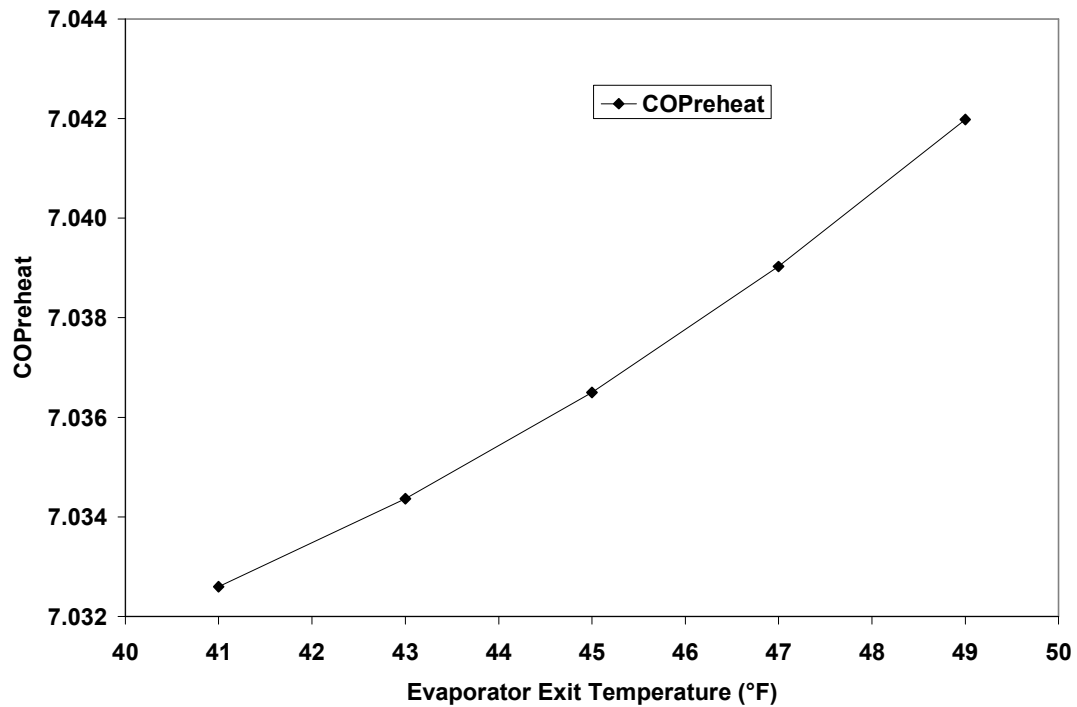


Figure 3.46 COPreheat as a Function of Evaporator Exit Temperature

Figure 3.47 illustrates how the reheat COP reacts to an increase in m_{reheat} / m_{total} .

The trend is expected since Q_{reheat} increases as m_{reheat} increases, which drives down the reheat COP. The enthalpies at the inlet and exit to the reheat coil remain constant in this analysis, as does the total mass flow rate. The values for the reheat coefficient of performance are closer to those obtained in Figures 3.34 and 3.26 for the two hot gas cycles.

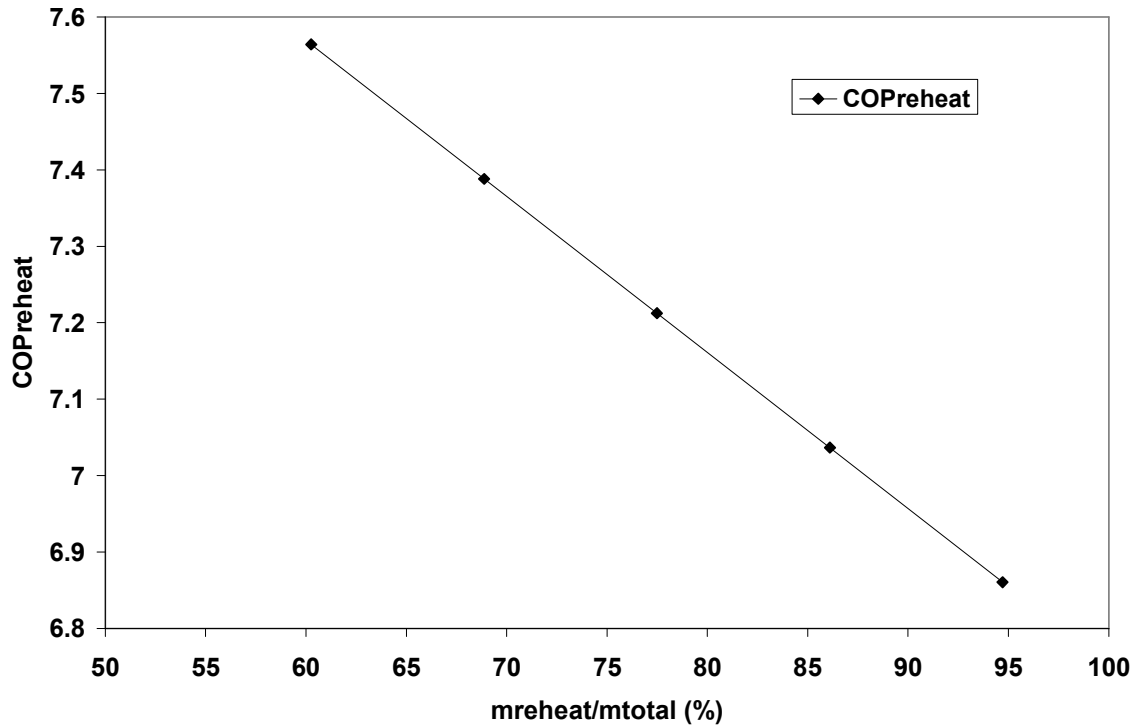


Figure 3.47 COPreheat vs. mreheat/mtotal

The ratio COP_{reheat} / COP decreases as the reheat factor increases in Figure 3.48.

The reheat COP remains constant as the reheat factor increases, since the work decreases at the same rate that Q_{reheat} increases. The COP increases as the reheat factor increases since the work decreases. This explains the decrease in the coefficient of performance ratio. The values for the reheat COP again match those obtained in Figures 3.33 and 3.24.

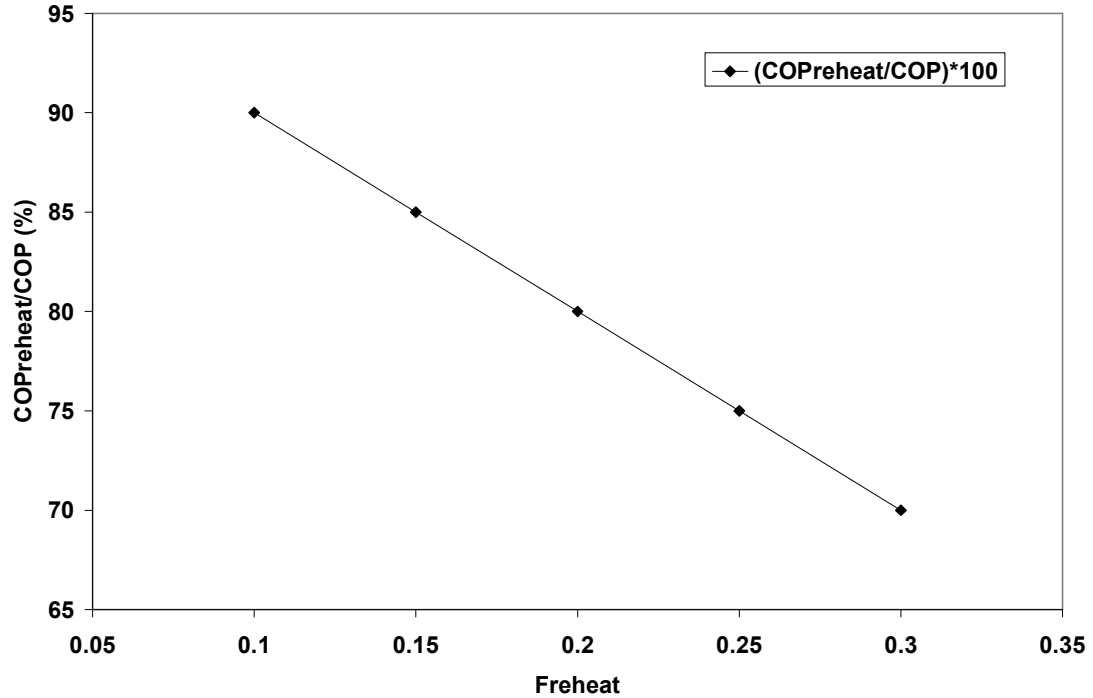


Figure 3.48 COPreheat/COP as a Function of Reheat Factor

Figures 3.49 and 3.50 resemble Figures 3.35 and 3.36, and 3.19 and 3.20 for the two hot gas cycles. A practical condensing pressure range of 174 to 214 psia is used to develop Figure 3.50. The corresponding condensing temperature range is 115.35 to 130.2 degrees F. The reheat COP is nearly cut in half compared to Figure 3.49. Trends in Figure 3.50 seem to flatten out compared to those in Figure 3.49. In both figures, the reheat COP decreases with an increasing condensing pressure. The reasoning behind the trend is discussed for the Warm Liquid Refrigerant Cycle, and presented in Figures 3.7 and 3.8. The reheat COP values for the Two-phase Mixture Refrigerant Cycle correspond closely with the two hot gas cycles.

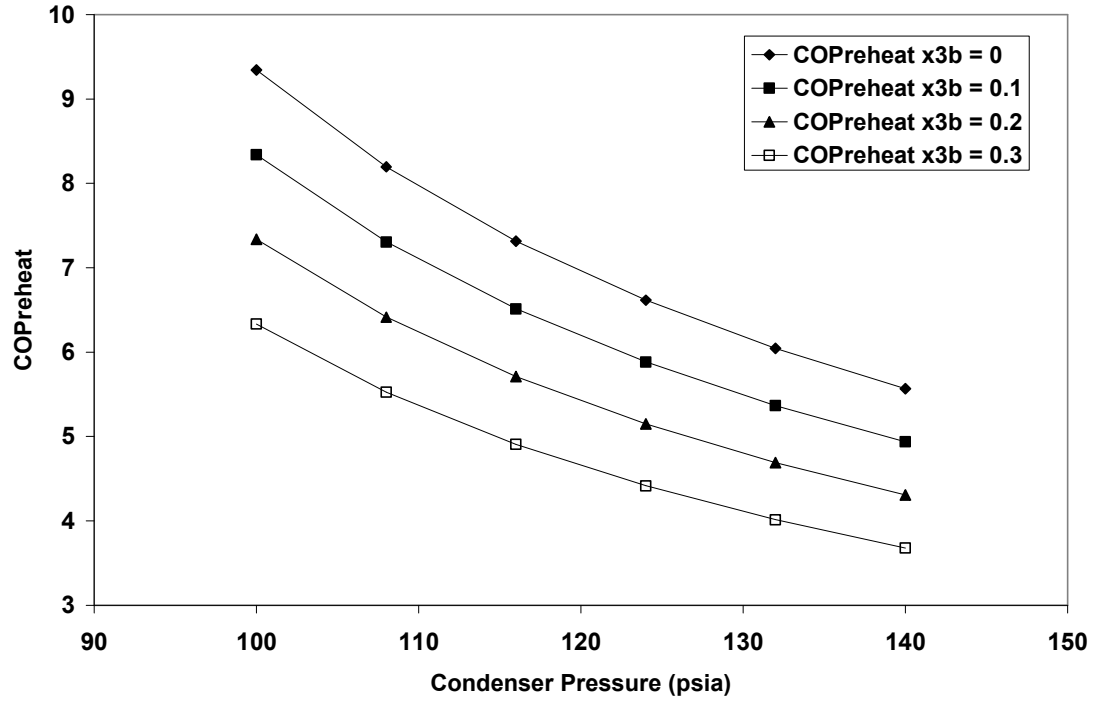


Figure 3.49 COPreheat vs. Condenser Pressure for Different Qualities at Condenser Exit

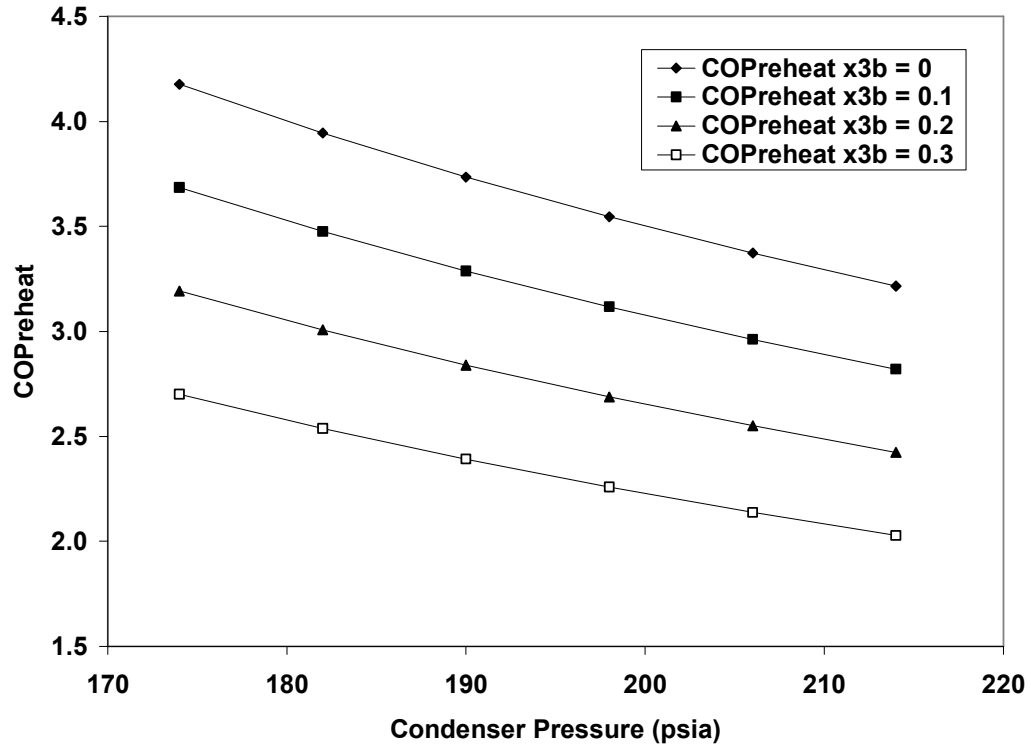


Figure 3.50 COPreheat vs. Condenser Pressure for Different Qualities at Condenser Exit (High Pressure Range)

Figure 3.51 is similar to Figures 3.49 and 3.50 in the trends shown for the reheat COP as a function of condensing pressure. Figure 3.51 shows the COP_{reheat} decreasing with increasing condensing pressure. The explanation for this result is identical to that given for Figures 3.7 and 3.8 in the Warm Liquid Refrigerant section. The only difference in Figure 3.51 is the added compressor efficiency as a parameter. Decreasing the efficiency of the compressor, increases the work input which decreases the COP_{reheat} as shown.

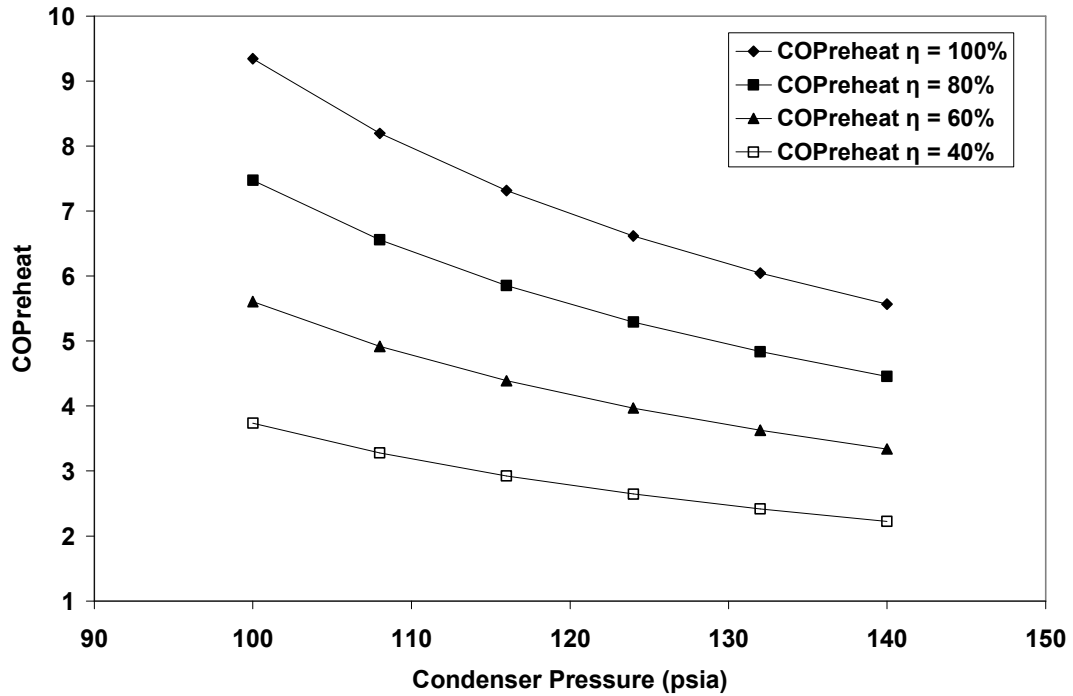


Figure 3.51 COPreheat as a Function of Condenser Pressure for Different Compressor Efficiencies

The reheat coefficient of performance is plotted as a function of the evaporator pressure for different qualities at the condenser exit in Figure 3.52. The input temperature at point 1 changes as the input evaporator pressure changes. The temperature at point 1 is always 5°F greater than the saturation temperature at the evaporator pressure for this analysis. For example, T_1 is 44.227°F at an evaporating pressure of 49 psia. As the evaporating pressure increases, the enthalpy at point 1 increases, which broadens the gap between the enthalpies at points 5 and 1. The enthalpy at point 3 decreases as the evaporator pressure increases. This also causes the difference between points 5 and 1 to increase. The total mass flow rate decreases from equation (3.7), and the work input decreases from equation (3.1). This drives up the reheat COP from equation (3.9).

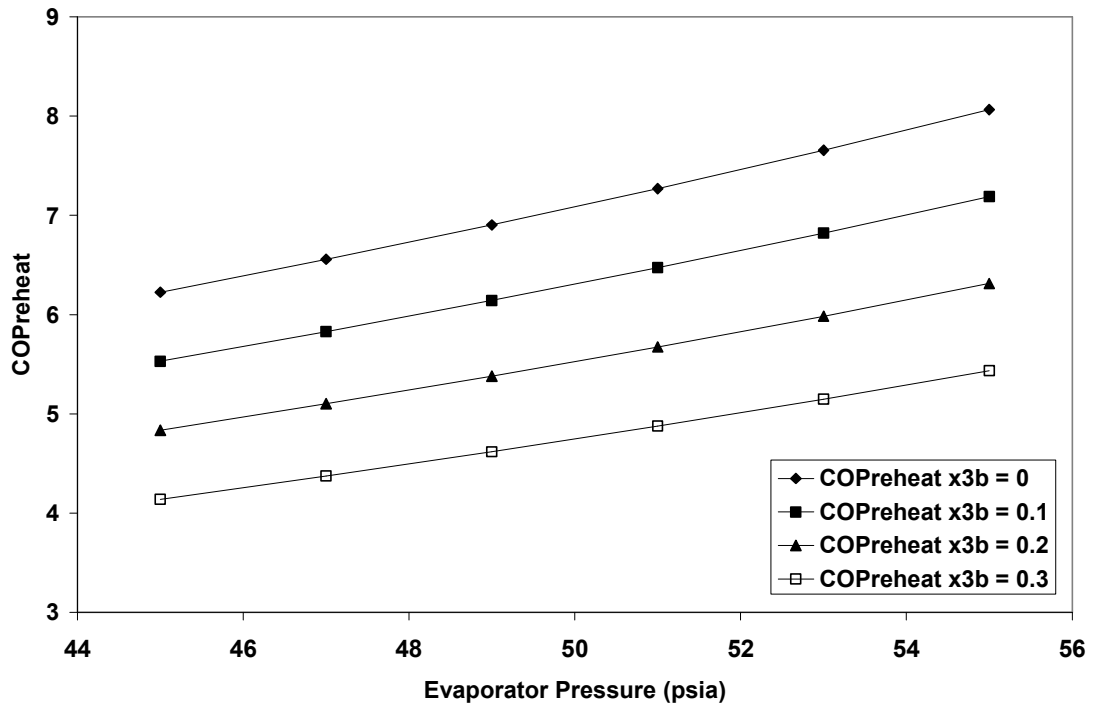


Figure 3.52 COPreheat vs. Evaporator Pressure for Different Qualities at Condenser Exit

Figures 3.53 through 3.56 plot the reheat COP for all the cycles versus a representative parameter. These two parameters were determined to be the most representative parameters for the analyses. Figures 3.53 and 3.54 show the COP reheat versus the quality at the condenser exit. Figure 3.53 shows results using the base case conditions listed in Tables 3.2 through 3.5. Figure 3.54 shows results based on a practical condensing pressure and temperature of 194 psia and 123.06°F, respectively. The temperature of the refrigerant at the exit of the reheat coil is 113.06°F for Figure 3.54. The values for the remaining variables used in developing Figure 3.54 are identical to those presented in Tables 3.2 through 3.5 for their respective cycle. The 2 plots show similar trends, with the COP values cut by a factor of about 2 in Figure 3.54. The slopes of the trend lines are very similar for all cycles except for the line representing the

Parallel Hot Gas Refrigerant Cycle. The slope of this line is slightly more positive than the slope for the other three cycles. It is clear that the Warm Liquid Refrigerant Cycle operates with a higher COP reheat than the other three cycles. This could be the result of the base case reheat factor used for the Warm Liquid Refrigerant Cycle. The base case reheat factor was 0.02 for the Warm Liquid Refrigerant Cycle, whereas it was 0.2 for the other three cycles. By examining equation (3.9), one can see that the reheat COP will be smaller for a higher reheat factor. Figures 3.55 and 3.56 show a plot of the reheat COP versus the condenser pressure for all four cycles. A practical condensing pressure range of 174 to 214 psia is used to develop Figure 3.56. The corresponding condensing temperature range is 115.35 to 130.2 degrees F. The values for reheat COP in Figure 3.55 are over 2 times those in Figure 3.56. Trends in Figure 3.56 seem to flatten out compared to those in Figure 3.55. Again, the curves are nearly identical except for the curve representing the Warm Liquid Refrigerant Cycle. The reheat COP values are elevated with respect to the other cycles, which can be explained by the smaller base case reheat factor. The Two-phase Mixture Refrigerant Cycle tends to see slightly higher reheat COP values than the two hot gas refrigerant cycles for low condensing pressures using the base case condensing pressure range. The Parallel Hot Gas Refrigerant Cycle has the highest COP_{reheat} values, next to the Warm Liquid Refrigerant Cycle for the higher condensing pressure range

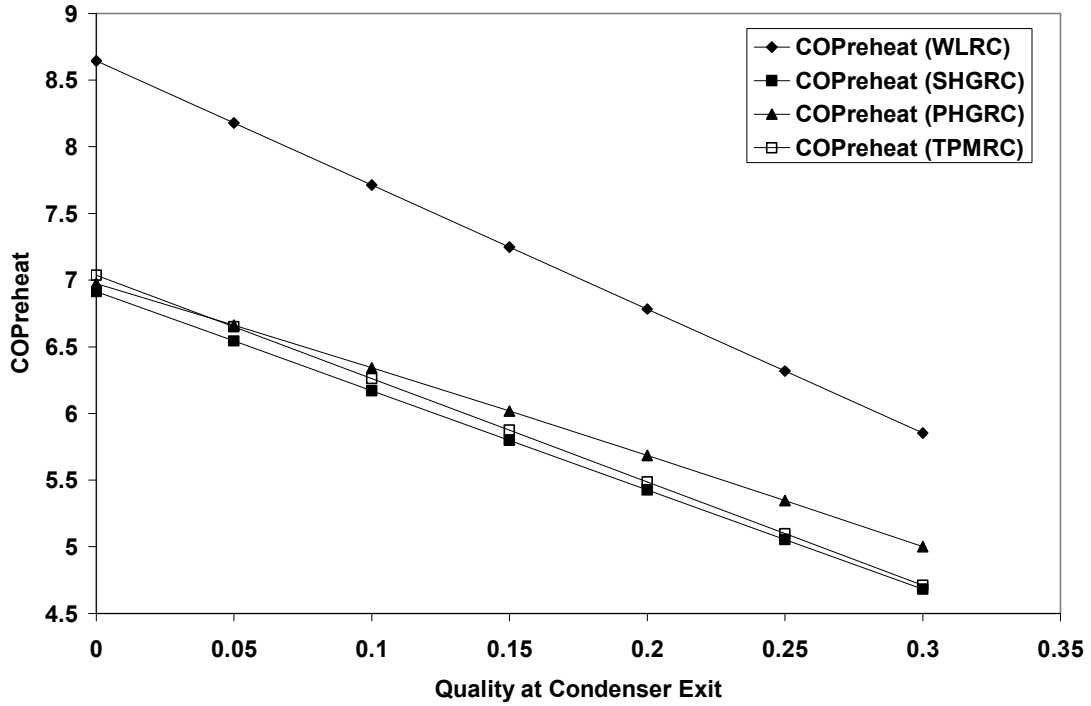


Figure 3.53 COPreheat vs. Quality at Condenser Exit for Different Refrigerant Cycles

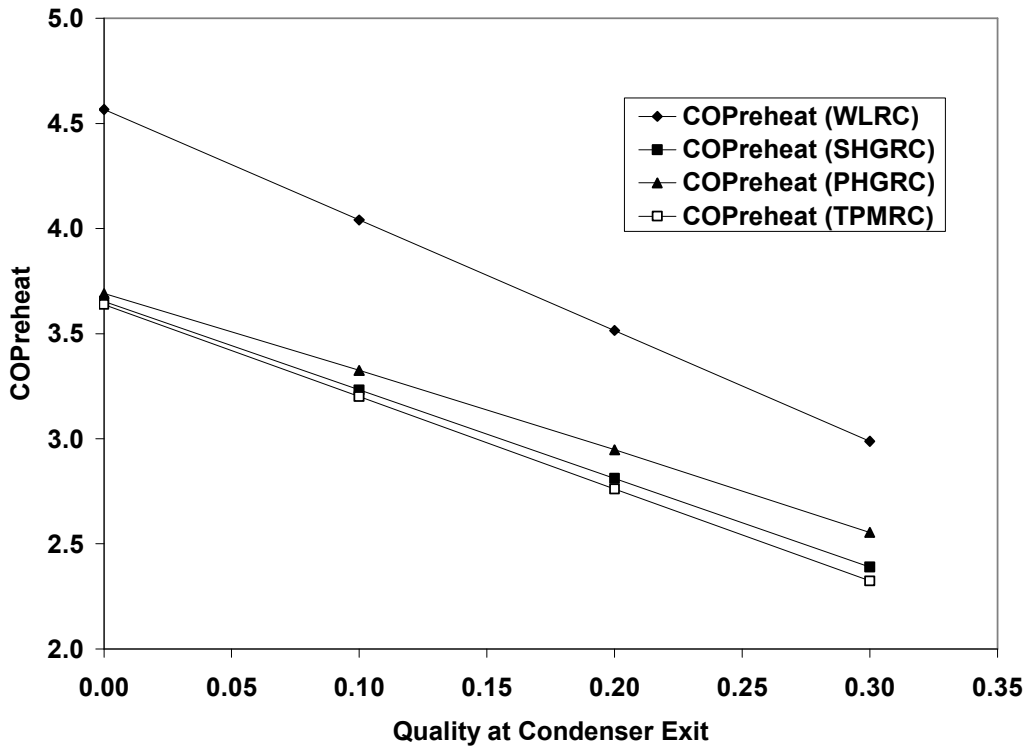


Figure 3.54 COPreheat vs. Quality at Condenser Exit for Different Refrigerant Cycles (High Pressure of 194 psia)

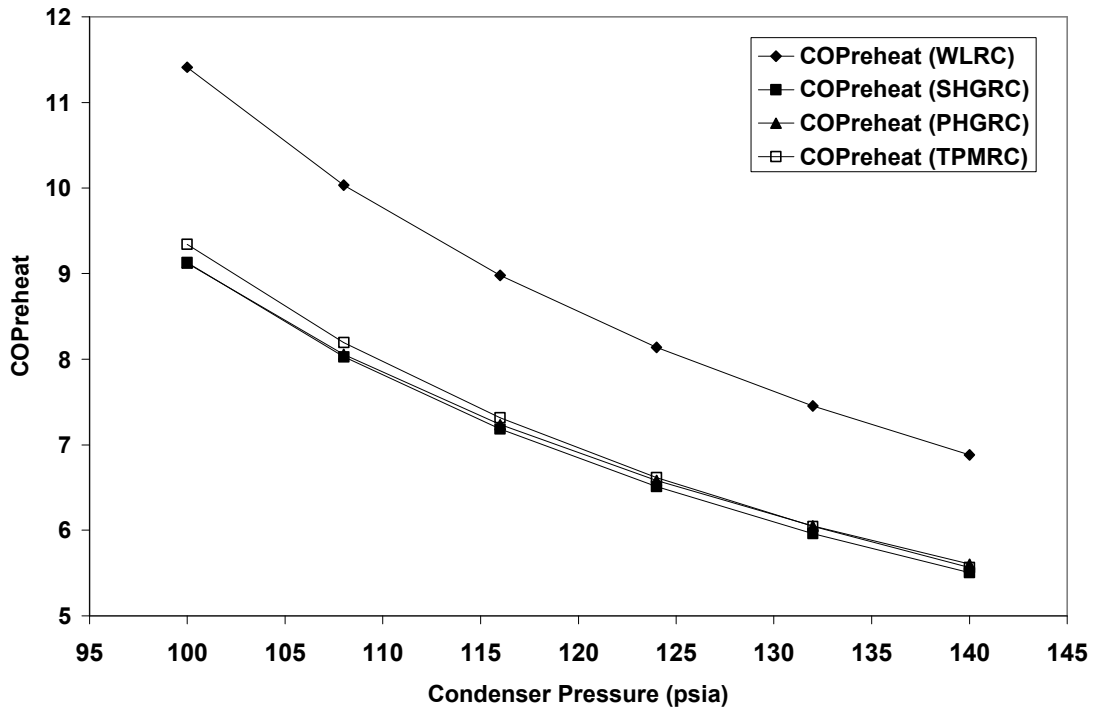


Figure 3.55 COPreheat as a Function of Condenser Pressure for Different Refrigerant Cycles

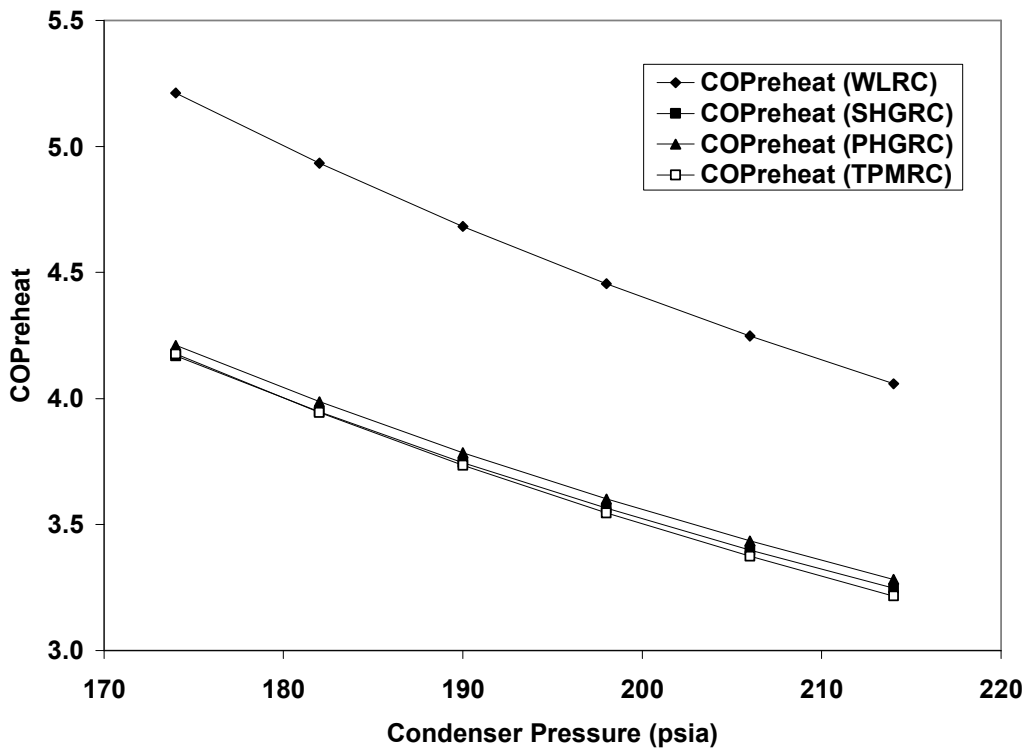


Figure 3.56 COPreheat as a Function of Condenser Pressure for Different Refrigerant Cycles (High Pressure Range)

Chapter 4

Conclusions and Recommendations

4.1 Summary of Carbon Dioxide Cycles

A CO_2 vapor compression refrigeration cycle was considered in this thesis. A thermodynamic analysis based on traditional one and two-stage vapor compression cycle analyses was carried out using properties of carbon dioxide in the subcritical and supercritical regions. Several visual basic programs were written with interpolation functions used to determine the enthalpies needed for the analysis. A sensitivity analysis was carried out to determine the characteristics of the cycles. Different parameters were used as input to the programs to create 14 plots of coefficient of performance versus input parameters of interest. The programs contained ranges for high, low, and intermediate pressures that are of particular importance in common refrigeration and air conditioning applications. In the supercritical region, pressure is independent of temperature. Figures 2.14 and 2.15, as well as 2.17 and 2.18 present the coefficient of performance as a function of gas cooler exit temperature at a constant high pressure. This is a distinguishing point from the R-134a cycle, which operates in the subcritical region only, where the temperature is dependent upon pressure and vice versa. Figures 2.15 and 2.18 utilize a higher condenser temperature exit range, simulating a practical operating range

where the ambient air is around 100°F. The COP is reduced by a value of 1 to 2 for the higher condenser temperature exit range. The coefficient of performance for the CO_2 cycle has an inflection point when plotted versus the intermediate pressure as shown in Figures 2.16, 2.17, 2.18, and 2.20. Table 2.1 shows a comparison of the COP for one and two-stage CO_2 vapor compression cycles versus the COP for a one-stage R-134a vapor compression cycle. The R-134a cycle is about 3 times as effective as the two-stage CO_2 cycle when looking at the coefficient of performance. Improvements to this analysis could be made to increase the accuracy of the results by decreasing the intervals between the constant pressure and constant temperature interpolation equations used in the programs. Another source of error occurs in the difference in results presented in Figure 2.19. Several figures were constructed from data using visual basic programs consisting of no intercooler efficiency calculation. Other figures were derived from programs involving an intercooler efficiency calculation.

This paper offers a method of analyzing a CO_2 vapor compression system based on concepts used in analyzing R134a vapor compression cycles. The CO_2 cycle operates in the transcritical region whereas the R134a cycle operates strictly in the saturated dome region. This difference results in several additional interpolation functions based on both constant pressure and constant temperature equations to obtain the properties at each state. The simulations discussed above utilize these interpolation functions as well as the equations for each process to determine the parameters of interest. The interpolation functions and the equations describing the cycles were incorporated into the visual basic programs so the simulations could be run for any value of the inputs within the stated

bounds. The results from these programs were graphed and performance trends were observed and analyzed. Diagrams and schematics for the analyses were presented along with sample programs with calculated properties at each state.

Overall, potential exists for the use of CO_2 as a natural refrigerant in refrigeration and air-conditioning applications. Specific interest lies in automobile air-conditioning systems, where the need for compact parts is essential. This characteristic is an attribute of CO_2 systems due to their high operating pressures. One drawback of the high operating pressures is the need for heavy duty thick tubing. This would drive up the weight and material costs of these air conditioning systems and could restrict the use of such systems in automobiles. Another advantage of using CO_2 as a refrigerant is its already known effects on the environment. The pollution involved with R134a systems is detrimental to the global-warming impact, and can be reduced by using a naturally occurring refrigerant such as CO_2 . To endure these environmental advantages, further investigation to improve the safety and operating efficiency of CO_2 systems is still needed. The performance of such replacement systems are not yet competitive with current systems, but refrigerants such as CO_2 offer a realistic alternative for the future.

4.2 Summary of Reheat Dehumidification Cycles

Four Reheat Dehumidification cycles were analyzed in the second half of this thesis. Each cycle presented a slightly different method for reheating the air. The first cycle discussed, the Warm Liquid Refrigerant Cycle, used liquid as the refrigerant, while the next two cycles used hot gas as the refrigerant in different reheat arrangements. The

last cycle discussed used a two-phase mixture as the refrigerant. A general visual basic program was written to define the states of the refrigerant at the entrance and exit of each cycle component. The program was modified for each of the four cycles to represent different locations of the components, such as the reheat coil, mixing valves, and bypass valves. These components controlled several key parameters in the cycle including the amount of mass flow rate passing through the condenser. Interpolation equations were used to locate enthalpies in a similar manner as presented in the first section of the paper. These equations were input into the program at the appropriate locations to define the state enthalpies. At the end of the program, the calculations involved in determining the reheat coefficient of performance are carried out.

The subscripts section of the Nomenclature is repeated for the four cycles, as the numbering changes slightly for each cycle. A schematic and p-h diagram of each cycle is presented at the start of their respective sections. Table 3.1 compares the performance of different refrigerants using the Warm Liquid Refrigerant Cycle. The reheat coefficient of performance is used as the basis for this comparison. The values are very similar for the four refrigerants used. As noted previously, R-134a was used in the programs throughout the reheat section of this thesis. The relative performance of the four cycles is illustrated in the figures and explained in the results and discussion section at the end of chapter 3. The quality at the condenser exit and the condenser pressure seem to be the parameters that have the most impact on the reheat coefficient of performance for all four cycles, as seen in Figures 3.53 through 3.56. Three of the four cycles perform very similarly in performance based on the COP_{reheat} . The most efficient cycle cannot be determined from simulations as presented in this thesis. An indepth look into the material and cost of

manufacturing of the different configurations needs to be carried out and considered before a particular cycle is chosen for each individual application. This study is outside the scope of the thesis. Figures 3.54 and 3.56 present plots based on an elevated condensing pressure range, which represents a practical temperature range for the condenser. The trends that make up these 4 figures are shown in each individual section describing the four different reheat cycles. The values for COP_{reheat} in Figures 3.54 and 3.56 are reduced by a factor of about 2 as compared with Figures 3.53 and 3.56. As seen in these 4 figures, the Warm Liquid Refrigerant Cycle operates at higher reheat coefficient of performance values than the other three cycles. As noted in the results and discussion section, this could be the result of the smaller reheat factor that was used for the Warm Liquid Refrigerant Cycle.

The second portion of the thesis deals with the concept of reheat air conditioning, and looks at the performance of different reheat cycles. Reheat in HVAC systems is needed to reheat the air exiting the evaporator. The following paper looks at reheat systems that utilize different placements of the reheat coil, and their overall performance. These systems require no additional electric power to reheat the air. This concept is very important for the overall efficiency of the air conditioning system. The above concepts as well as those presented in Subramanyam [8] and Ghaddar [7], involving the use of desiccants, have potential and need to be explored further. The need to reduce electrical power requirements will continue to increase with time. The concepts presented in this thesis have promising futures in dehumidifying and cooling air for the air conditioning industry.

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Appendices

Appendix A: Visual Basic Programs for Carbon Dioxide Simulations

The visual basic programs written for this thesis are presented in Appendices A and B. In instances where several similar programs were used with different input variables, one representative program is given in the appendices. Along with the code written in visual basic, a form with textboxes and command buttons must be created corresponding to each separate program. The form is where inputs are typed in and outputs are displayed. The code is where textboxes and command buttons are defined and equation solving is carried out.

Carbon Dioxide One-Stage Cycle (sample program)

```
Private Sub cmdEvaluate_Click()
pL = Val(txtlowpressure.Text)
hfL = 0.388253238395919 * pL ^ 3 - 5.63524645623147 * pL ^ 2 + 51.6141789425074
* pL + 72.1357439195153
hgL = -0.25680643377018 * pL ^ 3 + 1.51249308505976 * pL ^ 2 - 7.52151410094484
* pL + 449.565120098356
sgL = (-1.47212490011839E-03) * pL ^ 3 + (0.018132863014813) * pL ^ 2 -
(0.133482747715874) * pL + 2.15251870289757
Tpoint1 = -0.781347962381233 * pL ^ 2 + 16.129712306592 * pL + 226.37560471233
txttempoint1.Text = Round(Tpoint1, 4)
txtentropy2.Text = Round(sgL, 4)
entropy2 = sgL
txtenthalpy1.Text = Round(hgL, 4)
x4 = Val(txtquality4.Text)
enthalpy4 = hfL + x4 * (hgL - hfL)
enthalpy3 = enthalpy4
txtenthalpy4.Text = Round(enthalpy4, 4)
P6 = 10
P7 = 11
P8 = 12
P9 = 13
P10 = 14
P11 = 15
hP6point2 = 88.0737 * entropy2 ^ 2 + 34.7292 * entropy2 + 109.3531
hP7point2 = 84.4374 * entropy2 ^ 3 - 367.7565 * entropy2 ^ 2 + 857.7234 * entropy2 -
383.3664
hP8point2 = 72.827 * entropy2 ^ 2 + 104.0573 * entropy2 + 42.2693
hP9point2 = 70.8998 * entropy2 ^ 2 + 116.3412 * entropy2 + 30.0972
hP10point2 = 70.4255 * entropy2 ^ 2 + 122.9464 * entropy2 + 23.2073
hP11point2 = 70.5044 * entropy2 ^ 2 + 127.1495 * entropy2 + 18.6597
pH = Val(txtpressurehigh.Text)
If (pH < P6) Or (pH > P11) Then
MsgBox "pH is out of range"
```

Appendix A: (Continued)

```
End If
If (pH >= P6) And (pH < P7) Then
enthalpy2 = (pH - P6) * ((hP7point2 - hP6point2) / (P7 - P6)) + hP6point2
End If
If (pH >= P7) And (pH < P8) Then
enthalpy2 = (pH - P7) * ((hP8point2 - hP7point2) / (P8 - P7)) + hP7point2
End If
If (pH >= P8) And (pH < P9) Then
enthalpy2 = (pH - P8) * ((hP9point2 - hP8point2) / (P9 - P8)) + hP8point2
End If
If (pH >= P9) And (pH < P10) Then
enthalpy2 = (pH - P9) * ((hP10point2 - hP9point2) / (P10 - P9)) + hP9point2
End If
If (pH >= P10) And (pH <= P11) Then
enthalpy2 = (pH - P10) * ((hP11point2 - hP10point2) / (P11 - P10)) + hP10point2
End If
txtenthalpy2.Text = Round(enthalpy2, 4)
compressorefficiency = Val(txtcompeff.Text)
enthalpy2a = (enthalpy2 - hgL * (1 - compressorefficiency)) / compressorefficiency
txtenthalpy2a.Text = Round(enthalpy2a, 4)
Qevap = Val(txtevap.Text)
mevap = Qevap / (hgL - enthalpy4)
txtmevap.Text = Round(mevap, 6)
Win = mevap * (enthalpy2a - hgL)
txtWin.Text = Round(Win, 4)
COP = Qevap / Win
txtCOP.Text = Round(COP, 4)
Qgc = mevap * (enthalpy3 - enthalpy2a)
txtQgc.Text = Round(Qgc, 4)
End Sub
```

Appendix A: (Continued)

Carbon Dioxide One-Stage Cycle (sample program)

The form is titled "Form1" and is set against a dotted grid background. It contains the following fields and a button:

- High Pressure 10 - 15 (MPa)
- Low Pressure 3 - 6 (MPa)
- Quality at point 4 x4
- Qevap (kW)
- compressor efficiency
- Evaluate** button
- $s1 = s2 = sgL$ (kJ/kg*K)
- $h3 = h4$ (kJ/kg)
- $T1 = T4$ (K)
- $T4$
- $h1$ (kJ/kg)
- $T2$ (K)
- $h2$ (kJ/kg)
- $h2a$ (kJ/kg)
- Work Input (kW)
- mevap
- Q gas cooler (kW)
- C.O.P.

Figure A.1 Form for One-Stage Cycle Sample Program

Appendix A: (Continued)

Carbon Dioxide Two-Stage Cycle (sample program)

```
Private Sub cmdEvaluate_Click()  
pL = Val(txtlowpressure.Text)  
hfL = 0.388253238395919 * pL ^ 3 - 5.63524645623147 * pL ^ 2 + 51.6141789425074  
* pL + 72.1357439195153  
hgL = -0.25680643377018 * pL ^ 3 + 1.51249308505976 * pL ^ 2 - 7.52151410094484  
* pL + 449.565120098356  
sgL = (-1.47212490011839E-03) * pL ^ 3 + (0.018132863014813) * pL ^ 2 -  
(0.133482747715874) * pL + 2.15251870289757  
Tpoint1 = -0.781347962381233 * pL ^ 2 + 16.129712306592 * pL + 226.37560471233  
txttemppoint1.Text = Round(Tpoint1, 4)  
txtentropy2.Text = Round(sgL, 4)  
entropy2 = sgL  
txtenthalpy1.Text = Round(hgL, 4)  
pI = Val(txtintermpressure.Text)  
If (pI < 3.1) Or (pI > 7) Then  
MsgBox "pI is out of range"  
End If  
hfI = 0.131186999264173 * pI ^ 6 - 3.85673214551061 * pI ^ 5 + 46.6648352296266 *  
pI ^ 4 - 296.846443875409 * pI ^ 3 + 1044.89522096063 * pI ^ 2 - 1900.87377231913 *  
pI + 1562.49748266668  
hgI = -0.184641699190252 * pI ^ 6 + 5.43377673898358 * pI ^ 5 - 65.8615234197176 *  
pI ^ 4 + 420.231263078607 * pI ^ 3 - 1488.756136809 * pI ^ 2 + 2770.74700840007 *  
pI - 1677.97046401057  
sfI = (4.3234525975322E-04) * pI ^ 6 - (1.27082040247046E-02) * pI ^ 5 +  
(0.153688155803408) * pI ^ 4 - (0.976668121437018) * pI ^ 3 + 3.43046740565357 *  
pI ^ 2 - 6.21103087925459 * pI + 5.40805781152115  
sgI = (-6.01148295515941E-04) * pI ^ 6 + (1.76760031549179E-02) * pI ^ 5 -  
(0.213969170083274) * pI ^ 4 + 1.36234129472157 * pI ^ 3 - 4.80611857653728 * pI ^  
2 + 8.84127736535787 * pI - 4.70494506046663  
Tintsat = (6.39972687986301E-02) * pI ^ 3 - 1.63528824459627 * pI ^ 2 +  
(19.8353674381343) * pI + (221.157559227957)  
txttintsattemp.Text = Round(Tintsat, 4)  
enthalpy3 = hgI  
enthalpy7 = hfI  
enthalpy8 = enthalpy7  
txtenthalpy3.Text = Round(enthalpy3, 4)  
txtenthalpy7.Text = Round(enthalpy7, 4)  
enthalpy6 = Val(txtenthalpy6.Text)  
enthalpy5 = enthalpy6  
x6 = (enthalpy6 - enthalpy7) / (enthalpy3 - enthalpy7)
```

Appendix A: (Continued)

```
If (x6 < 0) Or (x6 > 1) Then
MsgBox "Quality is out of range"
End If
txtquality6.Text = Round(x6, 4)
P1 = 3
P2 = 4
P3 = 5
P4 = 6
P5 = 7
P6 = 10
P7 = 11
P8 = 12
P9 = 13
P10 = 14
P11 = 15
hP1point2 = 133.85 * entropy2 ^ 2 - 241.047 * entropy2 + 415.0516
hP2point2 = 121.7421 * entropy2 ^ 2 - 170.5809 * entropy2 + 336.099
hP3point2 = 107.3623 * entropy2 ^ 2 - 96.9642 * entropy2 + 257.4835
hP4point2 = 93.863 * entropy2 ^ 2 - 31.2242 * entropy2 + 189.3623
hP5point2 = 72.9872 * entropy2 ^ 2 + 58.4526 * entropy2 + 101.4427
If (pI <= pL) Then
MsgBox "pI is out of range"
End If
If (pI >= P1) And (pI < P2) Then
enthalpy2 = (pI - P1) * ((hP2point2 - hP1point2) / (P2 - P1)) + hP1point2
End If
If (pI >= P2) And (pI < P3) Then
enthalpy2 = (pI - P2) * ((hP3point2 - hP2point2) / (P3 - P2)) + hP2point2
End If
If (pI >= P3) And (pI < P4) Then
enthalpy2 = (pI - P3) * ((hP4point2 - hP3point2) / (P4 - P3)) + hP3point2
End If
If (pI >= P4) And (pI <= P5) Then
enthalpy2 = (pI - P4) * ((hP5point2 - hP4point2) / (P5 - P4)) + hP4point2
End If
txtenthalpy2.Text = Round(enthalpy2, 4)
entropy3 = sgl
txtentropy3.Text = Round(sgl, 4)
entropy4 = entropy3
hP6point4 = 88.0737 * entropy4 ^ 2 + 34.7292 * entropy4 + 109.3531
hP7point4 = 84.4374 * entropy4 ^ 3 - 367.7565 * entropy4 ^ 2 + 857.7234 * entropy4 -
383.3664
hP8point4 = 72.827 * entropy4 ^ 2 + 104.0573 * entropy4 + 42.2693
```

Appendix A: (Continued)

```

hP9point4 = 70.8998 * entropy4 ^ 2 + 116.3412 * entropy4 + 30.0972
hP10point4 = 70.4255 * entropy4 ^ 2 + 122.9464 * entropy4 + 23.2073
hP11point4 = 70.5044 * entropy4 ^ 2 + 127.1495 * entropy4 + 18.6597
pH = Val(txtpressurehigh.Text)
If (pH < P6) Or (pH > P11) Then
MsgBox "pH is out of range"
End If
If (pH >= P6) And (pH < P7) Then
enthalpy4 = (pH - P6) * ((hP7point4 - hP6point4) / (P7 - P6)) + hP6point4
End If
If (pH >= P7) And (pH < P8) Then
enthalpy4 = (pH - P7) * ((hP8point4 - hP7point4) / (P8 - P7)) + hP7point4
End If
If (pH >= P8) And (pH < P9) Then
enthalpy4 = (pH - P8) * ((hP9point4 - hP8point4) / (P9 - P8)) + hP8point4
End If
If (pH >= P9) And (pH < P10) Then
enthalpy4 = (pH - P9) * ((hP10point4 - hP9point4) / (P10 - P9)) + hP9point4
End If
If (pH >= P10) And (pH <= P11) Then
enthalpy4 = (pH - P10) * ((hP11point4 - hP10point4) / (P11 - P10)) + hP10point4
End If
txtenthalpy4.Text = Round(enthalpy4, 4)
compressorefficiency = Val(txtcompeff.Text)
compeff1 = compressorefficiency
compeff2 = compressorefficiency
enthalpy2a = (enthalpy2 - hgL * (1 - compeff1)) / compeff1
txtenthalpy2a = Round(enthalpy2a, 4)
enthalpy4a = (enthalpy4 - enthalpy3 * (1 - compeff2)) / compeff2
txtenthalpy4a.Text = Round(enthalpy4a, 4)
Qevap = Val(txtevap.Text)
m2 = Qevap / (hgL - enthalpy8)
txtm2.Text = Round(m2, 6)
m3 = m2 * ((enthalpy7 - enthalpy2a) / (enthalpy6 - enthalpy3))
txtm3.Text = Round(m3, 6)
W12 = m2 * (enthalpy2a - hgL)
W34 = m3 * (enthalpy4a - enthalpy3)
Win = W12 + W34
txtWin.Text = Round(Win, 4)
COP = Qevap / Win
txtCOP.Text = Round(COP, 4)
Qgc = m3 * (enthalpy5 - enthalpy4a)
txtQgc.Text = Round(Qgc, 4)

```

Appendix A: (Continued)

End Sub

Carbon Dioxide Two-Stage Cycle (sample program)

The form is titled "Form1" and contains the following fields and controls:

- High Pressure (10 - 15 (MPa))
- Low Pressure (3 - 6 (MPa))
- Intermediate Pressure (3.1 - 7 (MPa))
- h6 = h5
- Q evap (kW)
- efficiency for compressor 1 and 2
- s1 = s2 = sgL (kJ/kg*K)
- h1 (kJ/kg)
- T1 = T4 (K)
- T2 (K)
- h2a (kJ/kg)
- h2 (kJ/kg)
- s3
- h3 (kJ/kg)
- Work Input (kW)
- Q gas cooler (kW)
- m2
- C.O.P.
- h7 = h8
- Quality at point 6 x6
- h4
- h4a (kJ/kg)
- m3
- Buttons: Evaluate

Figure A.2 Form for Two-Stage Cycle Sample Program

Appendix A: (Continued)

Carbon Dioxide Two-Stage Cycle with Intercooler (sample program)

Private Sub cmdEvaluate_Click()

T1 = 320

T2 = 340

T3 = 360

T4 = 380

T5 = 300

T6 = 280

T7 = 260

T8 = 400

T9 = 420

pL = Val(txtlowpressure.Text)

hfL = 0.3883 * pL ^ 3 - 5.6352 * pL ^ 2 + 51.6142 * pL + 72.1357

hgL = -0.2568 * pL ^ 3 + 1.5125 * pL ^ 2 - 7.5215 * pL + 449.5651

sfL = (1.5095 * 10 ^ -3) * pL ^ 3 - (2.3331 * 10 ^ -2) * pL ^ 2 + (2.0063 * 10 ^ -1) * pL + (5.2025 * 10 ^ -1)

sgL = (-1.4721 * 10 ^ -3) * pL ^ 3 + (1.8133 * 10 ^ -2) * pL ^ 2 - (1.3348 * 10 ^ -1) * pL + 2.1525

Tpoint1 = -0.7813 * pL ^ 2 + 16.1297 * pL + 226.3756

txttemppoint1.Text = Round(Tpoint1, 4)

txtentropy2.Text = Round(sgL, 4)

entropy2 = Val(txtentropy2.Text)

txtenthalpy1.Text = Round(hgL, 4)

pI = Val(txtintermpressure.Text)

If (pI <= pL) Then

MsgBox "Increase pI or decrease pL"

End If

hfI = 0.1312 * pI ^ 6 - 3.8567 * pI ^ 5 + 46.6648 * pI ^ 4 - 296.8464 * pI ^ 3 + 1044.8952 * pI ^ 2 - 1900.8738 * pI + 1562.4975

hgI = -0.1846 * pI ^ 6 + 5.4338 * pI ^ 5 - 65.8615 * pI ^ 4 + 420.2313 * pI ^ 3 - 1488.7561 * pI ^ 2 + 2770.747 * pI - 1677.9705

sfI = (4.3235 * 10 ^ -4) * pI ^ 6 - (1.2708 * 10 ^ -2) * pI ^ 5 + (1.5369 * 10 ^ -1) * pI ^ 4 - (9.7667 * 10 ^ -1) * pI ^ 3 + 3.4305 * pI ^ 2 - 6.211 * pI + 5.4081

sgI = (-6.0115 * 10 ^ -4) * pI ^ 6 + (1.7676 * 10 ^ -2) * pI ^ 5 - (2.1397 * 10 ^ -1) * pI ^ 4 + 1.3623 * pI ^ 3 - 4.8061 * pI ^ 2 + 8.8413 * pI - 4.7049

Tintsat = (6.3997 * 10 ^ -2) * pI ^ 3 - 1.6353 * pI ^ 2 + (1.9835 * 10 ^ 1) * pI + (2.2116 * 10 ^ 2)

txtintermsattemp.Text = Round(Tintsat, 4)

enthalpy9 = hgI

enthalpy7 = hfI

enthalpy8 = hfI

txtenthalpy9.Text = Round(enthalpy9, 4)

Appendix A: (Continued)

```

txtenthalpy7.Text = Round(enthalpy7, 4)
x6 = Val(txtquality6.Text)
enthalpy6 = hfl + x6 * (hgI - hfl)
enthalpy5 = enthalpy6
txtenthalpy6.Text = Round(enthalpy6, 4)
s5point2 = -0.001 * pI ^ 5 + 0.0223 * pI ^ 4 -
0.1971 * pI ^ 3 + 0.8664 * pI ^ 2 - 1.9819 * pI + 3.9328
s1point2 = -0.0009 * pI ^ 3 + 0.0151 * pI ^ 2 - 0.151 * pI + 2.4409
s2point2 = -0.0007 * pI ^ 3 + 0.0135 * pI ^ 2 - 0.1414 * pI + 2.4858
s3point2 = -0.0006 * pI ^ 3 + 0.0133 * pI ^ 2 - 0.1376 * pI + 2.5348
If (entropy2 < s5point2) Or (entropy2 > s3point2) Then
MsgBox "Out of range, increase (pI - pL)"
End If
If (entropy2 >= s5point2) And (entropy2 < s1point2) Then
txttemp2point2.Text = (entropy2 - s5point2) * ((T1 - T5) / (s1point2 - s5point2)) + T5
End If
If (entropy2 >= s1point2) And (entropy2 < s2point2) Then
txttemp2point2.Text = (entropy2 - s1point2) * ((T2 - T1) / (s2point2 - s1point2)) + T1
End If
If (entropy2 >= s2point2) And (entropy2 <= s3point2) Then
txttemp2point2.Text = (entropy2 - s2point2) * ((T3 - T2) / (s3point2 - s2point2)) + T2
End If
temperature2 = Val(txttemp2point2.Text)
h5 = -0.3021 * pI ^ 5 + 6.6329 * pI ^ 4 - 57.947 * pI ^ 3 + 249.66 * pI ^ 2 - 542.09 * pI
+ 956.72
h1 = -0.8021 * pI ^ 2 - 4.57 * pI + 519.74
h2 = -0.3468 * pI ^ 2 - 6.0045 * pI + 541.43
h3 = -0.1803 * pI ^ 2 - 5.8726 * pI + 560.4
If (temperature2 >= T5) And (temperature2 < T1) Then
txtenthalpy2.Text = Round((temperature2 - T5) * ((h1 - h5) / (T1 - T5)) + h5, 4)
End If
If (temperature2 >= T1) And (temperature2 < T2) Then
txtenthalpy2.Text = Round((temperature2 - T1) * ((h2 - h1) / (T2 - T1)) + h1, 4)
End If
If (temperature2 >= T2) And (temperature2 <= T3) Then
txtenthalpy2.Text = Round((temperature2 - T2) * ((h3 - h2) / (T3 - T2)) + h2, 4)
End If
enthalpy2 = Val(txtenthalpy2)
Qevap = Val(txttevap.Text)
mevap = Qevap / (hgL - enthalpy8)
txtmevap.Text = Round(mevap, 6)
m2 = mevap
m3 = m2 * ((enthalpy7 - enthalpy9) / (enthalpy6 - enthalpy9))
txtm3.Text = Round(m3, 6)

```

Appendix A: (Continued)

```
m9 = m3 - m2
txtm9.Text = Round(m9, 6)
enthalpy3 = (m9 * enthalpy9 + m2 * enthalpy2) / m3
txtenthalpy3.Text = Round(enthalpy3, 4)
P1 = 3
P2 = 4
P3 = 5
P4 = 6
P5 = 7
sP1point3 = (-4.5678 * 10 ^ -6) * enthalpy3 ^ 2 + (7.6909 * 10 ^ -3) * enthalpy3 -
(6.0054 * 10 ^ -1)
sP2point3 = (-3.9595 * 10 ^ -6) * enthalpy3 ^ 2 + (6.9953 * 10 ^ -3) * enthalpy3 -
(4.5153 * 10 ^ -1)
sP3point3 = (-3.3722 * 10 ^ -6) * enthalpy3 ^ 2 + (6.3367 * 10 ^ -3) * enthalpy3 -
(3.0415 * 10 ^ -1)
sP4point3 = (-2.8083 * 10 ^ -6) * enthalpy3 ^ 2 + (5.7162 * 10 ^ -3) * enthalpy3 -
(1.6282 * 10 ^ -1)
sP5point3 = (-2.1486 * 10 ^ -6) * enthalpy3 ^ 2 + (5.0252 * 10 ^ -3) * enthalpy3 -
(5.0307 * 10 ^ -3)
If (pI < P1) Or (pI > P5) Then
MsgBox "Use different p intermediate"
End If
If (pI >= P1) And (pI < P2) Then
txtentropy3.Text = Round((pI - P1) * ((sP2point3 - sP1point3) / (P2 - P1)) + sP1point3,
4)
End If
If (pI >= P2) And (pI < P3) Then
txtentropy3.Text = Round((pI - P2) * ((sP3point3 - sP2point3) / (P3 - P2)) + sP2point3,
4)
End If
If (pI >= P3) And (pI < P4) Then
txtentropy3.Text = Round((pI - P3) * ((sP4point3 - sP3point3) / (P4 - P3)) + sP3point3,
4)
End If
If (pI >= P4) And (pI <= P5) Then
txtentropy3.Text = Round((pI - P4) * ((sP5point3 - sP4point3) / (P5 - P4)) + sP4point3,
4)
End If
entropy3 = Val(txtentropy3.Text)
entropy4 = entropy3
pH = Val(txtpressurehigh.Text)
sT1point4 = (4.9887 * 10 ^ -4) * pH ^ 4 - (2.7015 * 10 ^ -2) * pH ^ 3 + (5.504 * 10 ^ -1)
* pH ^ 2 - 5.0224 * pH + (1.8724 * 10 ^ 1)
```

Appendix A: (Continued)

$$sT2point4 = (5.8686 * 10^{-4}) * pH^3 - (1.9556 * 10^{-2}) * pH^2 + (1.5954 * 10^{-1}) * pH + 1.5326$$

$$sT3point4 = (5.5266 * 10^{-4}) * pH^2 - (5.2376 * 10^{-2}) * pH + 2.3414$$

$$sT4point4 = (5.4655 * 10^{-4}) * pH^2 - (4.5016 * 10^{-2}) * pH + 2.3527$$

If (entropy4 < sT1point4) Or (entropy4 > sT4point4) Then

MsgBox “Out of s Range”

End If

If (entropy4 >= sT1point4) And (entropy4 < sT2point4) Then

$$txttemp4point4.Text = (entropy4 - sT1point4) * ((T2 - T1) / (sT2point4 - sT1point4)) + T1$$

End If

If (entropy4 >= sT2point4) And (entropy4 < sT3point4) Then

$$txttemp4point4.Text = (entropy4 - sT2point4) * ((T3 - T2) / (sT3point4 - sT2point4)) + T2$$

End If

If (entropy4 >= sT3point4) And (entropy4 <= sT4point4) Then

$$txttemp4point4.Text = (entropy4 - sT3point4) * ((T4 - T3) / (sT4point4 - sT3point4)) + T3$$

End If

temperature4 = Val(txttemp4point4.Text)

$$hT1point4 = (-2.6901 * 10^{-2}) * pH^5 + 1.8372 * pH^4 - (5.0277 * 10^1) * pH^3 + (6.9 * 10^2) * pH^2 - (4.7596 * 10^3) * pH + (1.3555 * 10^4)$$

$$hT2point4 = (2.1939 * 10^{-1}) * pH^3 - 7.5905 * pH^2 + (7.0974 * 10^1) * pH + (2.7333 * 10^2)$$

$$hT3point4 = (4.1723 * 10^{-2}) * pH^3 - 1.5852 * pH^2 + 9.5062 * pH + (5.0473 * 10^2)$$

$$hT4point4 = (-2.0452 * 10^{-2}) * pH^2 - 7.226 * pH + (5.887 * 10^2)$$

If (temperature4 < T1) Or (temperature4 > T4) Then

MsgBox “Out of T Range”

End If

If (temperature4 >= T1) And (temperature4 < T2) Then

$$txtenthalpy4.Text = (temperature4 - T1) * ((hT2point4 - hT1point4) / (T2 - T1)) + hT1point4$$

End If

If (temperature4 >= T2) And (temperature4 < T3) Then

$$txtenthalpy4.Text = (temperature4 - T2) * ((hT3point4 - hT2point4) / (T3 - T2)) + hT2point4$$

End If

If (temperature4 >= T3) And (temperature4 <= T4) Then

$$txtenthalpy4.Text = (temperature4 - T3) * ((hT4point4 - hT3point4) / (T4 - T3)) + hT3point4$$

End If

enthalpy4 = Val(txtenthalpy4.Text)

Appendix A: (Continued)

```

Win = m2 * (enthalpy2 - hgL) + m3 * (enthalpy4 - enthalpy3)
txtWin.Text = Round(Win, 4)
COP = Qevap / Win
txtCOP.Text = Round(COP, 4)
Qgc = m3 * (enthalpy5 - enthalpy4)
txtQgc.Text = Round(Qgc, 4)
End Sub
    
```

Carbon Dioxide Two-Stage Cycle with Intercooler (sample program)

The screenshot shows a software interface titled "Calculation" with a grid background. It contains several input fields and a list of temperature options. The inputs include High Pressure (10-15 MPa), Low Pressure (3-6 MPa), Quality at point 6 (x6), Intermediate Pressure (3.1-7 MPa), and Qevap (kW). A central "Evaluate" button is present. Below it, there are two vertical lists of temperature options: one for Entropy (320K, 340K, 360K, 380K, 400K, 420K) and one for Enthalpy (260K, 280K, 300K, 320K, 340K, 360K, 380K, 400K, 420K). Other fields include s1 = s2 = sgL (kJ/kg*K), h1 (kJ/kg), T3 (K), s3, h2 (kJ/kg), h3 (kJ/kg), T7 = T6 = T9, h9, T1 = T8 (K), T2 (K), h7 = h8, h6 = h5, T4, h4, Work Input (kW), m2, m3, Q gas cooler (kW), C.O.P., and m9.

Figure A.3 Form for Two-Stage Cycle with Intercooler Program

Appendix B: Visual Basic Programs for Reheat Dehumidification Simulations

Warm Liquid Refrigerant Cycle

```
Private Sub cmdevaluate_Click()  
evappressure = Val(txtevappressure.Text)  
evappressurerounded = Round(evappressure, 0)  
txtevappressurerounded = evappressurerounded  
T1 = Val(txttemp1.Text)  
If (evappressure >= evappressurerounded) Then  
txtlowp.Text = evappressurerounded  
End If  
If (evappressure > evappressurerounded) Then  
txthighp.Text = evappressurerounded + 1  
End If  
If (evappressure <= evappressurerounded) Then  
txthighp.Text = evappressurerounded  
End If  
If (evappressure < evappressurerounded) Then  
txtlowp.Text = evappressurerounded - 1  
End If  
p1 = 45  
p2 = 46  
p3 = 47  
p4 = 48  
p5 = 49  
p6 = 50  
p7 = 51  
p8 = 52  
p9 = 53  
p10 = 54  
p11 = 55  
Tsat1 = 34.897  
Tsat2 = 36.006  
Tsat3 = 37.098  
Tsat4 = 38.171  
Tsat5 = 39.227  
Tsat6 = 40.267  
Tsat7 = 41.292  
Tsat8 = 42.301  
Tsat9 = 43.295  
Tsat10 = 44.275  
Tsat11 = 45.241  
h1 = (-8.55494591860406E-05) * T1 ^ 2 + (0.221803709111986) * T1 +  
(164.251339451151)
```

Appendix B: (Continued)

$$h2 = (-1.04453973165164E-04) * T1 ^ 2 + (0.224294986034621) * T1 + 164.0994957513$$

$$h3 = (-1.70924683359885E-04) * T1 ^ 2 + (0.230698866947877) * T1 + (163.867146163839)$$

$$h4 = (-9.21268362219507E-05) * T1 ^ 2 + (0.224999664161904) * T1 + (163.884920315296)$$

$$h5 = (-1.45660586440499E-04) * T1 ^ 2 + (0.230612768300361) * T1 + (163.660593095293)$$

$$h6 = (-8.21518737410543E-05) * T1 ^ 2 + (0.225745230044991) * T1 + (163.669848007973)$$

$$h7 = (-1.12163878597471E-04) * T1 ^ 2 + (0.229275983250786) * T1 + (163.49043486943)$$

$$h8 = (-1.41086913643562E-04) * T1 ^ 2 + (0.232871991082073) * T1 + (163.305535881264)$$

$$h9 = (-7.64892314037979E-05) * T1 ^ 2 + (0.227560040562432) * T1 + (163.330623395824)$$

$$h10 = (-9.60906859432953E-05) * T1 ^ 2 + (0.230211818547635) * T1 + (163.168495290491)$$

$$h11 = (-1.18784814304718E-04) * T1 ^ 2 + (0.233243428018642) * T1 + (162.994242756115)$$

$$s1 = (-6.0803711907087E-07) * T1 ^ 2 + (4.79110474060067E-04) * T1 + (0.396595113510306)$$

$$s2 = (-6.25417075461598E-07) * T1 ^ 2 + (4.82232881662558E-04) * T1 + (0.395942612567429)$$

$$s3 = (-6.3338833347637E-07) * T1 ^ 2 + (4.84618356885164E-04) * T1 + (0.395313013521716)$$

$$s4 = (-5.72841618529107E-07) * T1 ^ 2 + (4.81048526321251E-04) * T1 + (0.394819557534999)$$

$$s5 = (-7.03779334892962E-07) * T1 ^ 2 + (4.94256622175797E-04) * T1 + (0.393967537270816)$$

$$s6 = (-6.7611950432811E-07) * T1 ^ 2 + (4.93501395964934E-04) * T1 + (0.393429028182591)$$

$$s7 = (-6.58521754043351E-07) * T1 ^ 2 + (4.93457265859189E-04) * T1 + (0.392885330772991)$$

$$s8 = (-6.47501380623972E-07) * T1 ^ 2 + (4.94182527420029E-04) * T1 + (0.3923266406261)$$

$$s9 = (-5.96537599012459E-07) * T1 ^ 2 + (4.91008706960247E-04) * T1 + (0.391868567094144)$$

$$s10 = (-7.13188032908096E-07) * T1 ^ 2 + (5.04008662543318E-04) * T1 + (0.391027694896258)$$

$$s11 = (-6.79822001331543E-07) * T1 ^ 2 + (5.02477295152442E-04) * T1 + (0.390542594477737)$$

If (txtevappressure.Text < p1) Or (txtevappressure.Text > p11) Then

Appendix B: (Continued)

MsgBox "evaporator pressure is out of range"

End If

If (txtlowp.Text = p1) Then

txtlowsattemp.Text = Tsat1

End If

If (txtlowp.Text = p2) Then

txtlowsattemp.Text = Tsat2

End If

If (txtlowp.Text = p3) Then

txtlowsattemp.Text = Tsat3

End If

If (txtlowp.Text = p4) Then

txtlowsattemp.Text = Tsat4

End If

If (txtlowp.Text = p5) Then

txtlowsattemp.Text = Tsat5

End If

If (txtlowp.Text = p6) Then

txtlowsattemp.Text = Tsat6

End If

If (txtlowp.Text = p7) Then

txtlowsattemp.Text = Tsat7

End If

If (txtlowp.Text = p8) Then

txtlowsattemp.Text = Tsat8

End If

If (txtlowp.Text = p9) Then

txtlowsattemp.Text = Tsat9

End If

If (txtlowp.Text = p10) Then

txtlowsattemp.Text = Tsat10

End If

If (txtlowp.Text = p11) Then

txtlowsattemp.Text = Tsat11

End If

If (txthighp.Text = p1) Then

txthighsattemp.Text = Tsat1

End If

If (txthighp.Text = p2) Then

txthighsattemp.Text = Tsat2

End If

If (txthighp.Text = p3) Then

txthighsattemp.Text = Tsat3

Appendix B: (Continued)

```
End If
If (txthighp.Text = p4) Then
txthighsattemp.Text = Tsat4
End If
If (txthighp.Text = p5) Then
txthighsattemp.Text = Tsat5
End If
If (txthighp.Text = p6) Then
txthighsattemp.Text = Tsat6
End If
If (txthighp.Text = p7) Then
txthighsattemp.Text = Tsat7
End If
If (txthighp.Text = p8) Then
txthighsattemp.Text = Tsat8
End If
If (txthighp.Text = p9) Then
txthighsattemp.Text = Tsat9
End If
If (txthighp.Text = p10) Then
txthighsattemp.Text = Tsat10
End If
If (txthighp.Text = p11) Then
txthighsattemp.Text = Tsat11
End If
txtlowsattempplus10.Text = txtlowsattemp.Text + 10
T1 = Val(txttemp1.Text)
If (T1 < txthighsattemp.Text) Or (T1 > txtlowsattempplus10.Text) Then
MsgBox "Temperature at point 1 is out of range for given pressure"
End If
If (evappressure >= p1) And (evappressure < p2) Then
evapexitenthalpy = (evappressure - p1) * ((h2 - h1) / (p2 - p1)) + h1
End If
If (evappressure >= p2) And (evappressure < p3) Then
evapexitenthalpy = (evappressure - p2) * ((h3 - h2) / (p3 - p2)) + h2
End If
If (evappressure >= p3) And (evappressure < p4) Then
evapexitenthalpy = (evappressure - p3) * ((h4 - h3) / (p4 - p3)) + h3
End If
If (evappressure >= p4) And (evappressure < p5) Then
evapexitenthalpy = (evappressure - p4) * ((h5 - h4) / (p5 - p4)) + h4
End If
If (evappressure >= p5) And (evappressure < p6) Then
```

Appendix B: (Continued)

```
evapexitenthalpy = (evappressure - p5) * ((h6 - h5) / (p6 - p5)) + h5
End If
If (evappressure >= p6) And (evappressure < p7) Then
evapexitenthalpy = (evappressure - p6) * ((h7 - h6) / (p7 - p6)) + h6
End If
If (evappressure >= p7) And (evappressure < p8) Then
evapexitenthalpy = (evappressure - p7) * ((h8 - h7) / (p8 - p7)) + h7
End If
If (evappressure >= p8) And (evappressure < p9) Then
evapexitenthalpy = (evappressure - p8) * ((h9 - h8) / (p9 - p8)) + h8
End If
If (evappressure >= p9) And (evappressure < p10) Then
evapexitenthalpy = (evappressure - p9) * ((h10 - h9) / (p10 - p9)) + h9
End If
If (evappressure >= p10) And (evappressure <= p11) Then
evapexitenthalpy = (evappressure - p10) * ((h11 - h10) / (p11 - p10)) + h10
End If
txtevapexitenthalpy.Text = Round(evapexitenthalpy, 5)
txttestenthalpy1 = h2
If (evappressure >= p1) And (evappressure < p2) Then
evapexitentropy = (evappressure - p1) * ((s2 - s1) / (p2 - p1)) + s1
End If
If (evappressure >= p2) And (evappressure < p3) Then
evapexitentropy = (evappressure - p2) * ((s3 - s2) / (p3 - p2)) + s2
End If
If (evappressure >= p3) And (evappressure < p4) Then
evapexitentropy = (evappressure - p3) * ((s4 - s3) / (p4 - p3)) + s3
End If
If (evappressure >= p4) And (evappressure < p5) Then
evapexitentropy = (evappressure - p4) * ((s5 - s4) / (p5 - p4)) + s4
End If
If (evappressure >= p5) And (evappressure < p6) Then
evapexitentropy = (evappressure - p5) * ((s6 - s5) / (p6 - p5)) + s5
End If
If (evappressure >= p6) And (evappressure < p7) Then
evapexitentropy = (evappressure - p6) * ((s7 - s6) / (p7 - p6)) + s6
End If
If (evappressure >= p7) And (evappressure < p8) Then
evapexitentropy = (evappressure - p7) * ((s8 - s7) / (p8 - p7)) + s7
End If
If (evappressure >= p8) And (evappressure < p9) Then
evapexitentropy = (evappressure - p8) * ((s9 - s8) / (p9 - p8)) + s8
End If
```

Appendix B: (Continued)

```
If (evappressure >= p9) And (evappressure < p10) Then
evapexitentropy = (evappressure - p9) * ((s10 - s9) / (p10 - p9)) + s9
End If
If (evappressure >= p10) And (evappressure <= p11) Then
evapexitentropy = (evappressure - p10) * ((s11 - s10) / (p11 - p10)) + s10
End If
txtevapexitentropy.Text = Round(evapexitentropy, 5)
txttestentropy1 = s4
compexitentropy = evapexitentropy
txtcompexitentropy.Text = Round(compexitentropy, 5)
p21 = 100
p22 = 104
p23 = 108
p24 = 112
p25 = 116
p26 = 120
p27 = 124
p28 = 128
p29 = 132
p210 = 136
p211 = 140
Tsat21 = 79.159
Tsat22 = 81.561
Tsat23 = 83.894
Tsat24 = 86.164
Tsat25 = 88.373
Tsat26 = 90.526
Tsat27 = 92.625
Tsat28 = 94.674
Tsat29 = 96.675
Tsat210 = 98.632
Tsat211 = 100.55
h21 = 1140.33482740819 * compexitentropy ^ 2 - 396.658048826921 * compexitentropy
+ 148.543589272253
h22 = 1116.79531031847 * compexitentropy ^ 2 - 374.742307050553 * compexitentropy
+ 143.863072320317
h23 = 1140.53734263777 * compexitentropy ^ 2 - 391.945459033649 * compexitentropy
+ 147.259853282843
h24 = 1244.42484858632 * compexitentropy ^ 2 - 475.137371935914 * compexitentropy
+ 164.224679495585
h25 = 1104.91427125036 * compexitentropy ^ 2 - 357.304208273241 * compexitentropy
+ 139.675233637429
```

Appendix B: (Continued)

$$h26 = 1164.58516219258 * \text{compexitentropy}^2 - 404.524050813997 * \text{compexitentropy} + 149.305123171225$$

$$h27 = 1113.95974990725 * \text{compexitentropy}^2 - 360.490942444008 * \text{compexitentropy} + 140.051997716919$$

$$h28 = 993.009925991296 * \text{compexitentropy}^2 - 258.119517517082 * \text{compexitentropy} + 118.690310440396$$

$$h29 = 1102.44195953011 * \text{compexitentropy}^2 - 346.252324193361 * \text{compexitentropy} + 136.701072757343$$

$$h210 = 1185.92752987146 * \text{compexitentropy}^2 - 413.446234645956 * \text{compexitentropy} + 150.482425772728$$

$$h211 = 1113.86845897138 * \text{compexitentropy}^2 - 351.641910220986 * \text{compexitentropy} + 137.510255260159$$

condenserpressure = Val(txtcondenserpressure.Text)

If (condenserpressure < p21) Or (condenserpressure > p211) Then

MsgBox "condenser pressure is out of range"

End If

If (condenserpressure >= p21) And (condenserpressure < p22) Then

$$\text{compexitenthalpy} = (\text{condenserpressure} - p21) * ((h22 - h21) / (p22 - p21)) + h21$$

End If

If (condenserpressure >= p22) And (condenserpressure < p23) Then

$$\text{compexitenthalpy} = (\text{condenserpressure} - p22) * ((h23 - h22) / (p23 - p22)) + h22$$

End If

If (condenserpressure >= p23) And (condenserpressure < p24) Then

$$\text{compexitenthalpy} = (\text{condenserpressure} - p23) * ((h24 - h23) / (p24 - p23)) + h23$$

End If

If (condenserpressure >= p24) And (condenserpressure < p25) Then

$$\text{compexitenthalpy} = (\text{condenserpressure} - p24) * ((h25 - h24) / (p25 - p24)) + h24$$

End If

If (condenserpressure >= p25) And (condenserpressure < p26) Then

$$\text{compexitenthalpy} = (\text{condenserpressure} - p25) * ((h26 - h25) / (p26 - p25)) + h25$$

End If

If (condenserpressure >= p26) And (condenserpressure < p27) Then

$$\text{compexitenthalpy} = (\text{condenserpressure} - p26) * ((h27 - h26) / (p27 - p26)) + h26$$

End If

If (condenserpressure >= p27) And (condenserpressure < p28) Then

$$\text{compexitenthalpy} = (\text{condenserpressure} - p27) * ((h28 - h27) / (p28 - p27)) + h27$$

End If

If (condenserpressure >= p28) And (condenserpressure < p29) Then

$$\text{compexitenthalpy} = (\text{condenserpressure} - p28) * ((h29 - h28) / (p29 - p28)) + h28$$

End If

If (condenserpressure >= p29) And (condenserpressure < p210) Then

$$\text{compexitenthalpy} = (\text{condenserpressure} - p29) * ((h210 - h29) / (p210 - p29)) + h29$$

End If

Appendix B: (Continued)

```
If (condenserpressure >= p210) And (condenserpressure <= p211) Then
compexitenthalpy = (condenserpressure - p210) * ((h211 - h210) / (p211 - p210)) + h210
End If
txtcompexitenthalpy.Text = Round(compexitenthalpy, 5)
txttestenthalpy2.Text = h24
hsatvap1 = 177.65
hsatvap2 = 177.94
hsatvap3 = 178.21
hsatvap4 = 178.48
hsatvap5 = 178.73
hsatvap6 = 178.98
hsatvap7 = 179.22
hsatvap8 = 179.44
hsatvap9 = 179.66
hsatvap10 = 179.88
hsatvap11 = 180.08
hsatLiq1 = 101.64
hsatLiq2 = 102.46
hsatLiq3 = 103.27
hsatLiq4 = 104.05
hsatLiq5 = 104.81
hsatLiq6 = 105.56
hsatLiq7 = 106.29
hsatLiq8 = 107.01
hsatLiq9 = 107.71
hsatLiq10 = 108.4
hsatLiq11 = 109.08
x = Val(txtquality3.Text)
If (x < 0) Or (x > 0.3) Then
MsgBox "Quality at point 3 is out of range"
End If
h31 = hsatLiq1 + x * (hsatvap1 - hsatLiq1)
h32 = hsatLiq2 + x * (hsatvap2 - hsatLiq2)
h33 = hsatLiq3 + x * (hsatvap3 - hsatLiq3)
h34 = hsatLiq4 + x * (hsatvap4 - hsatLiq4)
h35 = hsatLiq5 + x * (hsatvap5 - hsatLiq5)
h36 = hsatLiq6 + x * (hsatvap6 - hsatLiq6)
h37 = hsatLiq7 + x * (hsatvap7 - hsatLiq7)
h38 = hsatLiq8 + x * (hsatvap8 - hsatLiq8)
h39 = hsatLiq9 + x * (hsatvap9 - hsatLiq9)
h310 = hsatLiq10 + x * (hsatvap10 - hsatLiq10)
h311 = hsatLiq11 + x * (hsatvap11 - hsatLiq11)
If (condenserpressure >= p21) And (condenserpressure < p22) Then
```

Appendix B: (Continued)

```
enthalpy3 = (condenserpressure - p21) * ((h32 - h31) / (p22 - p21)) + h31
End If
If (condenserpressure >= p22) And (condenserpressure < p23) Then
enthalpy3 = (condenserpressure - p22) * ((h33 - h32) / (p23 - p22)) + h32
End If
If (condenserpressure >= p23) And (condenserpressure < p24) Then
enthalpy3 = (condenserpressure - p23) * ((h34 - h33) / (p24 - p23)) + h33
End If
If (condenserpressure >= p24) And (condenserpressure < p25) Then
enthalpy3 = (condenserpressure - p24) * ((h35 - h34) / (p25 - p24)) + h34
End If
If (condenserpressure >= p25) And (condenserpressure < p26) Then
enthalpy3 = (condenserpressure - p25) * ((h36 - h35) / (p26 - p25)) + h35
End If
If (condenserpressure >= p26) And (condenserpressure < p27) Then
enthalpy3 = (condenserpressure - p26) * ((h37 - h36) / (p27 - p26)) + h36
End If
If (condenserpressure >= p27) And (condenserpressure < p28) Then
enthalpy3 = (condenserpressure - p27) * ((h38 - h37) / (p28 - p27)) + h37
End If
If (condenserpressure >= p28) And (condenserpressure < p29) Then
enthalpy3 = (condenserpressure - p28) * ((h39 - h38) / (p29 - p28)) + h38
End If
If (condenserpressure >= p29) And (condenserpressure < p210) Then
enthalpy3 = (condenserpressure - p29) * ((h310 - h39) / (p210 - p29)) + h39
End If
If (condenserpressure >= p210) And (condenserpressure <= p211) Then
enthalpy3 = (condenserpressure - p210) * ((h311 - h310) / (p211 - p210)) + h310
End If
txtenthalpy3.Text = enthalpy3
txttestenthalpy3.Text = h32
If (condenserpressure > p21) And (condenserpressure < p22) Then
txtlowpressure.Text = p21
End If
If (condenserpressure > p21) And (condenserpressure < p22) Then
txthighpressure.Text = p22
End If
If (condenserpressure > p22) And (condenserpressure < p23) Then
txtlowpressure.Text = p22
End If
If (condenserpressure > p22) And (condenserpressure < p23) Then
txthighpressure.Text = p23
End If
```

Appendix B: (Continued)

If (condenserpressure > p23) And (condenserpressure < p24) Then
txtlowpressure.Text = p23
End If
If (condenserpressure > p23) And (condenserpressure < p24) Then
txthighpressure.Text = p24
End If
If (condenserpressure > p24) And (condenserpressure < p25) Then
txtlowpressure.Text = p24
End If
If (condenserpressure > p24) And (condenserpressure < p25) Then
txthighpressure.Text = p25
End If
If (condenserpressure > p25) And (condenserpressure < p26) Then
txtlowpressure.Text = p25
End If
If (condenserpressure > p25) And (condenserpressure < p26) Then
txthighpressure.Text = p26
End If
If (condenserpressure > p26) And (condenserpressure < p27) Then
txtlowpressure.Text = p26
End If
If (condenserpressure > p26) And (condenserpressure < p27) Then
txthighpressure.Text = p27
End If
If (condenserpressure > p27) And (condenserpressure < p28) Then
txtlowpressure.Text = p27
End If
If (condenserpressure > p27) And (condenserpressure < p28) Then
txthighpressure.Text = p28
End If
If (condenserpressure > p28) And (condenserpressure < p29) Then
txtlowpressure.Text = p28
End If
If (condenserpressure > p28) And (condenserpressure < p29) Then
txthighpressure.Text = p29
End If
If (condenserpressure > p29) And (condenserpressure < p210) Then
txtlowpressure.Text = p29
End If
If (condenserpressure > p29) And (condenserpressure < p210) Then
txthighpressure.Text = p210
End If
If (condenserpressure > p210) And (condenserpressure < p211) Then

Appendix B: (Continued)

```
txtlowpressure.Text = p210
End If
If (condenserpressure > p210) And (condenserpressure < p211) Then
txthighpressure.Text = p211
End If
If (condenserpressure = p21) Then
txtlowpressure.Text = p21
End If
If (condenserpressure = p21) Then
txthighpressure.Text = p21
End If
If (condenserpressure = p22) Then
txtlowpressure.Text = p22
End If
If (condenserpressure = p22) Then
txthighpressure.Text = p22
End If
If (condenserpressure = p23) Then
txtlowpressure.Text = p23
End If
If (condenserpressure = p23) Then
txthighpressure.Text = p23
End If
If (condenserpressure = p24) Then
txtlowpressure.Text = p24
End If
If (condenserpressure = p24) Then
txthighpressure.Text = p24
End If
If (condenserpressure = p25) Then
txtlowpressure.Text = p25
End If
If (condenserpressure = p25) Then
txthighpressure.Text = p25
End If
If (condenserpressure = p26) Then
txtlowpressure.Text = p26
End If
If (condenserpressure = p26) Then
txthighpressure.Text = p26
End If
If (condenserpressure = p27) Then
txtlowpressure.Text = p27
```

Appendix B: (Continued)

```
End If
If (condenserpressure = p27) Then
txthighpressure.Text = p27
End If
If (condenserpressure = p28) Then
txtlowpressure.Text = p28
End If
If (condenserpressure = p28) Then
txthighpressure.Text = p28
End If
If (condenserpressure = p29) Then
txtlowpressure.Text = p29
End If
If (condenserpressure = p29) Then
txthighpressure.Text = p29
End If
If (condenserpressure = p210) Then
txtlowpressure.Text = p210
End If
If (condenserpressure = p210) Then
txthighpressure.Text = p210
End If
If (condenserpressure = p211) Then
txtlowpressure.Text = p211
End If
If (condenserpressure = p211) Then
txthighpressure.Text = p211
End If
If (txtlowpressure.Text = p21) Then
txtlowsaturationtemp.Text = Tsat21
End If
If (txtlowpressure.Text = p22) Then
txtlowsaturationtemp.Text = Tsat22
End If
If (txtlowpressure.Text = p23) Then
txtlowsaturationtemp.Text = Tsat23
End If
If (txtlowpressure.Text = p24) Then
txtlowsaturationtemp.Text = Tsat24
End If
If (txtlowpressure.Text = p25) Then
txtlowsaturationtemp.Text = Tsat25
End If
```

Appendix B: (Continued)

```
If (txtlowpressure.Text = p26) Then
txtlowsaturationtemp.Text = Tsat26
End If
If (txtlowpressure.Text = p27) Then
txtlowsaturationtemp.Text = Tsat27
End If
If (txtlowpressure.Text = p28) Then
txtlowsaturationtemp.Text = Tsat28
End If
If (txtlowpressure.Text = p29) Then
txtlowsaturationtemp.Text = Tsat29
End If
If (txtlowpressure.Text = p210) Then
txtlowsaturationtemp.Text = Tsat210
End If
If (txtlowpressure.Text = p211) Then
txtlowsaturationtemp.Text = Tsat211
End If
If (txthighpressure.Text = p21) Then
txthighsaturationtemp.Text = Tsat21
End If
If (txthighpressure.Text = p22) Then
txthighsaturationtemp.Text = Tsat22
End If
If (txthighpressure.Text = p23) Then
txthighsaturationtemp.Text = Tsat23
End If
If (txthighpressure.Text = p24) Then
txthighsaturationtemp.Text = Tsat24
End If
If (txthighpressure.Text = p25) Then
txthighsaturationtemp.Text = Tsat25
End If
If (txthighpressure.Text = p26) Then
txthighsaturationtemp.Text = Tsat26
End If
If (txthighpressure.Text = p27) Then
txthighsaturationtemp.Text = Tsat27
End If
If (txthighpressure.Text = p28) Then
txthighsaturationtemp.Text = Tsat28
End If
If (txthighpressure.Text = p29) Then
```

Appendix B: (Continued)

```
txthighsaturationtemp.Text = Tsat29
End If
If (txthighpressure.Text = p210) Then
txthighsaturationtemp.Text = Tsat210
End If
If (txthighpressure.Text = p211) Then
txthighsaturationtemp.Text = Tsat211
End If
txtTsathighminus30.Text = txthighsaturationtemp.Text - 30
temp4a = Val(txttemp4a.Text)
lowsaturationtemp = txtlowsaturationtemp.Text
If (temp4a < txtTsathighminus30.Text) Or (temp4a > lowsaturationtemp) Then
MsgBox "Temperature at point 4a is out of range for given pressure"
End If
enthalpy21 = (2.49559427061286E-04) * temp4a ^ 2 + (0.301660442186451) * temp4a
+ 76.1968840437323
enthalpy22 = (2.55102040815913E-04) * temp4a ^ 2 + (0.300870019546351) * temp4a
+ 76.2257559012309
enthalpy23 = (2.63612459980855E-04) * temp4a ^ 2 + (0.299653384463703) * temp4a
+ 76.2696376882216
enthalpy24 = (2.6709232314559E-04) * temp4a ^ 2 + (0.299079853967074) * temp4a +
76.293514322721
enthalpy25 = (2.75604678251717E-04) * temp4a ^ 2 + (0.297786734286484) * temp4a
+ 76.342762029641
enthalpy26 = (2.78250632621102E-04) * temp4a ^ 2 + (0.29735641243981) * temp4a +
76.3610240995769
enthalpy27 = (2.84649418547112E-04) * temp4a ^ 2 + (0.296270772039061) * temp4a
+ 76.4063482714235
enthalpy28 = (2.96088924200077E-04) * temp4a ^ 2 + (0.294413241412689) * temp4a
+ 76.4812482760129
enthalpy29 = (3.0060355056083E-04) * temp4a ^ 2 + (0.293615414540774) * temp4a +
76.516363731521
enthalpy210 = (3.06069694449462E-04) * temp4a ^ 2 + (0.29261717250391) * temp4a
+ 76.5616714129494
enthalpy211 = (3.19055537065793E-04) * temp4a ^ 2 + (0.290347455828256) * temp4a
+ 76.6595686734113
If (condenserpressure >= p21) And (condenserpressure < p22) Then
reheatexitenthalpy = (condenserpressure - p21) * ((enthalpy22 - enthalpy21) / (p22 -
p21)) + enthalpy21
End If
If (condenserpressure >= p22) And (condenserpressure < p23) Then
reheatexitenthalpy = (condenserpressure - p22) * ((enthalpy23 - enthalpy22) / (p23 -
p22)) + enthalpy22
```

Appendix B: (Continued)

End If

If (condenserpressure >= p23) And (condenserpressure < p24) Then
reheatexitenthalpy = (condenserpressure - p23) * ((enthalpy24 - enthalpy23) / (p24 - p23)) + enthalpy23

End If

If (condenserpressure >= p24) And (condenserpressure < p25) Then
reheatexitenthalpy = (condenserpressure - p24) * ((enthalpy25 - enthalpy24) / (p25 - p24)) + enthalpy24

End If

If (condenserpressure >= p25) And (condenserpressure < p26) Then
reheatexitenthalpy = (condenserpressure - p25) * ((enthalpy26 - enthalpy25) / (p26 - p25)) + enthalpy25

End If

If (condenserpressure >= p26) And (condenserpressure < p27) Then
reheatexitenthalpy = (condenserpressure - p26) * ((enthalpy27 - enthalpy26) / (p27 - p26)) + enthalpy26

End If

If (condenserpressure >= p27) And (condenserpressure < p28) Then
reheatexitenthalpy = (condenserpressure - p27) * ((enthalpy28 - enthalpy27) / (p28 - p27)) + enthalpy27

End If

If (condenserpressure >= p28) And (condenserpressure < p29) Then
reheatexitenthalpy = (condenserpressure - p28) * ((enthalpy29 - enthalpy28) / (p29 - p28)) + enthalpy28

End If

If (condenserpressure >= p29) And (condenserpressure < p210) Then
reheatexitenthalpy = (condenserpressure - p29) * ((enthalpy210 - enthalpy29) / (p210 - p29)) + enthalpy29

End If

If (condenserpressure >= p210) And (condenserpressure <= p211) Then
reheatexitenthalpy = (condenserpressure - p210) * ((enthalpy211 - enthalpy210) / (p211 - p210)) + enthalpy210

End If

txtreheatexitenthalpy.Text = reheatexitenthalpy

txttestenthalpy4a.Text = enthalpy27

Qevap = Val(txtQevap.Text)

reheatfactor = Val(txtreheatfactor.Text)

Qreheat = reheatfactor * Qevap

txtQreheat.Text = Round(Qreheat, 5)

enthalpy4 = (enthalpy3 * Qevap - ((enthalpy3 * evapexitenthalpy * Qreheat) / (enthalpy3 - reheatexitenthalpy)) + ((reheatexitenthalpy * evapexitenthalpy * Qreheat) / (enthalpy3 - reheatexitenthalpy))) / (Qevap - ((enthalpy3 * Qreheat) / (enthalpy3 - reheatexitenthalpy)) + ((reheatexitenthalpy * Qreheat) / (enthalpy3 - reheatexitenthalpy)))

Appendix B: (Continued)

```
txtenthalpy4.Text = enthalpy4
mref = Qevap / (evapexitenthalpy - enthalpy4)
txtmref.Text = mref
mreheat = Qreheat / (enthalpy3 - reheatexitenthalpy)
txtmreheat.Text = mreheat
m3b = mref - mreheat
txtm3b.Text = m3b
Win = mref * (compexitenthalpy - evapexitenthalpy)
txtWin.Text = Win
COPreheat = (Qevap - Qreheat) / Win
txtCOPreheat.Text = Round(COPreheat, 5)
COP = Qevap / Win
txtCOP.Text = Round(COP, 5)
End Sub
```

Appendix B: (Continued)

Warm Liquid Refrigerant Cycle

Form1

evap pressure (psia)	Temperature at point 1 (F)	Condenser Pressure (psia)	quality at 3	Temperature at point 4a (F)	reheat factor	Q evaporator (Btu/h)
<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>
evap pressure rounded	high pressure (evap exit)	High Saturation Temperature (evap exit)	Eval 1	low pressure (reheat exit)	high pressure (reheat exit)	
<input type="text"/>	<input type="text"/>	<input type="text"/>		<input type="text"/>	<input type="text"/>	
	low pressure (evap exit)	Low Saturation Temperature (evap exit)	Low Saturation Temperature plus 10	Low Saturation Temperature (reheat exit)	High Saturation Temperature (reheat exit)	
	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>	
Evaporator Exit Enthalpy (State 1)	test enthalpy 1 (Btu/lbm)	Evaporator Exit Entropy (State 1)	test entropy 1 (Btu/lbmR)	Reheat Exit Enthalpy (State 4a)	Tsat high minus 30	
<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>	
Compressor Exit Enthalpy (State 2)	test enthalpy 2	test entropy 2	mass flow rate (3b)	Enthalpy at State 4	test enthalpy 4a	
<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>	
Condenser Exit Enthalpy (State 3)	test enthalpy 3	mass flow rate through reheat (lbm/h)	mass flow rate of refrigerant (lbm/h)	COP	Q reheat (Btu/h)	
<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>	
				Work Input (Btu/h)	COP reheat	
				<input type="text"/>	<input type="text"/>	

Figure B.1 Form for Warm Liquid Refrigerant Cycle Program

Appendix B: (Continued)

Sequential Hot Gas Refrigerant Cycle

```
Private Sub cmdevaluate_Click()  
evappressure = Val(txtevappressure.Text)  
evappressurerounded = Round(evappressure, 0)  
txtevappressurerounded = evappressurerounded  
T1 = Val(txttemp1.Text)  
If (evappressure >= evappressurerounded) Then  
txtlowp.Text = evappressurerounded  
End If  
If (evappressure > evappressurerounded) Then  
txthighp.Text = evappressurerounded + 1  
End If  
If (evappressure <= evappressurerounded) Then  
txthighp.Text = evappressurerounded  
End If  
If (evappressure < evappressurerounded) Then  
txtlowp.Text = evappressurerounded - 1  
End If  
p1 = 45  
p2 = 46  
p3 = 47  
p4 = 48  
p5 = 49  
p6 = 50  
p7 = 51  
p8 = 52  
p9 = 53  
p10 = 54  
p11 = 55  
Tsat1 = 34.897  
Tsat2 = 36.006  
Tsat3 = 37.098  
Tsat4 = 38.171  
Tsat5 = 39.227  
Tsat6 = 40.267  
Tsat7 = 41.292  
Tsat8 = 42.301  
Tsat9 = 43.295  
Tsat10 = 44.275  
Tsat11 = 45.241  
h1 = (-8.55494591860406E-05) * T1 ^ 2 + (0.221803709111986) * T1 +  
(164.251339451151)
```

Appendix B: (Continued)

$h2 = (-1.04453973165164E-04) * T1 ^ 2 + (0.224294986034621) * T1 + 164.0994957513$
 $h3 = (-1.70924683359885E-04) * T1 ^ 2 + (0.230698866947877) * T1 + (163.867146163839)$
 $h4 = (-9.21268362219507E-05) * T1 ^ 2 + (0.224999664161904) * T1 + (163.884920315296)$
 $h5 = (-1.45660586440499E-04) * T1 ^ 2 + (0.230612768300361) * T1 + (163.660593095293)$
 $h6 = (-8.21518737410543E-05) * T1 ^ 2 + (0.225745230044991) * T1 + (163.669848007973)$
 $h7 = (-1.12163878597471E-04) * T1 ^ 2 + (0.229275983250786) * T1 + (163.49043486943)$
 $h8 = (-1.41086913643562E-04) * T1 ^ 2 + (0.232871991082073) * T1 + (163.305535881264)$
 $h9 = (-7.64892314037979E-05) * T1 ^ 2 + (0.227560040562432) * T1 + (163.330623395824)$
 $h10 = (-9.60906859432953E-05) * T1 ^ 2 + (0.230211818547635) * T1 + (163.168495290491)$
 $h11 = (-1.18784814304718E-04) * T1 ^ 2 + (0.233243428018642) * T1 + (162.994242756115)$
 $s1 = (-6.0803711907087E-07) * T1 ^ 2 + (4.79110474060067E-04) * T1 + (0.396595113510306)$
 $s2 = (-6.25417075461598E-07) * T1 ^ 2 + (4.82232881662558E-04) * T1 + (0.395942612567429)$
 $s3 = (-6.3338833347637E-07) * T1 ^ 2 + (4.84618356885164E-04) * T1 + (0.395313013521716)$
 $s4 = (-5.72841618529107E-07) * T1 ^ 2 + (4.81048526321251E-04) * T1 + (0.394819557534999)$
 $s5 = (-7.03779334892962E-07) * T1 ^ 2 + (4.94256622175797E-04) * T1 + (0.393967537270816)$
 $s6 = (-6.7611950432811E-07) * T1 ^ 2 + (4.93501395964934E-04) * T1 + (0.393429028182591)$
 $s7 = (-6.58521754043351E-07) * T1 ^ 2 + (4.93457265859189E-04) * T1 + (0.392885330772991)$
 $s8 = (-6.47501380623972E-07) * T1 ^ 2 + (4.94182527420029E-04) * T1 + (0.3923266406261)$
 $s9 = (-5.96537599012459E-07) * T1 ^ 2 + (4.91008706960247E-04) * T1 + (0.391868567094144)$
 $s10 = (-7.13188032908096E-07) * T1 ^ 2 + (5.04008662543318E-04) * T1 + (0.391027694896258)$
 $s11 = (-6.79822001331543E-07) * T1 ^ 2 + (5.02477295152442E-04) * T1 + (0.390542594477737)$

If (txtevappressure.Text < p1) Or (txtevappressure.Text > p11) Then

Appendix B: (Continued)

MsgBox "evaporator pressure is out of range"

End If

If (txtlowp.Text = p1) Then

txtlowsattemp.Text = Tsat1

End If

If (txtlowp.Text = p2) Then

txtlowsattemp.Text = Tsat2

End If

If (txtlowp.Text = p3) Then

txtlowsattemp.Text = Tsat3

End If

If (txtlowp.Text = p4) Then

txtlowsattemp.Text = Tsat4

End If

If (txtlowp.Text = p5) Then

txtlowsattemp.Text = Tsat5

End If

If (txtlowp.Text = p6) Then

txtlowsattemp.Text = Tsat6

End If

If (txtlowp.Text = p7) Then

txtlowsattemp.Text = Tsat7

End If

If (txtlowp.Text = p8) Then

txtlowsattemp.Text = Tsat8

End If

If (txtlowp.Text = p9) Then

txtlowsattemp.Text = Tsat9

End If

If (txtlowp.Text = p10) Then

txtlowsattemp.Text = Tsat10

End If

If (txtlowp.Text = p11) Then

txtlowsattemp.Text = Tsat11

End If

If (txthighp.Text = p1) Then

txthighsattemp.Text = Tsat1

End If

If (txthighp.Text = p2) Then

txthighsattemp.Text = Tsat2

End If

If (txthighp.Text = p3) Then

txthighsattemp.Text = Tsat3

Appendix B: (Continued)

```
End If
If (txthighp.Text = p4) Then
txthighsattemp.Text = Tsat4
End If
If (txthighp.Text = p5) Then
txthighsattemp.Text = Tsat5
End If
If (txthighp.Text = p6) Then
txthighsattemp.Text = Tsat6
End If
If (txthighp.Text = p7) Then
txthighsattemp.Text = Tsat7
End If
If (txthighp.Text = p8) Then
txthighsattemp.Text = Tsat8
End If
If (txthighp.Text = p9) Then
txthighsattemp.Text = Tsat9
End If
If (txthighp.Text = p10) Then
txthighsattemp.Text = Tsat10
End If
If (txthighp.Text = p11) Then
txthighsattemp.Text = Tsat11
End If
txtlowsattempplus10.Text = txtlowsattemp.Text + 10
T1 = Val(txttemp1.Text)
If (T1 < txthighsattemp.Text) Or (T1 > txtlowsattempplus10.Text) Then
MsgBox "Temperature at point 1 is out of range for given pressure"
End If
If (evappressure >= p1) And (evappressure < p2) Then
evapexitenthalpy = (evappressure - p1) * ((h2 - h1) / (p2 - p1)) + h1
End If
If (evappressure >= p2) And (evappressure < p3) Then
evapexitenthalpy = (evappressure - p2) * ((h3 - h2) / (p3 - p2)) + h2
End If
If (evappressure >= p3) And (evappressure < p4) Then
evapexitenthalpy = (evappressure - p3) * ((h4 - h3) / (p4 - p3)) + h3
End If
If (evappressure >= p4) And (evappressure < p5) Then
evapexitenthalpy = (evappressure - p4) * ((h5 - h4) / (p5 - p4)) + h4
End If
If (evappressure >= p5) And (evappressure < p6) Then
```

Appendix B: (Continued)

```
evapexitenthalpy = (evappressure - p5) * ((h6 - h5) / (p6 - p5)) + h5
End If
If (evappressure >= p6) And (evappressure < p7) Then
evapexitenthalpy = (evappressure - p6) * ((h7 - h6) / (p7 - p6)) + h6
End If
If (evappressure >= p7) And (evappressure < p8) Then
evapexitenthalpy = (evappressure - p7) * ((h8 - h7) / (p8 - p7)) + h7
End If
If (evappressure >= p8) And (evappressure < p9) Then
evapexitenthalpy = (evappressure - p8) * ((h9 - h8) / (p9 - p8)) + h8
End If
If (evappressure >= p9) And (evappressure < p10) Then
evapexitenthalpy = (evappressure - p9) * ((h10 - h9) / (p10 - p9)) + h9
End If
If (evappressure >= p10) And (evappressure <= p11) Then
evapexitenthalpy = (evappressure - p10) * ((h11 - h10) / (p11 - p10)) + h10
End If
txtevapexitenthalpy.Text = Round(evapexitenthalpy, 5)
txttestenthalpy1 = h2
If (evappressure >= p1) And (evappressure < p2) Then
evapexitentropy = (evappressure - p1) * ((s2 - s1) / (p2 - p1)) + s1
End If
If (evappressure >= p2) And (evappressure < p3) Then
evapexitentropy = (evappressure - p2) * ((s3 - s2) / (p3 - p2)) + s2
End If
If (evappressure >= p3) And (evappressure < p4) Then
evapexitentropy = (evappressure - p3) * ((s4 - s3) / (p4 - p3)) + s3
End If
If (evappressure >= p4) And (evappressure < p5) Then
evapexitentropy = (evappressure - p4) * ((s5 - s4) / (p5 - p4)) + s4
End If
If (evappressure >= p5) And (evappressure < p6) Then
evapexitentropy = (evappressure - p5) * ((s6 - s5) / (p6 - p5)) + s5
End If
If (evappressure >= p6) And (evappressure < p7) Then
evapexitentropy = (evappressure - p6) * ((s7 - s6) / (p7 - p6)) + s6
End If
If (evappressure >= p7) And (evappressure < p8) Then
evapexitentropy = (evappressure - p7) * ((s8 - s7) / (p8 - p7)) + s7
End If
If (evappressure >= p8) And (evappressure < p9) Then
evapexitentropy = (evappressure - p8) * ((s9 - s8) / (p9 - p8)) + s8
End If
```

Appendix B: (Continued)

```
If (evappressure >= p9) And (evappressure < p10) Then
evapexitentropy = (evappressure - p9) * ((s10 - s9) / (p10 - p9)) + s9
End If
If (evappressure >= p10) And (evappressure <= p11) Then
evapexitentropy = (evappressure - p10) * ((s11 - s10) / (p11 - p10)) + s10
End If
txtevapexitentropy.Text = Round(evapexitentropy, 5)
txttestentropy1 = s4
compexitentropy = evapexitentropy
txtcompexitentropy.Text = Round(compexitentropy, 5)
p21 = 100
p22 = 104
p23 = 108
p24 = 112
p25 = 116
p26 = 120
p27 = 124
p28 = 128
p29 = 132
p210 = 136
p211 = 140
Tsat21 = 79.159
Tsat22 = 81.561
Tsat23 = 83.894
Tsat24 = 86.164
Tsat25 = 88.373
Tsat26 = 90.526
Tsat27 = 92.625
Tsat28 = 94.674
Tsat29 = 96.675
Tsat210 = 98.632
Tsat211 = 100.55
h21 = 1140.33482740819 * compexitentropy ^ 2 - 396.658048826921 * compexitentropy
+ 148.543589272253
h22 = 1116.79531031847 * compexitentropy ^ 2 - 374.742307050553 * compexitentropy
+ 143.863072320317
h23 = 1140.53734263777 * compexitentropy ^ 2 - 391.945459033649 * compexitentropy
+ 147.259853282843
h24 = 1244.42484858632 * compexitentropy ^ 2 - 475.137371935914 * compexitentropy
+ 164.224679495585
h25 = 1104.91427125036 * compexitentropy ^ 2 - 357.304208273241 * compexitentropy
+ 139.675233637429
```


Appendix B: (Continued)

$$h26 = 1164.58516219258 * \text{compexitentropy}^2 - 404.524050813997 * \text{compexitentropy} + 149.305123171225$$

$$h27 = 1113.95974990725 * \text{compexitentropy}^2 - 360.490942444008 * \text{compexitentropy} + 140.051997716919$$

$$h28 = 993.009925991296 * \text{compexitentropy}^2 - 258.119517517082 * \text{compexitentropy} + 118.690310440396$$

$$h29 = 1102.44195953011 * \text{compexitentropy}^2 - 346.252324193361 * \text{compexitentropy} + 136.701072757343$$

$$h210 = 1185.92752987146 * \text{compexitentropy}^2 - 413.446234645956 * \text{compexitentropy} + 150.482425772728$$

$$h211 = 1113.86845897138 * \text{compexitentropy}^2 - 351.641910220986 * \text{compexitentropy} + 137.510255260159$$

condenserpressure = Val(txtcondenserpressure.Text)

If (condenserpressure < p21) Or (condenserpressure > p211) Then

MsgBox "condenser pressure is out of range"

End If

If (condenserpressure >= p21) And (condenserpressure < p22) Then

$$\text{compexitenthalpy} = (\text{condenserpressure} - p21) * ((h22 - h21) / (p22 - p21)) + h21$$

End If

If (condenserpressure >= p22) And (condenserpressure < p23) Then

$$\text{compexitenthalpy} = (\text{condenserpressure} - p22) * ((h23 - h22) / (p23 - p22)) + h22$$

End If

If (condenserpressure >= p23) And (condenserpressure < p24) Then

$$\text{compexitenthalpy} = (\text{condenserpressure} - p23) * ((h24 - h23) / (p24 - p23)) + h23$$

End If

If (condenserpressure >= p24) And (condenserpressure < p25) Then

$$\text{compexitenthalpy} = (\text{condenserpressure} - p24) * ((h25 - h24) / (p25 - p24)) + h24$$

End If

If (condenserpressure >= p25) And (condenserpressure < p26) Then

$$\text{compexitenthalpy} = (\text{condenserpressure} - p25) * ((h26 - h25) / (p26 - p25)) + h25$$

End If

If (condenserpressure >= p26) And (condenserpressure < p27) Then

$$\text{compexitenthalpy} = (\text{condenserpressure} - p26) * ((h27 - h26) / (p27 - p26)) + h26$$

End If

If (condenserpressure >= p27) And (condenserpressure < p28) Then

$$\text{compexitenthalpy} = (\text{condenserpressure} - p27) * ((h28 - h27) / (p28 - p27)) + h27$$

End If

If (condenserpressure >= p28) And (condenserpressure < p29) Then

$$\text{compexitenthalpy} = (\text{condenserpressure} - p28) * ((h29 - h28) / (p29 - p28)) + h28$$

End If

If (condenserpressure >= p29) And (condenserpressure < p210) Then

$$\text{compexitenthalpy} = (\text{condenserpressure} - p29) * ((h210 - h29) / (p210 - p29)) + h29$$

End If

Appendix B: (Continued)

```
If (condenserpressure >= p210) And (condenserpressure <= p211) Then
compexitenthalpy = (condenserpressure - p210) * ((h211 - h210) / (p211 - p210)) + h210
End If
txtcompexitenthalpy.Text = Round(compexitenthalpy, 5)
txttestenthalpy2.Text = h24
hsatvap1 = 177.65
hsatvap2 = 177.94
hsatvap3 = 178.21
hsatvap4 = 178.48
hsatvap5 = 178.73
hsatvap6 = 178.98
hsatvap7 = 179.22
hsatvap8 = 179.44
hsatvap9 = 179.66
hsatvap10 = 179.88
hsatvap11 = 180.08
hsatLiq1 = 101.64
hsatLiq2 = 102.46
hsatLiq3 = 103.27
hsatLiq4 = 104.05
hsatLiq5 = 104.81
hsatLiq6 = 105.56
hsatLiq7 = 106.29
hsatLiq8 = 107.01
hsatLiq9 = 107.71
hsatLiq10 = 108.4
hsatLiq11 = 109.08
x = Val(txtquality4.Text)
If (x < 0) Or (x > 0.3) Then
MsgBox "Quality at point 4 is out of range"
End If
h41 = hsatLiq1 + x * (hsatvap1 - hsatLiq1)
h42 = hsatLiq2 + x * (hsatvap2 - hsatLiq2)
h43 = hsatLiq3 + x * (hsatvap3 - hsatLiq3)
h44 = hsatLiq4 + x * (hsatvap4 - hsatLiq4)
h45 = hsatLiq5 + x * (hsatvap5 - hsatLiq5)
h46 = hsatLiq6 + x * (hsatvap6 - hsatLiq6)
h47 = hsatLiq7 + x * (hsatvap7 - hsatLiq7)
h48 = hsatLiq8 + x * (hsatvap8 - hsatLiq8)
h49 = hsatLiq9 + x * (hsatvap9 - hsatLiq9)
h410 = hsatLiq10 + x * (hsatvap10 - hsatLiq10)
h411 = hsatLiq11 + x * (hsatvap11 - hsatLiq11)
If (condenserpressure >= p21) And (condenserpressure < p22) Then
```

Appendix B: (Continued)

```
enthalpy4 = (condenserpressure - p21) * ((h42 - h41) / (p22 - p21)) + h41
End If
If (condenserpressure >= p22) And (condenserpressure < p23) Then
enthalpy4 = (condenserpressure - p22) * ((h43 - h42) / (p23 - p22)) + h42
End If
If (condenserpressure >= p23) And (condenserpressure < p24) Then
enthalpy4 = (condenserpressure - p23) * ((h44 - h43) / (p24 - p23)) + h43
End If
If (condenserpressure >= p24) And (condenserpressure < p25) Then
enthalpy4 = (condenserpressure - p24) * ((h45 - h44) / (p25 - p24)) + h44
End If
If (condenserpressure >= p25) And (condenserpressure < p26) Then
enthalpy4 = (condenserpressure - p25) * ((h46 - h45) / (p26 - p25)) + h45
End If
If (condenserpressure >= p26) And (condenserpressure < p27) Then
enthalpy4 = (condenserpressure - p26) * ((h47 - h46) / (p27 - p26)) + h46
End If
If (condenserpressure >= p27) And (condenserpressure < p28) Then
enthalpy4 = (condenserpressure - p27) * ((h48 - h47) / (p28 - p27)) + h47
End If
If (condenserpressure >= p28) And (condenserpressure < p29) Then
enthalpy4 = (condenserpressure - p28) * ((h49 - h48) / (p29 - p28)) + h48
End If
If (condenserpressure >= p29) And (condenserpressure < p210) Then
enthalpy4 = (condenserpressure - p29) * ((h410 - h49) / (p210 - p29)) + h49
End If
If (condenserpressure >= p210) And (condenserpressure <= p211) Then
enthalpy4 = (condenserpressure - p210) * ((h411 - h410) / (p211 - p210)) + h410
End If
txtenthalpy4.Text = enthalpy4
If (condenserpressure > p21) And (condenserpressure < p22) Then
txtlowpressure.Text = p21
End If
If (condenserpressure > p21) And (condenserpressure < p22) Then
txthighpressure.Text = p22
End If
If (condenserpressure > p22) And (condenserpressure < p23) Then
txtlowpressure.Text = p22
End If
If (condenserpressure > p22) And (condenserpressure < p23) Then
txthighpressure.Text = p23
End If
If (condenserpressure > p23) And (condenserpressure < p24) Then
```

Appendix B: (Continued)

```
txtlowpressure.Text = p23
End If
If (condenserpressure > p23) And (condenserpressure < p24) Then
txthighpressure.Text = p24
End If
If (condenserpressure > p24) And (condenserpressure < p25) Then
txtlowpressure.Text = p24
End If
If (condenserpressure > p24) And (condenserpressure < p25) Then
txthighpressure.Text = p25
End If
If (condenserpressure > p25) And (condenserpressure < p26) Then
txtlowpressure.Text = p25
End If
If (condenserpressure > p25) And (condenserpressure < p26) Then
txthighpressure.Text = p26
End If
If (condenserpressure > p26) And (condenserpressure < p27) Then
txtlowpressure.Text = p26
End If
If (condenserpressure > p26) And (condenserpressure < p27) Then
txthighpressure.Text = p27
End If
If (condenserpressure > p27) And (condenserpressure < p28) Then
txtlowpressure.Text = p27
End If
If (condenserpressure > p27) And (condenserpressure < p28) Then
txthighpressure.Text = p28
End If
If (condenserpressure > p28) And (condenserpressure < p29) Then
txtlowpressure.Text = p28
End If
If (condenserpressure > p28) And (condenserpressure < p29) Then
txthighpressure.Text = p29
End If
If (condenserpressure > p29) And (condenserpressure < p210) Then
txtlowpressure.Text = p29
End If
If (condenserpressure > p29) And (condenserpressure < p210) Then
txthighpressure.Text = p210
End If
If (condenserpressure > p210) And (condenserpressure < p211) Then
txtlowpressure.Text = p210
```

Appendix B: (Continued)

```
End If
If (condenserpressure > p210) And (condenserpressure < p211) Then
txthighpressure.Text = p211
End If
If (condenserpressure = p21) Then
txtlowpressure.Text = p21
End If
If (condenserpressure = p21) Then
txthighpressure.Text = p21
End If
If (condenserpressure = p22) Then
txtlowpressure.Text = p22
End If
If (condenserpressure = p22) Then
txthighpressure.Text = p22
End If
If (condenserpressure = p23) Then
txtlowpressure.Text = p23
End If
If (condenserpressure = p23) Then
txthighpressure.Text = p23
End If
If (condenserpressure = p24) Then
txtlowpressure.Text = p24
End If
If (condenserpressure = p24) Then
txthighpressure.Text = p24
End If
If (condenserpressure = p25) Then
txtlowpressure.Text = p25
End If
If (condenserpressure = p25) Then
txthighpressure.Text = p25
End If
If (condenserpressure = p26) Then
txtlowpressure.Text = p26
End If
If (condenserpressure = p26) Then
txthighpressure.Text = p26
End If
If (condenserpressure = p27) Then
txtlowpressure.Text = p27
End If
```

Appendix B: (Continued)

```
If (condenserpressure = p27) Then
txthighpressure.Text = p27
End If
If (condenserpressure = p28) Then
txtlowpressure.Text = p28
End If
If (condenserpressure = p28) Then
txthighpressure.Text = p28
End If
If (condenserpressure = p29) Then
txtlowpressure.Text = p29
End If
If (condenserpressure = p29) Then
txthighpressure.Text = p29
End If
If (condenserpressure = p210) Then
txtlowpressure.Text = p210
End If
If (condenserpressure = p210) Then
txthighpressure.Text = p210
End If
If (condenserpressure = p211) Then
txtlowpressure.Text = p211
End If
If (condenserpressure = p211) Then
txthighpressure.Text = p211
End If
If (txtlowpressure.Text = p21) Then
txtlowsaturationtemp.Text = Tsat21
End If
If (txtlowpressure.Text = p22) Then
txtlowsaturationtemp.Text = Tsat22
End If
If (txtlowpressure.Text = p23) Then
txtlowsaturationtemp.Text = Tsat23
End If
If (txtlowpressure.Text = p24) Then
txtlowsaturationtemp.Text = Tsat24
End If
If (txtlowpressure.Text = p25) Then
txtlowsaturationtemp.Text = Tsat25
End If
If (txtlowpressure.Text = p26) Then
```

Appendix B: (Continued)

```
txtlowsaturationtemp.Text = Tsat26
End If
If (txtlowpressure.Text = p27) Then
txtlowsaturationtemp.Text = Tsat27
End If
If (txtlowpressure.Text = p28) Then
txtlowsaturationtemp.Text = Tsat28
End If
If (txtlowpressure.Text = p29) Then
txtlowsaturationtemp.Text = Tsat29
End If
If (txtlowpressure.Text = p210) Then
txtlowsaturationtemp.Text = Tsat210
End If
If (txtlowpressure.Text = p211) Then
txtlowsaturationtemp.Text = Tsat211
End If
If (txthighpressure.Text = p21) Then
txthighsaturationtemp.Text = Tsat21
End If
If (txthighpressure.Text = p22) Then
txthighsaturationtemp.Text = Tsat22
End If
If (txthighpressure.Text = p23) Then
txthighsaturationtemp.Text = Tsat23
End If
If (txthighpressure.Text = p24) Then
txthighsaturationtemp.Text = Tsat24
End If
If (txthighpressure.Text = p25) Then
txthighsaturationtemp.Text = Tsat25
End If
If (txthighpressure.Text = p26) Then
txthighsaturationtemp.Text = Tsat26
End If
If (txthighpressure.Text = p27) Then
txthighsaturationtemp.Text = Tsat27
End If
If (txthighpressure.Text = p28) Then
txthighsaturationtemp.Text = Tsat28
End If
If (txthighpressure.Text = p29) Then
txthighsaturationtemp.Text = Tsat29
```

Appendix B: (Continued)

```
End If
If (txthighpressure.Text = p210) Then
txthighsaturationtemp.Text = Tsat210
End If
If (txthighpressure.Text = p211) Then
txthighsaturationtemp.Text = Tsat211
End If
txtTsathighminus30.Text = txthighsaturationtemp.Text - 30
temp3a = Val(txttemp3a.Text)
lowsaturationtemp = txtlowsaturationtemp.Text
If (temp3a < txtTsathighminus30.Text) Or (temp3a > lowsaturationtemp) Then
MsgBox "Temperature at point 3a is out of range for given pressure"
End If
enthalpy21 = (2.49559427061286E-04) * temp3a ^ 2 + (0.301660442186451) * temp3a
+ 76.1968840437323
enthalpy22 = (2.55102040815913E-04) * temp3a ^ 2 + (0.300870019546351) * temp3a
+ 76.2257559012309
enthalpy23 = (2.63612459980855E-04) * temp3a ^ 2 + (0.299653384463703) * temp3a
+ 76.2696376882216
enthalpy24 = (2.6709232314559E-04) * temp3a ^ 2 + (0.299079853967074) * temp3a +
76.293514322721
enthalpy25 = (2.75604678251717E-04) * temp3a ^ 2 + (0.297786734286484) * temp3a
+ 76.342762029641
enthalpy26 = (2.78250632621102E-04) * temp3a ^ 2 + (0.29735641243981) * temp3a +
76.3610240995769
enthalpy27 = (2.84649418547112E-04) * temp3a ^ 2 + (0.296270772039061) * temp3a
+ 76.4063482714235
enthalpy28 = (2.96088924200077E-04) * temp3a ^ 2 + (0.294413241412689) * temp3a
+ 76.4812482760129
enthalpy29 = (3.0060355056083E-04) * temp3a ^ 2 + (0.293615414540774) * temp3a +
76.516363731521
enthalpy210 = (3.06069694449462E-04) * temp3a ^ 2 + (0.29261717250391) * temp3a
+ 76.5616714129494
enthalpy211 = (3.19055537065793E-04) * temp3a ^ 2 + (0.290347455828256) * temp3a
+ 76.6595686734113
If (condenserpressure >= p21) And (condenserpressure < p22) Then
reheatexitenthalpy = (condenserpressure - p21) * ((enthalpy22 - enthalpy21) / (p22 -
p21)) + enthalpy21
End If
If (condenserpressure >= p22) And (condenserpressure < p23) Then
reheatexitenthalpy = (condenserpressure - p22) * ((enthalpy23 - enthalpy22) / (p23 -
p22)) + enthalpy22
End If
```


Appendix B: (Continued)

```
If (condenserpressure >= p23) And (condenserpressure < p24) Then
reheatexitenthalpy = (condenserpressure - p23) * ((enthalpy24 - enthalpy23) / (p24 -
p23)) + enthalpy23
End If
If (condenserpressure >= p24) And (condenserpressure < p25) Then
reheatexitenthalpy = (condenserpressure - p24) * ((enthalpy25 - enthalpy24) / (p25 -
p24)) + enthalpy24
End If
If (condenserpressure >= p25) And (condenserpressure < p26) Then
reheatexitenthalpy = (condenserpressure - p25) * ((enthalpy26 - enthalpy25) / (p26 -
p25)) + enthalpy25
End If
If (condenserpressure >= p26) And (condenserpressure < p27) Then
reheatexitenthalpy = (condenserpressure - p26) * ((enthalpy27 - enthalpy26) / (p27 -
p26)) + enthalpy26
End If
If (condenserpressure >= p27) And (condenserpressure < p28) Then
reheatexitenthalpy = (condenserpressure - p27) * ((enthalpy28 - enthalpy27) / (p28 -
p27)) + enthalpy27
End If
If (condenserpressure >= p28) And (condenserpressure < p29) Then
reheatexitenthalpy = (condenserpressure - p28) * ((enthalpy29 - enthalpy28) / (p29 -
p28)) + enthalpy28
End If
If (condenserpressure >= p29) And (condenserpressure < p210) Then
reheatexitenthalpy = (condenserpressure - p29) * ((enthalpy210 - enthalpy29) / (p210 -
p29)) + enthalpy29
End If
If (condenserpressure >= p210) And (condenserpressure <= p211) Then
reheatexitenthalpy = (condenserpressure - p210) * ((enthalpy211 - enthalpy210) / (p211 -
p210)) + enthalpy210
End If
txtreheatexitenthalpy.Text = reheatexitenthalpy
txttestenthalpy3a.Text = enthalpy27
Qevap = Val(txtQevap.Text)
reheatfactor = Val(txtreheatfactor.Text)
Qreheat = reheatfactor * Qevap
txtQreheat.Text = Round(Qreheat, 5)
enthalpy3 = (1 - (Qreheat * (evapexitenthalpy - enthalpy4)) / (Qevap * (compexitenthalpy
- reheatexitenthalpy))) * compexitenthalpy + (Qreheat * (evapexitenthalpy - enthalpy4) *
reheatexitenthalpy) / (Qevap * (compexitenthalpy - reheatexitenthalpy))
txtenthalpy3.Text = enthalpy3
mref = Qevap / (evapexitenthalpy - enthalpy4)
```

Appendix B: (Continued)

```
txtmref.Text = mref
mreheat = Qreheat / (compexitenthalpy - reheatexitenthalpy)
txtmreheat.Text = mreheat
Win = mref * (compexitenthalpy - evapexitenthalpy)
txtWin.Text = Win
COPreheat = (Qevap - Qreheat) / Win
txtCOPreheat.Text = Round(COPreheat, 5)
COP = Qevap / Win
txtCOP.Text = Round(COP, 5)
End Sub
```

Appendix B: (Continued)

Sequential Hot Gas Refrigerant Cycle

Form1						
evap pressure (psia)	Temperature at point 1 (F)	Condenser Pressure (psia)	quality at 4	Temperature at point 3a (F)	reheat factor	Q evaporator (Btu/h)
<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>
evap pressure rounded	high pressure (evap exit)	High Saturation Temperature (evap exit)	Eval 1	low pressure (reheat exit)	high pressure (reheat exit)	
<input type="text"/>	<input type="text"/>	<input type="text"/>		<input type="text"/>	<input type="text"/>	
	low pressure (evap exit)	Low Saturation Temperature (evap exit)	Low Saturation Temperature plus 10	Low Saturation Temperature (reheat exit)	High Saturation Temperature (reheat exit)	
	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>	
Evaporator Exit Enthalpy (State 1)	test enthalpy 1 (Btu/lbm)	Evaporator Exit Entropy (State 1)	test entropy 1 (Btu/lbmR)	Reheat Exit Enthalpy (State 3a)	Tsat high minus 30	
<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>	
Compressor Exit Enthalpy (State 2)	test enthalpy 2	test entropy 2		Enthalpy at State 4	test enthalpy 3a	
<input type="text"/>	<input type="text"/>	<input type="text"/>		<input type="text"/>	<input type="text"/>	
Condenser Exit Enthalpy (State 3)		mass flow rate through reheat (lbm/h)	mass flow rate of refrigerant (lbm/h)	COP	Q reheat (Btu/h)	
<input type="text"/>		<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>	
				Work Input (Btu/h)	COP reheat	
				<input type="text"/>	<input type="text"/>	

Figure B.2 Form for Sequential Hot Gas Refrigerant Cycle Program

Appendix B: (Continued)

Parallel Hot Gas Refrigerant Cycle

```
Private Sub cmdevaluate_Click()  
evappressure = Val(txtevappressure.Text)  
evappressurerounded = Round(evappressure, 0)  
txtevappressurerounded = evappressurerounded  
T1 = Val(txttemp1.Text)  
If (evappressure >= evappressurerounded) Then  
txtlowp.Text = evappressurerounded  
End If  
If (evappressure > evappressurerounded) Then  
txthighp.Text = evappressurerounded + 1  
End If  
If (evappressure <= evappressurerounded) Then  
txthighp.Text = evappressurerounded  
End If  
If (evappressure < evappressurerounded) Then  
txtlowp.Text = evappressurerounded - 1  
End If  
p1 = 45  
p2 = 46  
p3 = 47  
p4 = 48  
p5 = 49  
p6 = 50  
p7 = 51  
p8 = 52  
p9 = 53  
p10 = 54  
p11 = 55  
Tsat1 = 34.897  
Tsat2 = 36.006  
Tsat3 = 37.098  
Tsat4 = 38.171  
Tsat5 = 39.227  
Tsat6 = 40.267  
Tsat7 = 41.292  
Tsat8 = 42.301  
Tsat9 = 43.295  
Tsat10 = 44.275  
Tsat11 = 45.241  
h1 = (-8.55494591860406E-05) * T1 ^ 2 + (0.221803709111986) * T1 +  
(164.251339451151)
```

Appendix B: (Continued)

$h2 = (-1.04453973165164E-04) * T1 ^ 2 + (0.224294986034621) * T1 + 164.0994957513$
 $h3 = (-1.70924683359885E-04) * T1 ^ 2 + (0.230698866947877) * T1 + (163.867146163839)$
 $h4 = (-9.21268362219507E-05) * T1 ^ 2 + (0.224999664161904) * T1 + (163.884920315296)$
 $h5 = (-1.45660586440499E-04) * T1 ^ 2 + (0.230612768300361) * T1 + (163.660593095293)$
 $h6 = (-8.21518737410543E-05) * T1 ^ 2 + (0.225745230044991) * T1 + (163.669848007973)$
 $h7 = (-1.12163878597471E-04) * T1 ^ 2 + (0.229275983250786) * T1 + (163.49043486943)$
 $h8 = (-1.41086913643562E-04) * T1 ^ 2 + (0.232871991082073) * T1 + (163.305535881264)$
 $h9 = (-7.64892314037979E-05) * T1 ^ 2 + (0.227560040562432) * T1 + (163.330623395824)$
 $h10 = (-9.60906859432953E-05) * T1 ^ 2 + (0.230211818547635) * T1 + (163.168495290491)$
 $h11 = (-1.18784814304718E-04) * T1 ^ 2 + (0.233243428018642) * T1 + (162.994242756115)$
 $s1 = (-6.0803711907087E-07) * T1 ^ 2 + (4.79110474060067E-04) * T1 + (0.396595113510306)$
 $s2 = (-6.25417075461598E-07) * T1 ^ 2 + (4.82232881662558E-04) * T1 + (0.395942612567429)$
 $s3 = (-6.3338833347637E-07) * T1 ^ 2 + (4.84618356885164E-04) * T1 + (0.395313013521716)$
 $s4 = (-5.72841618529107E-07) * T1 ^ 2 + (4.81048526321251E-04) * T1 + (0.394819557534999)$
 $s5 = (-7.03779334892962E-07) * T1 ^ 2 + (4.94256622175797E-04) * T1 + (0.393967537270816)$
 $s6 = (-6.7611950432811E-07) * T1 ^ 2 + (4.93501395964934E-04) * T1 + (0.393429028182591)$
 $s7 = (-6.58521754043351E-07) * T1 ^ 2 + (4.93457265859189E-04) * T1 + (0.392885330772991)$
 $s8 = (-6.47501380623972E-07) * T1 ^ 2 + (4.94182527420029E-04) * T1 + (0.3923266406261)$
 $s9 = (-5.96537599012459E-07) * T1 ^ 2 + (4.91008706960247E-04) * T1 + (0.391868567094144)$
 $s10 = (-7.13188032908096E-07) * T1 ^ 2 + (5.04008662543318E-04) * T1 + (0.391027694896258)$
 $s11 = (-6.79822001331543E-07) * T1 ^ 2 + (5.02477295152442E-04) * T1 + (0.390542594477737)$

If (txtevappressure.Text < p1) Or (txtevappressure.Text > p11) Then

Appendix B: (Continued)

MsgBox "evaporator pressure is out of range"

End If

If (txtlowp.Text = p1) Then

txtlowsattemp.Text = Tsat1

End If

If (txtlowp.Text = p2) Then

txtlowsattemp.Text = Tsat2

End If

If (txtlowp.Text = p3) Then

txtlowsattemp.Text = Tsat3

End If

If (txtlowp.Text = p4) Then

txtlowsattemp.Text = Tsat4

End If

If (txtlowp.Text = p5) Then

txtlowsattemp.Text = Tsat5

End If

If (txtlowp.Text = p6) Then

txtlowsattemp.Text = Tsat6

End If

If (txtlowp.Text = p7) Then

txtlowsattemp.Text = Tsat7

End If

If (txtlowp.Text = p8) Then

txtlowsattemp.Text = Tsat8

End If

If (txtlowp.Text = p9) Then

txtlowsattemp.Text = Tsat9

End If

If (txtlowp.Text = p10) Then

txtlowsattemp.Text = Tsat10

End If

If (txtlowp.Text = p11) Then

txtlowsattemp.Text = Tsat11

End If

If (txthighp.Text = p1) Then

txthighsattemp.Text = Tsat1

End If

If (txthighp.Text = p2) Then

txthighsattemp.Text = Tsat2

End If

If (txthighp.Text = p3) Then

txthighsattemp.Text = Tsat3

Appendix B: (Continued)

```
End If
If (txthighp.Text = p4) Then
txthighsattemp.Text = Tsat4
End If
If (txthighp.Text = p5) Then
txthighsattemp.Text = Tsat5
End If
If (txthighp.Text = p6) Then
txthighsattemp.Text = Tsat6
End If
If (txthighp.Text = p7) Then
txthighsattemp.Text = Tsat7
End If
If (txthighp.Text = p8) Then
txthighsattemp.Text = Tsat8
End If
If (txthighp.Text = p9) Then
txthighsattemp.Text = Tsat9
End If
If (txthighp.Text = p10) Then
txthighsattemp.Text = Tsat10
End If
If (txthighp.Text = p11) Then
txthighsattemp.Text = Tsat11
End If
txtlowsattempplus10.Text = txtlowsattemp.Text + 10
T1 = Val(txttemp1.Text)
If (T1 < txthighsattemp.Text) Or (T1 > txtlowsattempplus10.Text) Then
MsgBox "Temperature at point 1 is out of range for given pressure"
End If
If (evappressure >= p1) And (evappressure < p2) Then
evapexitenthalpy = (evappressure - p1) * ((h2 - h1) / (p2 - p1)) + h1
End If
If (evappressure >= p2) And (evappressure < p3) Then
evapexitenthalpy = (evappressure - p2) * ((h3 - h2) / (p3 - p2)) + h2
End If
If (evappressure >= p3) And (evappressure < p4) Then
evapexitenthalpy = (evappressure - p3) * ((h4 - h3) / (p4 - p3)) + h3
End If
If (evappressure >= p4) And (evappressure < p5) Then
evapexitenthalpy = (evappressure - p4) * ((h5 - h4) / (p5 - p4)) + h4
End If
If (evappressure >= p5) And (evappressure < p6) Then
```

Appendix B: (Continued)

```
evapexitenthalpy = (evappressure - p5) * ((h6 - h5) / (p6 - p5)) + h5
End If
If (evappressure >= p6) And (evappressure < p7) Then
evapexitenthalpy = (evappressure - p6) * ((h7 - h6) / (p7 - p6)) + h6
End If
If (evappressure >= p7) And (evappressure < p8) Then
evapexitenthalpy = (evappressure - p7) * ((h8 - h7) / (p8 - p7)) + h7
End If
If (evappressure >= p8) And (evappressure < p9) Then
evapexitenthalpy = (evappressure - p8) * ((h9 - h8) / (p9 - p8)) + h8
End If
If (evappressure >= p9) And (evappressure < p10) Then
evapexitenthalpy = (evappressure - p9) * ((h10 - h9) / (p10 - p9)) + h9
End If
If (evappressure >= p10) And (evappressure <= p11) Then
evapexitenthalpy = (evappressure - p10) * ((h11 - h10) / (p11 - p10)) + h10
End If
txtevapexitenthalpy.Text = Round(evapexitenthalpy, 5)
txttestenthalpy1 = h2
If (evappressure >= p1) And (evappressure < p2) Then
evapexitentropy = (evappressure - p1) * ((s2 - s1) / (p2 - p1)) + s1
End If
If (evappressure >= p2) And (evappressure < p3) Then
evapexitentropy = (evappressure - p2) * ((s3 - s2) / (p3 - p2)) + s2
End If
If (evappressure >= p3) And (evappressure < p4) Then
evapexitentropy = (evappressure - p3) * ((s4 - s3) / (p4 - p3)) + s3
End If
If (evappressure >= p4) And (evappressure < p5) Then
evapexitentropy = (evappressure - p4) * ((s5 - s4) / (p5 - p4)) + s4
End If
If (evappressure >= p5) And (evappressure < p6) Then
evapexitentropy = (evappressure - p5) * ((s6 - s5) / (p6 - p5)) + s5
End If
If (evappressure >= p6) And (evappressure < p7) Then
evapexitentropy = (evappressure - p6) * ((s7 - s6) / (p7 - p6)) + s6
End If
If (evappressure >= p7) And (evappressure < p8) Then
evapexitentropy = (evappressure - p7) * ((s8 - s7) / (p8 - p7)) + s7
End If
If (evappressure >= p8) And (evappressure < p9) Then
evapexitentropy = (evappressure - p8) * ((s9 - s8) / (p9 - p8)) + s8
End If
```


Appendix B: (Continued)

```
If (evappressure >= p9) And (evappressure < p10) Then
evapexitentropy = (evappressure - p9) * ((s10 - s9) / (p10 - p9)) + s9
End If
If (evappressure >= p10) And (evappressure <= p11) Then
evapexitentropy = (evappressure - p10) * ((s11 - s10) / (p11 - p10)) + s10
End If
txtevapexitentropy.Text = Round(evapexitentropy, 5)
txttestentropy1 = s4
compexitentropy = evapexitentropy
txtcompexitentropy.Text = Round(compexitentropy, 5)
p21 = 100
p22 = 104
p23 = 108
p24 = 112
p25 = 116
p26 = 120
p27 = 124
p28 = 128
p29 = 132
p210 = 136
p211 = 140
Tsat21 = 79.159
Tsat22 = 81.561
Tsat23 = 83.894
Tsat24 = 86.164
Tsat25 = 88.373
Tsat26 = 90.526
Tsat27 = 92.625
Tsat28 = 94.674
Tsat29 = 96.675
Tsat210 = 98.632
Tsat211 = 100.55
h21 = 1140.33482740819 * compexitentropy ^ 2 - 396.658048826921 * compexitentropy
+ 148.543589272253
h22 = 1116.79531031847 * compexitentropy ^ 2 - 374.742307050553 * compexitentropy
+ 143.863072320317
h23 = 1140.53734263777 * compexitentropy ^ 2 - 391.945459033649 * compexitentropy
+ 147.259853282843
h24 = 1244.42484858632 * compexitentropy ^ 2 - 475.137371935914 * compexitentropy
+ 164.224679495585
h25 = 1104.91427125036 * compexitentropy ^ 2 - 357.304208273241 * compexitentropy
+ 139.675233637429
```

Appendix B: (Continued)

$$h26 = 1164.58516219258 * \text{compexitentropy}^2 - 404.524050813997 * \text{compexitentropy} + 149.305123171225$$

$$h27 = 1113.95974990725 * \text{compexitentropy}^2 - 360.490942444008 * \text{compexitentropy} + 140.051997716919$$

$$h28 = 993.009925991296 * \text{compexitentropy}^2 - 258.119517517082 * \text{compexitentropy} + 118.690310440396$$

$$h29 = 1102.44195953011 * \text{compexitentropy}^2 - 346.252324193361 * \text{compexitentropy} + 136.701072757343$$

$$h210 = 1185.92752987146 * \text{compexitentropy}^2 - 413.446234645956 * \text{compexitentropy} + 150.482425772728$$

$$h211 = 1113.86845897138 * \text{compexitentropy}^2 - 351.641910220986 * \text{compexitentropy} + 137.510255260159$$

condenserpressure = Val(txtcondenserpressure.Text)

If (condenserpressure < p21) Or (condenserpressure > p211) Then

MsgBox "condenser pressure is out of range"

End If

If (condenserpressure >= p21) And (condenserpressure < p22) Then

$$\text{compexitenthalpy} = (\text{condenserpressure} - p21) * ((h22 - h21) / (p22 - p21)) + h21$$

End If

If (condenserpressure >= p22) And (condenserpressure < p23) Then

$$\text{compexitenthalpy} = (\text{condenserpressure} - p22) * ((h23 - h22) / (p23 - p22)) + h22$$

End If

If (condenserpressure >= p23) And (condenserpressure < p24) Then

$$\text{compexitenthalpy} = (\text{condenserpressure} - p23) * ((h24 - h23) / (p24 - p23)) + h23$$

End If

If (condenserpressure >= p24) And (condenserpressure < p25) Then

$$\text{compexitenthalpy} = (\text{condenserpressure} - p24) * ((h25 - h24) / (p25 - p24)) + h24$$

End If

If (condenserpressure >= p25) And (condenserpressure < p26) Then

$$\text{compexitenthalpy} = (\text{condenserpressure} - p25) * ((h26 - h25) / (p26 - p25)) + h25$$

End If

If (condenserpressure >= p26) And (condenserpressure < p27) Then

$$\text{compexitenthalpy} = (\text{condenserpressure} - p26) * ((h27 - h26) / (p27 - p26)) + h26$$

End If

If (condenserpressure >= p27) And (condenserpressure < p28) Then

$$\text{compexitenthalpy} = (\text{condenserpressure} - p27) * ((h28 - h27) / (p28 - p27)) + h27$$

End If

If (condenserpressure >= p28) And (condenserpressure < p29) Then

$$\text{compexitenthalpy} = (\text{condenserpressure} - p28) * ((h29 - h28) / (p29 - p28)) + h28$$

End If

If (condenserpressure >= p29) And (condenserpressure < p210) Then

$$\text{compexitenthalpy} = (\text{condenserpressure} - p29) * ((h210 - h29) / (p210 - p29)) + h29$$

End If

Appendix B: (Continued)

```
If (condenserpressure >= p210) And (condenserpressure <= p211) Then
compexitenthalpy = (condenserpressure - p210) * ((h211 - h210) / (p211 - p210)) + h210
End If
txtcompexitenthalpy.Text = Round(compexitenthalpy, 5)
txttestenthalpy2.Text = h24
hsatvap1 = 177.65
hsatvap2 = 177.94
hsatvap3 = 178.21
hsatvap4 = 178.48
hsatvap5 = 178.73
hsatvap6 = 178.98
hsatvap7 = 179.22
hsatvap8 = 179.44
hsatvap9 = 179.66
hsatvap10 = 179.88
hsatvap11 = 180.08
hsatLiq1 = 101.64
hsatLiq2 = 102.46
hsatLiq3 = 103.27
hsatLiq4 = 104.05
hsatLiq5 = 104.81
hsatLiq6 = 105.56
hsatLiq7 = 106.29
hsatLiq8 = 107.01
hsatLiq9 = 107.71
hsatLiq10 = 108.4
hsatLiq11 = 109.08
x = Val(txtquality3b.Text)
If (x < 0) Or (x > 0.3) Then
MsgBox "Quality at point 3b is out of range"
End If
h31 = hsatLiq1 + x * (hsatvap1 - hsatLiq1)
h32 = hsatLiq2 + x * (hsatvap2 - hsatLiq2)
h33 = hsatLiq3 + x * (hsatvap3 - hsatLiq3)
h34 = hsatLiq4 + x * (hsatvap4 - hsatLiq4)
h35 = hsatLiq5 + x * (hsatvap5 - hsatLiq5)
h36 = hsatLiq6 + x * (hsatvap6 - hsatLiq6)
h37 = hsatLiq7 + x * (hsatvap7 - hsatLiq7)
h38 = hsatLiq8 + x * (hsatvap8 - hsatLiq8)
h39 = hsatLiq9 + x * (hsatvap9 - hsatLiq9)
h310 = hsatLiq10 + x * (hsatvap10 - hsatLiq10)
h311 = hsatLiq11 + x * (hsatvap11 - hsatLiq11)
If (condenserpressure >= p21) And (condenserpressure < p22) Then
```

Appendix B: (Continued)

```
enthalpy3b = (condenserpressure - p21) * ((h32 - h31) / (p22 - p21)) + h31
End If
If (condenserpressure >= p22) And (condenserpressure < p23) Then
enthalpy3b = (condenserpressure - p22) * ((h33 - h32) / (p23 - p22)) + h32
End If
If (condenserpressure >= p23) And (condenserpressure < p24) Then
enthalpy3b = (condenserpressure - p23) * ((h34 - h33) / (p24 - p23)) + h33
End If
If (condenserpressure >= p24) And (condenserpressure < p25) Then
enthalpy3b = (condenserpressure - p24) * ((h35 - h34) / (p25 - p24)) + h34
End If
If (condenserpressure >= p25) And (condenserpressure < p26) Then
enthalpy3b = (condenserpressure - p25) * ((h36 - h35) / (p26 - p25)) + h35
End If
If (condenserpressure >= p26) And (condenserpressure < p27) Then
enthalpy3b = (condenserpressure - p26) * ((h37 - h36) / (p27 - p26)) + h36
End If
If (condenserpressure >= p27) And (condenserpressure < p28) Then
enthalpy3b = (condenserpressure - p27) * ((h38 - h37) / (p28 - p27)) + h37
End If
If (condenserpressure >= p28) And (condenserpressure < p29) Then
enthalpy3b = (condenserpressure - p28) * ((h39 - h38) / (p29 - p28)) + h38
End If
If (condenserpressure >= p29) And (condenserpressure < p210) Then
enthalpy3b = (condenserpressure - p29) * ((h310 - h39) / (p210 - p29)) + h39
End If
If (condenserpressure >= p210) And (condenserpressure <= p211) Then
enthalpy3b = (condenserpressure - p210) * ((h311 - h310) / (p211 - p210)) + h310
End If
txtenthalpy3b.Text = enthalpy3b
txttestenthalpy3b.Text = h32
If (condenserpressure > p21) And (condenserpressure < p22) Then
txtlowpressure.Text = p21
End If
If (condenserpressure > p21) And (condenserpressure < p22) Then
txthighpressure.Text = p22
End If
If (condenserpressure > p22) And (condenserpressure < p23) Then
txtlowpressure.Text = p22
End If
If (condenserpressure > p22) And (condenserpressure < p23) Then
txthighpressure.Text = p23
End If
```

Appendix B: (Continued)

If (condenserpressure > p23) And (condenserpressure < p24) Then
txtlowpressure.Text = p23
End If
If (condenserpressure > p23) And (condenserpressure < p24) Then
txthighpressure.Text = p24
End If
If (condenserpressure > p24) And (condenserpressure < p25) Then
txtlowpressure.Text = p24
End If
If (condenserpressure > p24) And (condenserpressure < p25) Then
txthighpressure.Text = p25
End If
If (condenserpressure > p25) And (condenserpressure < p26) Then
txtlowpressure.Text = p25
End If
If (condenserpressure > p25) And (condenserpressure < p26) Then
txthighpressure.Text = p26
End If
If (condenserpressure > p26) And (condenserpressure < p27) Then
txtlowpressure.Text = p26
End If
If (condenserpressure > p26) And (condenserpressure < p27) Then
txthighpressure.Text = p27
End If
If (condenserpressure > p27) And (condenserpressure < p28) Then
txtlowpressure.Text = p27
End If
If (condenserpressure > p27) And (condenserpressure < p28) Then
txthighpressure.Text = p28
End If
If (condenserpressure > p28) And (condenserpressure < p29) Then
txtlowpressure.Text = p28
End If
If (condenserpressure > p28) And (condenserpressure < p29) Then
txthighpressure.Text = p29
End If
If (condenserpressure > p29) And (condenserpressure < p210) Then
txtlowpressure.Text = p29
End If
If (condenserpressure > p29) And (condenserpressure < p210) Then
txthighpressure.Text = p210
End If
If (condenserpressure > p210) And (condenserpressure < p211) Then

Appendix B: (Continued)

```
txtlowpressure.Text = p210
End If
If (condenserpressure > p210) And (condenserpressure < p211) Then
txthighpressure.Text = p211
End If
If (condenserpressure = p21) Then
txtlowpressure.Text = p21
End If
If (condenserpressure = p21) Then
txthighpressure.Text = p21
End If
If (condenserpressure = p22) Then
txtlowpressure.Text = p22
End If
If (condenserpressure = p22) Then
txthighpressure.Text = p22
End If
If (condenserpressure = p23) Then
txtlowpressure.Text = p23
End If
If (condenserpressure = p23) Then
txthighpressure.Text = p23
End If
If (condenserpressure = p24) Then
txtlowpressure.Text = p24
End If
If (condenserpressure = p24) Then
txthighpressure.Text = p24
End If
If (condenserpressure = p25) Then
txtlowpressure.Text = p25
End If
If (condenserpressure = p25) Then
txthighpressure.Text = p25
End If
If (condenserpressure = p26) Then
txtlowpressure.Text = p26
End If
If (condenserpressure = p26) Then
txthighpressure.Text = p26
End If
If (condenserpressure = p27) Then
txtlowpressure.Text = p27
```

Appendix B: (Continued)

```
End If
If (condenserpressure = p27) Then
txthighpressure.Text = p27
End If
If (condenserpressure = p28) Then
txtlowpressure.Text = p28
End If
If (condenserpressure = p28) Then
txthighpressure.Text = p28
End If
If (condenserpressure = p29) Then
txtlowpressure.Text = p29
End If
If (condenserpressure = p29) Then
txthighpressure.Text = p29
End If
If (condenserpressure = p210) Then
txtlowpressure.Text = p210
End If
If (condenserpressure = p210) Then
txthighpressure.Text = p210
End If
If (condenserpressure = p211) Then
txtlowpressure.Text = p211
End If
If (condenserpressure = p211) Then
txthighpressure.Text = p211
End If
If (txtlowpressure.Text = p21) Then
txtlowsaturationtemp.Text = Tsat21
End If
If (txtlowpressure.Text = p22) Then
txtlowsaturationtemp.Text = Tsat22
End If
If (txtlowpressure.Text = p23) Then
txtlowsaturationtemp.Text = Tsat23
End If
If (txtlowpressure.Text = p24) Then
txtlowsaturationtemp.Text = Tsat24
End If
If (txtlowpressure.Text = p25) Then
txtlowsaturationtemp.Text = Tsat25
End If
```

Appendix B: (Continued)

```
If (txtlowpressure.Text = p26) Then
txtlowsaturationtemp.Text = Tsat26
End If
If (txtlowpressure.Text = p27) Then
txtlowsaturationtemp.Text = Tsat27
End If
If (txtlowpressure.Text = p28) Then
txtlowsaturationtemp.Text = Tsat28
End If
If (txtlowpressure.Text = p29) Then
txtlowsaturationtemp.Text = Tsat29
End If
If (txtlowpressure.Text = p210) Then
txtlowsaturationtemp.Text = Tsat210
End If
If (txtlowpressure.Text = p211) Then
txtlowsaturationtemp.Text = Tsat211
End If
If (txthighpressure.Text = p21) Then
txthighsaturationtemp.Text = Tsat21
End If
If (txthighpressure.Text = p22) Then
txthighsaturationtemp.Text = Tsat22
End If
If (txthighpressure.Text = p23) Then
txthighsaturationtemp.Text = Tsat23
End If
If (txthighpressure.Text = p24) Then
txthighsaturationtemp.Text = Tsat24
End If
If (txthighpressure.Text = p25) Then
txthighsaturationtemp.Text = Tsat25
End If
If (txthighpressure.Text = p26) Then
txthighsaturationtemp.Text = Tsat26
End If
If (txthighpressure.Text = p27) Then
txthighsaturationtemp.Text = Tsat27
End If
If (txthighpressure.Text = p28) Then
txthighsaturationtemp.Text = Tsat28
End If
If (txthighpressure.Text = p29) Then
```


Appendix B: (Continued)

```
txthighsaturationtemp.Text = Tsat29
End If
If (txthighpressure.Text = p210) Then
txthighsaturationtemp.Text = Tsat210
End If
If (txthighpressure.Text = p211) Then
txthighsaturationtemp.Text = Tsat211
End If
txtTsathighminus30.Text = txthighsaturationtemp.Text - 30
temp3a = Val(txttemp3a.Text)
lowsaturationtemp = txtlowsaturationtemp.Text
If (temp3a < txtTsathighminus30.Text) Or (temp3a > lowsaturationtemp) Then
MsgBox "Temperature at point 3a is out of range for given pressure"
End If
enthalpy21 = (2.49559427061286E-04) * temp3a ^ 2 + (0.301660442186451) * temp3a
+ 76.1968840437323
enthalpy22 = (2.55102040815913E-04) * temp3a ^ 2 + (0.300870019546351) * temp3a
+ 76.2257559012309
enthalpy23 = (2.63612459980855E-04) * temp3a ^ 2 + (0.299653384463703) * temp3a
+ 76.2696376882216
enthalpy24 = (2.6709232314559E-04) * temp3a ^ 2 + (0.299079853967074) * temp3a +
76.293514322721
enthalpy25 = (2.75604678251717E-04) * temp3a ^ 2 + (0.297786734286484) * temp3a
+ 76.342762029641
enthalpy26 = (2.78250632621102E-04) * temp3a ^ 2 + (0.29735641243981) * temp3a +
76.3610240995769
enthalpy27 = (2.84649418547112E-04) * temp3a ^ 2 + (0.296270772039061) * temp3a
+ 76.4063482714235
enthalpy28 = (2.96088924200077E-04) * temp3a ^ 2 + (0.294413241412689) * temp3a
+ 76.4812482760129
enthalpy29 = (3.0060355056083E-04) * temp3a ^ 2 + (0.293615414540774) * temp3a +
76.516363731521
enthalpy210 = (3.06069694449462E-04) * temp3a ^ 2 + (0.29261717250391) * temp3a
+ 76.5616714129494
enthalpy211 = (3.19055537065793E-04) * temp3a ^ 2 + (0.290347455828256) * temp3a
+ 76.6595686734113
If (condenserpressure >= p21) And (condenserpressure < p22) Then
reheatexitenthalpy = (condenserpressure - p21) * ((enthalpy22 - enthalpy21) / (p22 -
p21)) + enthalpy21
End If
If (condenserpressure >= p22) And (condenserpressure < p23) Then
reheatexitenthalpy = (condenserpressure - p22) * ((enthalpy23 - enthalpy22) / (p23 -
p22)) + enthalpy22
```

Appendix B: (Continued)

End If

If (condenserpressure >= p23) And (condenserpressure < p24) Then

reheatexitenthalpy = (condenserpressure - p23) * ((enthalpy24 - enthalpy23) / (p24 - p23)) + enthalpy23

End If

If (condenserpressure >= p24) And (condenserpressure < p25) Then

reheatexitenthalpy = (condenserpressure - p24) * ((enthalpy25 - enthalpy24) / (p25 - p24)) + enthalpy24

End If

If (condenserpressure >= p25) And (condenserpressure < p26) Then

reheatexitenthalpy = (condenserpressure - p25) * ((enthalpy26 - enthalpy25) / (p26 - p25)) + enthalpy25

End If

If (condenserpressure >= p26) And (condenserpressure < p27) Then

reheatexitenthalpy = (condenserpressure - p26) * ((enthalpy27 - enthalpy26) / (p27 - p26)) + enthalpy26

End If

If (condenserpressure >= p27) And (condenserpressure < p28) Then

reheatexitenthalpy = (condenserpressure - p27) * ((enthalpy28 - enthalpy27) / (p28 - p27)) + enthalpy27

End If

If (condenserpressure >= p28) And (condenserpressure < p29) Then

reheatexitenthalpy = (condenserpressure - p28) * ((enthalpy29 - enthalpy28) / (p29 - p28)) + enthalpy28

End If

If (condenserpressure >= p29) And (condenserpressure < p210) Then

reheatexitenthalpy = (condenserpressure - p29) * ((enthalpy210 - enthalpy29) / (p210 - p29)) + enthalpy29

End If

If (condenserpressure >= p210) And (condenserpressure <= p211) Then

reheatexitenthalpy = (condenserpressure - p210) * ((enthalpy211 - enthalpy210) / (p211 - p210)) + enthalpy210

End If

txtreheatexitenthalpy.Text = reheatexitenthalpy

txttestenthalpy3a.Text = enthalpy27

Qevap = Val(txtQevap.Text)

reheatfactor = Val(txtreheatfactor.Text)

Qreheat = reheatfactor * Qevap

txtQreheat.Text = Round(Qreheat, 5)

enthalpy3 = (enthalpy3b * Qevap * compexitenthalpy - enthalpy3b * Qevap * reheatexitenthalpy - enthalpy3b * Qreheat * evapexitenthalpy + reheatexitenthalpy * Qreheat * evapexitenthalpy) / (Qevap * compexitenthalpy - Qevap * reheatexitenthalpy - Qreheat * enthalpy3b + Qreheat * reheatexitenthalpy)

Appendix B: (Continued)

```
txtenthalpy3.Text = enthalpy3
enthalpy4 = enthalpy3
mref = Qevap / (evapexitenthalpy - enthalpy4)
txtmref.Text = mref
mreheat = Qreheat / (compexitenthalpy - reheatexitenthalpy)
txtmreheat.Text = mreheat
m3b = mref - mreheat
txtm3b.Text = m3b
Win = mref * (compexitenthalpy - evapexitenthalpy)
txtWin.Text = Win
COPreheat = (Qevap - Qreheat) / Win
txtCOPreheat.Text = Round(COPreheat, 5)
COP = Qevap / Win
txtCOP.Text = Round(COP, 5)
End Sub
```

Appendix B: (Continued)

Parallel Hot Gas Refrigerant Cycle

Form1						
evap pressure (psia)	Temperature at point 1 (F)	Condenser Pressure (psia)	quality at 3b	Temperature at point 3a (F)	reheat factor	Q evaporator (Btu/h)
<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>
evap pressure rounded	high pressure (evap exit)	High Saturation Temperature (evap exit)	Eval 1	low pressure (reheat exit)	high pressure (reheat exit)	
<input type="text"/>	<input type="text"/>	<input type="text"/>		<input type="text"/>	<input type="text"/>	
	low pressure (evap exit)	Low Saturation Temperature (evap exit)	Low Saturation Temperature plus 10	Low Saturation Temperature (reheat exit)	High Saturation Temperature (reheat exit)	
	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>	
Evaporator Exit Enthalpy (State 1)	test enthalpy 1 (Btu/lbm)	Evaporator Exit Entropy (State 1)	test entropy 1 (Btu/lbmR)	Reheat Exit Enthalpy (State 3a)	Tsat high minus 30	
<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>	
Compressor Exit Enthalpy (State 2)	test enthalpy 2	test entropy 2	mass flow rate (3b)	Enthalpy at State 3	test enthalpy 3a	
<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>	
Condenser Exit Enthalpy (State 3b)	test enthalpy 3b	mass flow rate through reheat (lbm/h)	mass flow rate of refrigerant (lbm/h)	COP	Q reheat (Btu/h)	
<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>	
				Work Input (Btu/h)	COP reheat	
				<input type="text"/>	<input type="text"/>	

Figure B.3 Form for Parallel Hot Gas Refrigerant Cycle Program

Appendix B: (Continued)

Two-Phase Mixture Refrigerant Cycle

```
Private Sub cmdevaluate_Click()  
evappressure = Val(txtevappressure.Text)  
evappressurerounded = Round(evappressure, 0)  
txtevappressurerounded = evappressurerounded  
T1 = Val(txttemp1.Text)  
If (evappressure >= evappressurerounded) Then  
txtlowp.Text = evappressurerounded  
End If  
If (evappressure > evappressurerounded) Then  
txthighp.Text = evappressurerounded + 1  
End If  
If (evappressure <= evappressurerounded) Then  
txthighp.Text = evappressurerounded  
End If  
If (evappressure < evappressurerounded) Then  
txtlowp.Text = evappressurerounded - 1  
End If  
p1 = 45  
p2 = 46  
p3 = 47  
p4 = 48  
p5 = 49  
p6 = 50  
p7 = 51  
p8 = 52  
p9 = 53  
p10 = 54  
p11 = 55  
Tsat1 = 34.897  
Tsat2 = 36.006  
Tsat3 = 37.098  
Tsat4 = 38.171  
Tsat5 = 39.227  
Tsat6 = 40.267  
Tsat7 = 41.292  
Tsat8 = 42.301  
Tsat9 = 43.295  
Tsat10 = 44.275  
Tsat11 = 45.241  
h1 = (-8.55494591860406E-05) * T1 ^ 2 + (0.221803709111986) * T1 +  
(164.251339451151)
```

Appendix B: (Continued)

$h2 = (-1.04453973165164E-04) * T1 ^ 2 + (0.224294986034621) * T1 + 164.0994957513$
 $h3 = (-1.70924683359885E-04) * T1 ^ 2 + (0.230698866947877) * T1 + (163.867146163839)$
 $h4 = (-9.21268362219507E-05) * T1 ^ 2 + (0.224999664161904) * T1 + (163.884920315296)$
 $h5 = (-1.45660586440499E-04) * T1 ^ 2 + (0.230612768300361) * T1 + (163.660593095293)$
 $h6 = (-8.21518737410543E-05) * T1 ^ 2 + (0.225745230044991) * T1 + (163.669848007973)$
 $h7 = (-1.12163878597471E-04) * T1 ^ 2 + (0.229275983250786) * T1 + (163.49043486943)$
 $h8 = (-1.41086913643562E-04) * T1 ^ 2 + (0.232871991082073) * T1 + (163.305535881264)$
 $h9 = (-7.64892314037979E-05) * T1 ^ 2 + (0.227560040562432) * T1 + (163.330623395824)$
 $h10 = (-9.60906859432953E-05) * T1 ^ 2 + (0.230211818547635) * T1 + (163.168495290491)$
 $h11 = (-1.18784814304718E-04) * T1 ^ 2 + (0.233243428018642) * T1 + (162.994242756115)$
 $s1 = (-6.0803711907087E-07) * T1 ^ 2 + (4.79110474060067E-04) * T1 + (0.396595113510306)$
 $s2 = (-6.25417075461598E-07) * T1 ^ 2 + (4.82232881662558E-04) * T1 + (0.395942612567429)$
 $s3 = (-6.3338833347637E-07) * T1 ^ 2 + (4.84618356885164E-04) * T1 + (0.395313013521716)$
 $s4 = (-5.72841618529107E-07) * T1 ^ 2 + (4.81048526321251E-04) * T1 + (0.394819557534999)$
 $s5 = (-7.03779334892962E-07) * T1 ^ 2 + (4.94256622175797E-04) * T1 + (0.393967537270816)$
 $s6 = (-6.7611950432811E-07) * T1 ^ 2 + (4.93501395964934E-04) * T1 + (0.393429028182591)$
 $s7 = (-6.58521754043351E-07) * T1 ^ 2 + (4.93457265859189E-04) * T1 + (0.392885330772991)$
 $s8 = (-6.47501380623972E-07) * T1 ^ 2 + (4.94182527420029E-04) * T1 + (0.3923266406261)$
 $s9 = (-5.96537599012459E-07) * T1 ^ 2 + (4.91008706960247E-04) * T1 + (0.391868567094144)$
 $s10 = (-7.13188032908096E-07) * T1 ^ 2 + (5.04008662543318E-04) * T1 + (0.391027694896258)$
 $s11 = (-6.79822001331543E-07) * T1 ^ 2 + (5.02477295152442E-04) * T1 + (0.390542594477737)$

If (txtevappressure.Text < p1) Or (txtevappressure.Text > p11) Then

Appendix B: (Continued)

```
MsgBox "evaporator pressure is out of range"  
End If  
If (txtlowp.Text = p1) Then  
  txtlowsattemp.Text = Tsat1  
End If  
If (txtlowp.Text = p2) Then  
  txtlowsattemp.Text = Tsat2  
End If  
If (txtlowp.Text = p3) Then  
  txtlowsattemp.Text = Tsat3  
End If  
If (txtlowp.Text = p4) Then  
  txtlowsattemp.Text = Tsat4  
End If  
If (txtlowp.Text = p5) Then  
  txtlowsattemp.Text = Tsat5  
End If  
If (txtlowp.Text = p6) Then  
  txtlowsattemp.Text = Tsat6  
End If  
If (txtlowp.Text = p7) Then  
  txtlowsattemp.Text = Tsat7  
End If  
If (txtlowp.Text = p8) Then  
  txtlowsattemp.Text = Tsat8  
End If  
If (txtlowp.Text = p9) Then  
  txtlowsattemp.Text = Tsat9  
End If  
If (txtlowp.Text = p10) Then  
  txtlowsattemp.Text = Tsat10  
End If  
If (txtlowp.Text = p11) Then  
  txtlowsattemp.Text = Tsat11  
End If  
If (txthighp.Text = p1) Then  
  txthighsattemp.Text = Tsat1  
End If  
If (txthighp.Text = p2) Then  
  txthighsattemp.Text = Tsat2  
End If  
If (txthighp.Text = p3) Then  
  txthighsattemp.Text = Tsat3
```

Appendix B: (Continued)

```
End If
If (txthighp.Text = p4) Then
txthighsattmp.Text = Tsat4
End If
If (txthighp.Text = p5) Then
txthighsattmp.Text = Tsat5
End If
If (txthighp.Text = p6) Then
txthighsattmp.Text = Tsat6
End If
If (txthighp.Text = p7) Then
txthighsattmp.Text = Tsat7
End If
If (txthighp.Text = p8) Then
txthighsattmp.Text = Tsat8
End If
If (txthighp.Text = p9) Then
txthighsattmp.Text = Tsat9
End If
If (txthighp.Text = p10) Then
txthighsattmp.Text = Tsat10
End If
If (txthighp.Text = p11) Then
txthighsattmp.Text = Tsat11
End If
txtlowsattmpplus10.Text = txtlowsattmp.Text + 10
T1 = Val(txttemp1.Text)
If (T1 < txthighsattmp.Text) Or (T1 > txtlowsattmpplus10.Text) Then
MsgBox "Temperature at point 1 is out of range for given pressure"
End If
If (evappressure >= p1) And (evappressure < p2) Then
evapexitenthalpy = (evappressure - p1) * ((h2 - h1) / (p2 - p1)) + h1
End If
If (evappressure >= p2) And (evappressure < p3) Then
evapexitenthalpy = (evappressure - p2) * ((h3 - h2) / (p3 - p2)) + h2
End If
If (evappressure >= p3) And (evappressure < p4) Then
evapexitenthalpy = (evappressure - p3) * ((h4 - h3) / (p4 - p3)) + h3
End If
If (evappressure >= p4) And (evappressure < p5) Then
evapexitenthalpy = (evappressure - p4) * ((h5 - h4) / (p5 - p4)) + h4
End If
If (evappressure >= p5) And (evappressure < p6) Then
```


Appendix B: (Continued)

```
evapexitenthalpy = (evappressure - p5) * ((h6 - h5) / (p6 - p5)) + h5
End If
If (evappressure >= p6) And (evappressure < p7) Then
evapexitenthalpy = (evappressure - p6) * ((h7 - h6) / (p7 - p6)) + h6
End If
If (evappressure >= p7) And (evappressure < p8) Then
evapexitenthalpy = (evappressure - p7) * ((h8 - h7) / (p8 - p7)) + h7
End If
If (evappressure >= p8) And (evappressure < p9) Then
evapexitenthalpy = (evappressure - p8) * ((h9 - h8) / (p9 - p8)) + h8
End If
If (evappressure >= p9) And (evappressure < p10) Then
evapexitenthalpy = (evappressure - p9) * ((h10 - h9) / (p10 - p9)) + h9
End If
If (evappressure >= p10) And (evappressure <= p11) Then
evapexitenthalpy = (evappressure - p10) * ((h11 - h10) / (p11 - p10)) + h10
End If
txtevapexitenthalpy.Text = Round(evapexitenthalpy, 5)
txttestenthalpy1 = h2
If (evappressure >= p1) And (evappressure < p2) Then
evapexitentropy = (evappressure - p1) * ((s2 - s1) / (p2 - p1)) + s1
End If
If (evappressure >= p2) And (evappressure < p3) Then
evapexitentropy = (evappressure - p2) * ((s3 - s2) / (p3 - p2)) + s2
End If
If (evappressure >= p3) And (evappressure < p4) Then
evapexitentropy = (evappressure - p3) * ((s4 - s3) / (p4 - p3)) + s3
End If
If (evappressure >= p4) And (evappressure < p5) Then
evapexitentropy = (evappressure - p4) * ((s5 - s4) / (p5 - p4)) + s4
End If
If (evappressure >= p5) And (evappressure < p6) Then
evapexitentropy = (evappressure - p5) * ((s6 - s5) / (p6 - p5)) + s5
End If
If (evappressure >= p6) And (evappressure < p7) Then
evapexitentropy = (evappressure - p6) * ((s7 - s6) / (p7 - p6)) + s6
End If
If (evappressure >= p7) And (evappressure < p8) Then
evapexitentropy = (evappressure - p7) * ((s8 - s7) / (p8 - p7)) + s7
End If
If (evappressure >= p8) And (evappressure < p9) Then
evapexitentropy = (evappressure - p8) * ((s9 - s8) / (p9 - p8)) + s8
End If
```

Appendix B: (Continued)

```
If (evappressure >= p9) And (evappressure < p10) Then
evapexitentropy = (evappressure - p9) * ((s10 - s9) / (p10 - p9)) + s9
End If
If (evappressure >= p10) And (evappressure <= p11) Then
evapexitentropy = (evappressure - p10) * ((s11 - s10) / (p11 - p10)) + s10
End If
txtevapexitentropy.Text = Round(evapexitentropy, 5)
txttestentropy1 = s4
compexitentropy = evapexitentropy
txtcompexitentropy.Text = Round(compexitentropy, 5)
p21 = 100
p22 = 104
p23 = 108
p24 = 112
p25 = 116
p26 = 120
p27 = 124
p28 = 128
p29 = 132
p210 = 136
p211 = 140
Tsat21 = 79.159
Tsat22 = 81.561
Tsat23 = 83.894
Tsat24 = 86.164
Tsat25 = 88.373
Tsat26 = 90.526
Tsat27 = 92.625
Tsat28 = 94.674
Tsat29 = 96.675
Tsat210 = 98.632
Tsat211 = 100.55
h21 = 1140.33482740819 * compexitentropy ^ 2 - 396.658048826921 * compexitentropy
+ 148.543589272253
h22 = 1116.79531031847 * compexitentropy ^ 2 - 374.742307050553 * compexitentropy
+ 143.863072320317
h23 = 1140.53734263777 * compexitentropy ^ 2 - 391.945459033649 * compexitentropy
+ 147.259853282843
h24 = 1244.42484858632 * compexitentropy ^ 2 - 475.137371935914 * compexitentropy
+ 164.224679495585
h25 = 1104.91427125036 * compexitentropy ^ 2 - 357.304208273241 * compexitentropy
+ 139.675233637429
```

Appendix B: (Continued)

$$h26 = 1164.58516219258 * \text{compexitentropy}^2 - 404.524050813997 * \text{compexitentropy} + 149.305123171225$$

$$h27 = 1113.95974990725 * \text{compexitentropy}^2 - 360.490942444008 * \text{compexitentropy} + 140.051997716919$$

$$h28 = 993.009925991296 * \text{compexitentropy}^2 - 258.119517517082 * \text{compexitentropy} + 118.690310440396$$

$$h29 = 1102.44195953011 * \text{compexitentropy}^2 - 346.252324193361 * \text{compexitentropy} + 136.701072757343$$

$$h210 = 1185.92752987146 * \text{compexitentropy}^2 - 413.446234645956 * \text{compexitentropy} + 150.482425772728$$

$$h211 = 1113.86845897138 * \text{compexitentropy}^2 - 351.641910220986 * \text{compexitentropy} + 137.510255260159$$

condenserpressure = Val(txtcondenserpressure.Text)

If (condenserpressure < p21) Or (condenserpressure > p211) Then

MsgBox "condenser pressure is out of range"

End If

If (condenserpressure >= p21) And (condenserpressure < p22) Then

$$\text{compexitenthalpy} = (\text{condenserpressure} - p21) * ((h22 - h21) / (p22 - p21)) + h21$$

End If

If (condenserpressure >= p22) And (condenserpressure < p23) Then

$$\text{compexitenthalpy} = (\text{condenserpressure} - p22) * ((h23 - h22) / (p23 - p22)) + h22$$

End If

If (condenserpressure >= p23) And (condenserpressure < p24) Then

$$\text{compexitenthalpy} = (\text{condenserpressure} - p23) * ((h24 - h23) / (p24 - p23)) + h23$$

End If

If (condenserpressure >= p24) And (condenserpressure < p25) Then

$$\text{compexitenthalpy} = (\text{condenserpressure} - p24) * ((h25 - h24) / (p25 - p24)) + h24$$

End If

If (condenserpressure >= p25) And (condenserpressure < p26) Then

$$\text{compexitenthalpy} = (\text{condenserpressure} - p25) * ((h26 - h25) / (p26 - p25)) + h25$$

End If

If (condenserpressure >= p26) And (condenserpressure < p27) Then

$$\text{compexitenthalpy} = (\text{condenserpressure} - p26) * ((h27 - h26) / (p27 - p26)) + h26$$

End If

If (condenserpressure >= p27) And (condenserpressure < p28) Then

$$\text{compexitenthalpy} = (\text{condenserpressure} - p27) * ((h28 - h27) / (p28 - p27)) + h27$$

End If

If (condenserpressure >= p28) And (condenserpressure < p29) Then

$$\text{compexitenthalpy} = (\text{condenserpressure} - p28) * ((h29 - h28) / (p29 - p28)) + h28$$

End If

If (condenserpressure >= p29) And (condenserpressure < p210) Then

$$\text{compexitenthalpy} = (\text{condenserpressure} - p29) * ((h210 - h29) / (p210 - p29)) + h29$$

End If

Appendix B: (Continued)

```
If (condenserpressure >= p210) And (condenserpressure <= p211) Then
compexitenthalpy = (condenserpressure - p210) * ((h211 - h210) / (p211 - p210)) + h210
End If
txtcompexitenthalpy.Text = Round(compexitenthalpy, 5)
txttestenthalpy2.Text = h24
hsatvap1 = 177.65
hsatvap2 = 177.94
hsatvap3 = 178.21
hsatvap4 = 178.48
hsatvap5 = 178.73
hsatvap6 = 178.98
hsatvap7 = 179.22
hsatvap8 = 179.44
hsatvap9 = 179.66
hsatvap10 = 179.88
hsatvap11 = 180.08
hsatLiq1 = 101.64
hsatLiq2 = 102.46
hsatLiq3 = 103.27
hsatLiq4 = 104.05
hsatLiq5 = 104.81
hsatLiq6 = 105.56
hsatLiq7 = 106.29
hsatLiq8 = 107.01
hsatLiq9 = 107.71
hsatLiq10 = 108.4
hsatLiq11 = 109.08
x = Val(txtquality3b.Text)
If (x < 0) Or (x > 0.3) Then
MsgBox "Quality at point 3b is out of range"
End If
h31 = hsatLiq1 + x * (hsatvap1 - hsatLiq1)
h32 = hsatLiq2 + x * (hsatvap2 - hsatLiq2)
h33 = hsatLiq3 + x * (hsatvap3 - hsatLiq3)
h34 = hsatLiq4 + x * (hsatvap4 - hsatLiq4)
h35 = hsatLiq5 + x * (hsatvap5 - hsatLiq5)
h36 = hsatLiq6 + x * (hsatvap6 - hsatLiq6)
h37 = hsatLiq7 + x * (hsatvap7 - hsatLiq7)
h38 = hsatLiq8 + x * (hsatvap8 - hsatLiq8)
h39 = hsatLiq9 + x * (hsatvap9 - hsatLiq9)
h310 = hsatLiq10 + x * (hsatvap10 - hsatLiq10)
h311 = hsatLiq11 + x * (hsatvap11 - hsatLiq11)
If (condenserpressure >= p21) And (condenserpressure < p22) Then
```

Appendix B: (Continued)

```
enthalpy3b = (condenserpressure - p21) * ((h32 - h31) / (p22 - p21)) + h31
End If
If (condenserpressure >= p22) And (condenserpressure < p23) Then
enthalpy3b = (condenserpressure - p22) * ((h33 - h32) / (p23 - p22)) + h32
End If
If (condenserpressure >= p23) And (condenserpressure < p24) Then
enthalpy3b = (condenserpressure - p23) * ((h34 - h33) / (p24 - p23)) + h33
End If
If (condenserpressure >= p24) And (condenserpressure < p25) Then
enthalpy3b = (condenserpressure - p24) * ((h35 - h34) / (p25 - p24)) + h34
End If
If (condenserpressure >= p25) And (condenserpressure < p26) Then
enthalpy3b = (condenserpressure - p25) * ((h36 - h35) / (p26 - p25)) + h35
End If
If (condenserpressure >= p26) And (condenserpressure < p27) Then
enthalpy3b = (condenserpressure - p26) * ((h37 - h36) / (p27 - p26)) + h36
End If
If (condenserpressure >= p27) And (condenserpressure < p28) Then
enthalpy3b = (condenserpressure - p27) * ((h38 - h37) / (p28 - p27)) + h37
End If
If (condenserpressure >= p28) And (condenserpressure < p29) Then
enthalpy3b = (condenserpressure - p28) * ((h39 - h38) / (p29 - p28)) + h38
End If
If (condenserpressure >= p29) And (condenserpressure < p210) Then
enthalpy3b = (condenserpressure - p29) * ((h310 - h39) / (p210 - p29)) + h39
End If
If (condenserpressure >= p210) And (condenserpressure <= p211) Then
enthalpy3b = (condenserpressure - p210) * ((h311 - h310) / (p211 - p210)) + h310
End If
txtenthalpy3b.Text = enthalpy3b
txttestenthalpy3b.Text = h32
If (condenserpressure > p21) And (condenserpressure < p22) Then
txtlowpressure.Text = p21
End If
If (condenserpressure > p21) And (condenserpressure < p22) Then
txthighpressure.Text = p22
End If
If (condenserpressure > p22) And (condenserpressure < p23) Then
txtlowpressure.Text = p22
End If
If (condenserpressure > p22) And (condenserpressure < p23) Then
txthighpressure.Text = p23
End If
```

Appendix B: (Continued)

If (condenserpressure > p23) And (condenserpressure < p24) Then
txtlowpressure.Text = p23
End If
If (condenserpressure > p23) And (condenserpressure < p24) Then
txthighpressure.Text = p24
End If
If (condenserpressure > p24) And (condenserpressure < p25) Then
txtlowpressure.Text = p24
End If
If (condenserpressure > p24) And (condenserpressure < p25) Then
txthighpressure.Text = p25
End If
If (condenserpressure > p25) And (condenserpressure < p26) Then
txtlowpressure.Text = p25
End If
If (condenserpressure > p25) And (condenserpressure < p26) Then
txthighpressure.Text = p26
End If
If (condenserpressure > p26) And (condenserpressure < p27) Then
txtlowpressure.Text = p26
End If
If (condenserpressure > p26) And (condenserpressure < p27) Then
txthighpressure.Text = p27
End If
If (condenserpressure > p27) And (condenserpressure < p28) Then
txtlowpressure.Text = p27
End If
If (condenserpressure > p27) And (condenserpressure < p28) Then
txthighpressure.Text = p28
End If
If (condenserpressure > p28) And (condenserpressure < p29) Then
txtlowpressure.Text = p28
End If
If (condenserpressure > p28) And (condenserpressure < p29) Then
txthighpressure.Text = p29
End If
If (condenserpressure > p29) And (condenserpressure < p210) Then
txtlowpressure.Text = p29
End If
If (condenserpressure > p29) And (condenserpressure < p210) Then
txthighpressure.Text = p210
End If
If (condenserpressure > p210) And (condenserpressure < p211) Then

Appendix B: (Continued)

```
txtlowpressure.Text = p210
End If
If (condenserpressure > p210) And (condenserpressure < p211) Then
txthighpressure.Text = p211
End If
If (condenserpressure = p21) Then
txtlowpressure.Text = p21
End If
If (condenserpressure = p21) Then
txthighpressure.Text = p21
End If
If (condenserpressure = p22) Then
txtlowpressure.Text = p22
End If
If (condenserpressure = p22) Then
txthighpressure.Text = p22
End If
If (condenserpressure = p23) Then
txtlowpressure.Text = p23
End If
If (condenserpressure = p23) Then
txthighpressure.Text = p23
End If
If (condenserpressure = p24) Then
txtlowpressure.Text = p24
End If
If (condenserpressure = p24) Then
txthighpressure.Text = p24
End If
If (condenserpressure = p25) Then
txtlowpressure.Text = p25
End If
If (condenserpressure = p25) Then
txthighpressure.Text = p25
End If
If (condenserpressure = p26) Then
txtlowpressure.Text = p26
End If
If (condenserpressure = p26) Then
txthighpressure.Text = p26
End If
If (condenserpressure = p27) Then
txtlowpressure.Text = p27
```

Appendix B: (Continued)

```
End If
If (condenserpressure = p27) Then
txthighpressure.Text = p27
End If
If (condenserpressure = p28) Then
txtlowpressure.Text = p28
End If
If (condenserpressure = p28) Then
txthighpressure.Text = p28
End If
If (condenserpressure = p29) Then
txtlowpressure.Text = p29
End If
If (condenserpressure = p29) Then
txthighpressure.Text = p29
End If
If (condenserpressure = p210) Then
txtlowpressure.Text = p210
End If
If (condenserpressure = p210) Then
txthighpressure.Text = p210
End If
If (condenserpressure = p211) Then
txtlowpressure.Text = p211
End If
If (condenserpressure = p211) Then
txthighpressure.Text = p211
End If
If (txtlowpressure.Text = p21) Then
txtlowsaturationtemp.Text = Tsat21
End If
If (txtlowpressure.Text = p22) Then
txtlowsaturationtemp.Text = Tsat22
End If
If (txtlowpressure.Text = p23) Then
txtlowsaturationtemp.Text = Tsat23
End If
If (txtlowpressure.Text = p24) Then
txtlowsaturationtemp.Text = Tsat24
End If
If (txtlowpressure.Text = p25) Then
txtlowsaturationtemp.Text = Tsat25
End If
```


Appendix B: (Continued)

```
If (txtlowpressure.Text = p26) Then
txtlowsaturationtemp.Text = Tsat26
End If
If (txtlowpressure.Text = p27) Then
txtlowsaturationtemp.Text = Tsat27
End If
If (txtlowpressure.Text = p28) Then
txtlowsaturationtemp.Text = Tsat28
End If
If (txtlowpressure.Text = p29) Then
txtlowsaturationtemp.Text = Tsat29
End If
If (txtlowpressure.Text = p210) Then
txtlowsaturationtemp.Text = Tsat210
End If
If (txtlowpressure.Text = p211) Then
txtlowsaturationtemp.Text = Tsat211
End If
If (txthighpressure.Text = p21) Then
txthighsaturationtemp.Text = Tsat21
End If
If (txthighpressure.Text = p22) Then
txthighsaturationtemp.Text = Tsat22
End If
If (txthighpressure.Text = p23) Then
txthighsaturationtemp.Text = Tsat23
End If
If (txthighpressure.Text = p24) Then
txthighsaturationtemp.Text = Tsat24
End If
If (txthighpressure.Text = p25) Then
txthighsaturationtemp.Text = Tsat25
End If
If (txthighpressure.Text = p26) Then
txthighsaturationtemp.Text = Tsat26
End If
If (txthighpressure.Text = p27) Then
txthighsaturationtemp.Text = Tsat27
End If
If (txthighpressure.Text = p28) Then
txthighsaturationtemp.Text = Tsat28
End If
If (txthighpressure.Text = p29) Then
```

Appendix B: (Continued)

```
txthighsaturationtemp.Text = Tsat29
End If
If (txthighpressure.Text = p210) Then
txthighsaturationtemp.Text = Tsat210
End If
If (txthighpressure.Text = p211) Then
txthighsaturationtemp.Text = Tsat211
End If
txtTsathighminus30.Text = txthighsaturationtemp.Text - 30
temp4a = Val(txttemp4a.Text)
lowsaturationtemp = txtlowsaturationtemp.Text
If (temp4a < txtTsathighminus30.Text) Or (temp4a > lowsaturationtemp) Then
MsgBox "Temperature at point 4a is out of range for given pressure"
End If
enthalpy21 = (2.49559427061286E-04) * temp4a ^ 2 + (0.301660442186451) * temp4a
+ 76.1968840437323
enthalpy22 = (2.55102040815913E-04) * temp4a ^ 2 + (0.300870019546351) * temp4a
+ 76.2257559012309
enthalpy23 = (2.63612459980855E-04) * temp4a ^ 2 + (0.299653384463703) * temp4a
+ 76.2696376882216
enthalpy24 = (2.6709232314559E-04) * temp4a ^ 2 + (0.299079853967074) * temp4a +
76.293514322721
enthalpy25 = (2.75604678251717E-04) * temp4a ^ 2 + (0.297786734286484) * temp4a
+ 76.342762029641
enthalpy26 = (2.78250632621102E-04) * temp4a ^ 2 + (0.29735641243981) * temp4a +
76.3610240995769
enthalpy27 = (2.84649418547112E-04) * temp4a ^ 2 + (0.296270772039061) * temp4a
+ 76.4063482714235
enthalpy28 = (2.96088924200077E-04) * temp4a ^ 2 + (0.294413241412689) * temp4a
+ 76.4812482760129
enthalpy29 = (3.0060355056083E-04) * temp4a ^ 2 + (0.293615414540774) * temp4a +
76.516363731521
enthalpy210 = (3.06069694449462E-04) * temp4a ^ 2 + (0.29261717250391) * temp4a
+ 76.5616714129494
enthalpy211 = (3.19055537065793E-04) * temp4a ^ 2 + (0.290347455828256) * temp4a
+ 76.6595686734113
If (condenserpressure >= p21) And (condenserpressure < p22) Then
reheatexitenthalpy = (condenserpressure - p21) * ((enthalpy22 - enthalpy21) / (p22 -
p21)) + enthalpy21
End If
If (condenserpressure >= p22) And (condenserpressure < p23) Then
reheatexitenthalpy = (condenserpressure - p22) * ((enthalpy23 - enthalpy22) / (p23 -
p22)) + enthalpy22
```

Appendix B: (Continued)

End If

If (condenserpressure >= p23) And (condenserpressure < p24) Then

reheatexitenthalpy = (condenserpressure - p23) * ((enthalpy24 - enthalpy23) / (p24 - p23)) + enthalpy23

End If

If (condenserpressure >= p24) And (condenserpressure < p25) Then

reheatexitenthalpy = (condenserpressure - p24) * ((enthalpy25 - enthalpy24) / (p25 - p24)) + enthalpy24

End If

If (condenserpressure >= p25) And (condenserpressure < p26) Then

reheatexitenthalpy = (condenserpressure - p25) * ((enthalpy26 - enthalpy25) / (p26 - p25)) + enthalpy25

End If

If (condenserpressure >= p26) And (condenserpressure < p27) Then

reheatexitenthalpy = (condenserpressure - p26) * ((enthalpy27 - enthalpy26) / (p27 - p26)) + enthalpy26

End If

If (condenserpressure >= p27) And (condenserpressure < p28) Then

reheatexitenthalpy = (condenserpressure - p27) * ((enthalpy28 - enthalpy27) / (p28 - p27)) + enthalpy27

End If

If (condenserpressure >= p28) And (condenserpressure < p29) Then

reheatexitenthalpy = (condenserpressure - p28) * ((enthalpy29 - enthalpy28) / (p29 - p28)) + enthalpy28

End If

If (condenserpressure >= p29) And (condenserpressure < p210) Then

reheatexitenthalpy = (condenserpressure - p29) * ((enthalpy210 - enthalpy29) / (p210 - p29)) + enthalpy29

End If

If (condenserpressure >= p210) And (condenserpressure <= p211) Then

reheatexitenthalpy = (condenserpressure - p210) * ((enthalpy211 - enthalpy210) / (p211 - p210)) + enthalpy210

End If

txtreheatexitenthalpy.Text = reheatexitenthalpy

txttestenthalpy4a.Text = enthalpy27

Qevap = Val(txtQevap.Text)

reheatfactor = Val(txtreheatfactor.Text)

Qreheat = reheatfactor * Qevap

txtQreheat.Text = Round(Qreheat, 5)

n3a = Val(txtpercentmass3a)

mreheat = Qreheat / (((compexitenthalpy * n3a + enthalpy3b) / (n3a + 1)) - reheatexitenthalpy)

txtmreheat.Text = mreheat

Appendix B: (Continued)

```
enthalpy3 = (compexitenthalpy * n3a + enthalpy3b) / (n3a + 1)
txtenthalpy3.Text = enthalpy3
m4b = (reheatexitenthalpy * mreheat + Qevap - evapexitenthalpy * mreheat) /
(evapexitenthalpy - enthalpy3)
txtm4b.Text = Round(m4b, 5)
enthalpy4 = evapexitenthalpy - (Qevap / (mreheat + m4b))
txtenthalpy4.Text = enthalpy4
mref = Qevap / (evapexitenthalpy - enthalpy4)
txtmref.Text = mref
m3b = mref / (n3a + 1)
txtm3b.Text = m3b
m3a = mref - m3b
txtm3a.Text = m3a
Win = mref * (compexitenthalpy - evapexitenthalpy)
txtWin.Text = Win
COPreheat = (Qevap - Qreheat) / Win
txtCOPreheat.Text = Round(COPreheat, 5)
COP = Qevap / Win
txtCOP.Text = Round(COP, 5)
End Sub
```

Appendix B: (Continued)

Two-Phase Mixture Refrigerant Cycle

Form1						
evap pressure (psia)	Temperature at point 1 (F)	Condenser Pressure (psia)	quality at 3b	Temperature at point 4a (F)	reheat factor	Q evaporator (Btu/h)
<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>
percent mass flow rate through 3a (not a percent)	high pressure (evap exit)	High Saturation Temperature (evap exit)	Eval 1	low pressure (reheat exit)	high pressure (reheat exit)	
<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>	
evap pressure rounded	low pressure (evap exit)	Low Saturation Temperature (evap exit)	Low Saturation Temperature plus 10	Low Saturation Temperature (reheat exit)	High Saturation Temperature (reheat exit)	
<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>	
Evaporator Exit Enthalpy (State 1)	test enthalpy 1 (Btu/lbm)	Evaporator Exit Entropy (State 1)	test entropy 1 (Btu/lbmR)	Reheat Exit Enthalpy (State 4a)	Tsat high minus 30	
<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>	
Compressor Exit Enthalpy (State 2)	test enthalpy 2	test entropy 2	mass flow rate (3b)	Enthalpy at State 4	test enthalpy 4a	
<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>	
Condenser Exit Enthalpy (State 3b)	test enthalpy 3b	mass flow rate through reheat (lbm/h)	mass flow rate of refrigerant (lbm/h)	COP	Q reheat (Btu/h)	
<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>	
Enthalpy at State 3	mass flow rate (4b)	mass flow rate (3a)		Work Input (Btu/h)	COP reheat	
<input type="text"/>	<input type="text"/>	<input type="text"/>		<input type="text"/>	<input type="text"/>	

Figure B.4 Form for Two-Phase Mixture Refrigerant Cycle Program

Appendix C: Sample Interpolation Equations (R134a)

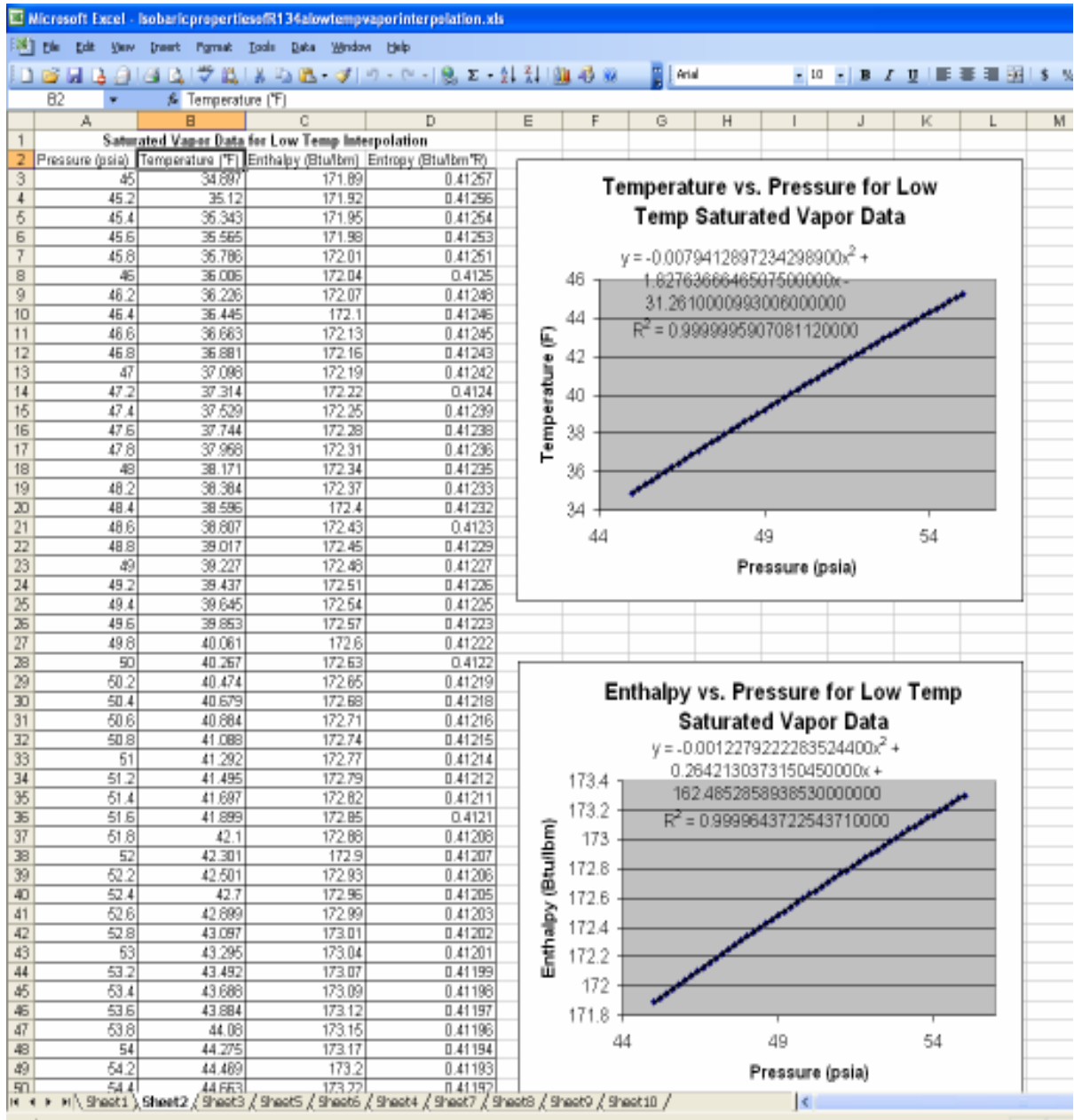


Figure C.1 Temperature and Enthalpy vs. Pressure Equations for R134a

Appendix C: (Continued)

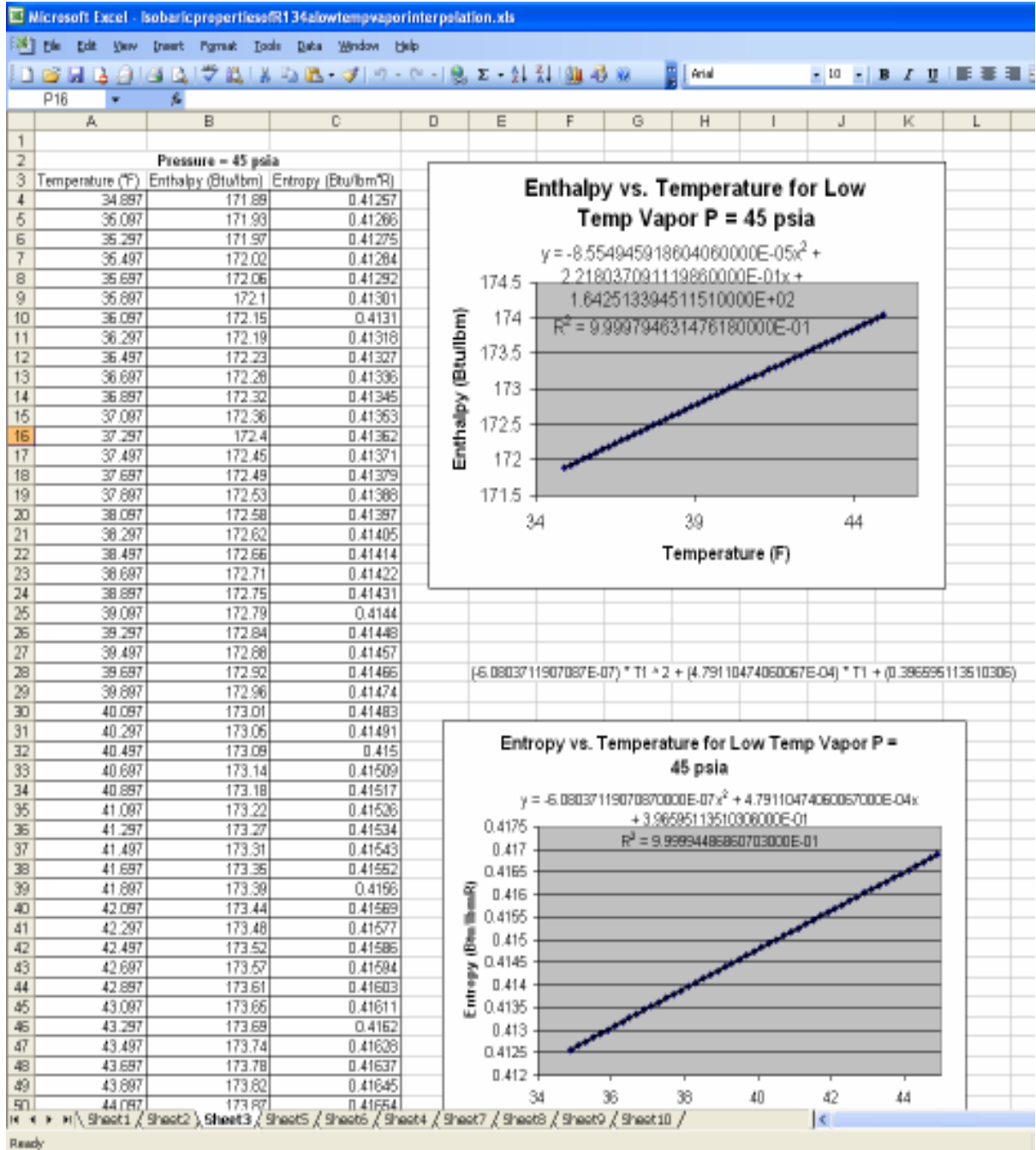


Figure C.2 Enthalpy and Entropy vs. Temperature Equations for R134a