PERFORMANCE STUDY OF A SOLAR REFRIGERATOR USING A MIXTURE OF PROPANE AND BUTANE WITH DIFFERENT RATIOS AS A REPLACEMENT TO R-134a

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This Thesis was Submitted in Partial fulfillment of the Requirements for the Master's Degree of Science in Mechanical Engineering

Faculty of Graduate Studies

The University of Jordan

December, 2008

This Thesis (Performance Study of a Solar Refrigerator Using a Mixture of Propane and Butane with Different Ratios as a Replacement to R-134a) was Successfully Defended and Approved on ...12/11/2002...

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DEDICATION

To ---

My Late Father

My Dearest Mother

This is Just a Part of Gratitude

With

Love and Respect

ACKNOWLEDGEMENT

I want to express my deep thanks and gratitude to my supervisor Prof. Mahmoud Hammad for his support, encouragement and valuable guidance.

Also I am deeply grateful for the Energy Center staff and also for the Mechanical Engineering labs staff for their assistance and help during this work.

I would like to pass my deep thanks, respect and appreciation to my family for their support and care, especially my beloved mother.

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NOMENCLATURE

COP : Coefficient of Performance

Cp : Specific heat, (kJ/kg.ºC)

h : Enthalpy, (kJ/kg)

I_{ref} : Refrigerator consumed current, (Ampere)

I_s : Solar current, (Ampere)

M : Mass, (kg)

m : Molecular weight (kg/kmol)

$\dot{m}$: Mass flow rate, (kg/s)

mf : Mass fraction

n : Number of moles

P : Pressure, (MPa)

P_b : Butane pressure

P_p : Propane pressure

P_{pb} : Butane partial pressure

P_{pp} : Propane partial pressure

Q_{ref} : Refrigeration capacity, (Watt)

q_{ref} : Refrigeration effect, (kJ/kg)

T : Temperature, (ºC)

t : Time, (sec)

V_{inv} : Inverter output voltage, (Volt)

V_n : Nominal voltage, (Volt)

w : Compression work, (kJ/kg)

W : Power consumption, (Watt)

y : Mole fraction

Subscripts

A: Air

a: Ambient

al: Aluminum

b: Butane

c: Condenser

co: Container

e: Evaporator

p: Propane

w: Water

Abbreviations

ASHRAE: American Society of Heating, Refrigerating and Air-conditioning Engineers

CFCs: Chlorofluorocarbons

GWP: Global Warming Potential

HCFCs: Hydrochlorofluorocarbons

HCs: Hydrocarbons

HFCs: Hydrofluorocarbons

ODP: Ozone Depletion Potential

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ABSTRACT

A domestic refrigerator was tested by using different mixtures of propane and butane without changing or modifying the refrigerator components using both electrical and solar power. The objective of this work was to check which LPG charge composition will give the optimum performance for the refrigerator as compared to R-134a.

Six compositions were tested. It was found that the best COP was at 40g charge (57% of the original R-134a quantity), this charge quantity was taken to be the best charge quantity for all refrigerant compositions used in this work. Various performance curves were presented for a range of evaporating and condensing temperatures.

Comparing power consumption for various compositions, it was found that a power saving of 7% was obtained in the case of LPG as compared to R-134a, and that power consumption increased to 6%, 9% and 13% in the case of 50% propane / 50% butane, 70% propane / 30% butane and pure propane, respectively.

In average and compared to COP of R-134a at constant Tc, the LPG gave a COP about 6% higher, but for 50% propane and 50% butane it was 10% lower than that for R-134a. Also for 70% propane and 30% butane it was 19% lower than that in R-134a, then the lowest COP was in the case of propane which gave 32% lower than R-134a.

Results showed that the net performance when using solar power was very close to that for electrical power, provided that the power is maintained in the period of no solar intensity available.

The results showed that the most attractive alternative refrigerant to R-134a is the LPG. All other experimented mixtures can be used as a replacement for R-134a, but their performance is not as attractive as that of LPG.

Chapter One

INTRODUCTION

1.1 Foreword

Natural ice was harvested, distributed and used in both commercial and home applications in the mid-1800s to refrigerate food. The idea that cold could be produced by the forced evaporation of a volatile liquid under reduced pressure had been previously pursued by William Cullen in the eighteenth century.

Chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs) which were produced first during the thirties of the 20th century have many suitable properties, for example, nonflammability, low toxicity and material compatibility that have led to their common widespread use by both consumers and industries around the world, especially as refrigerants in air conditioning and refrigerating systems.

Solar energy is available most of the year period in the countries of solar belts, such as Jordan with high intensity in some seasons. This led to increase the researches to get the benefit of this effective renewable energy source. That is because solar energy is clean, mobile energy source and effective for many applications; one of these applications is refrigeration system.

1.2 Refrigerants and Environment

Results from many researches show that ozone layer is being depleted by the chlorine atom in the CFCs and HCFCs. The general consensus for the cause of this event is that free chlorine radicals remove ozone from the atmosphere, and later, chlorine atoms continue to convert more ozone to oxygen. The presence of chlorine in the stratosphere is the result of the migration of chlorine containing chemicals. The CFCs and HCFCs are a large class of chemicals that behave in this manner.

Since the discovery of the depletion of the earth's ozone layer caused mainly by CFCs and HCFCs and as a result of the 1992 United Nations Environment Program meeting, the phase out of CFC-11 and CFC-12, used mainly in conventional refrigeration and air conditioning equipment, was expected by 1996. The thermophysical properties of HFC-134a are very similar to those of CFC-12 and are also non-toxic and environmentally safe refrigerant; the American Household Appliances Manufacturers have recommended HFC-134a as a potential replacement for CFC-12 in domestic refrigerators. However, while the ozone depletion potential (ODP) of HFC-134a is zero, the global warming potential (GWP) is extremely high. This refrigerant is highly expensive. Properties, ODP and GWP for some refrigerants are listed in Table 1.1. For this reason, it is expected that the production and use of HFC-134a may be terminated in the near future.

Table 1.1. Properties, ODPs and GWPs for some refrigerants

Designation	**Chemical Formula**	**Ozone Depletion Potential**[1]	**Global Warming Potential**[2]
Ozone Depleting & Global Warming Chemicals			
CFC-11	CCl_3F	1	3,400
CFC-12	CCl_2F_2	0.89	7,100
CFC-13	$CClF_3$		13,000
CFC-113	$C_2F_3Cl_3$	0.81	4,500
CFC-114	$C_2F_4Cl_2$	0.69	7,000
CFC-115	$C_2F_5Cl_1$	0.32	7,000
Halon-1211	CF_2ClBr	2.2-3.5	
Halon-1301	CF_3Br	8-16	4,900
Halon-2402	$C_2F_4Br_2$	5-6.2	
carbon tetrachloride	CCl_4	1.13	1,300
methyl chloroform	CH_3Ccl_3	0.14	
nitrous oxide	N_2O		270
Ozone Depleting & Global Warming Chemicals - Class 2			
HCFC-22	CHF_2Cl	0.048	1,600
HCFC-123	$C_2HF_3Cl_2$	0.017	90
HCFC-124	C_2HF_4Cl	0.019	440
HCFC-125	C_2HF_5	0.000	3,400
HCFC-141b	$C_2H_3FCl_2$	0.090	580
HCFC-142b	$C_2H_3F_2Cl$	0.054	1800
Global Warming, non-Ozone Depleting Chemicals			
carbon dioxide	CO_2	0	1
methane	CH_4	0	11
HFC-125	CHF_2CF_3	0	90
HFC-134a	CFH_2CF_3	0	1,000
HFC-152a	CH_3CHF_2	0	2,400
perfluorobutane	C_4F_{10}	0	5,500
perfluoropentane	C_5F_{12}	0	5,500
perfluorohexane	C_6F_{14}	0	5,100
perfluorotributylamine	$N(C_4F_9)_3$	0	4,300

1 - relative to R11

2 - relative to CO_2

1.3 Alternative Refrigerants

Alternative refrigerants are found to replace the CFCs because it is harmful to environment. Such alternative refrigerants should posses good thermodynamic and physical properties, high chemical and thermal stability, low toxicity, good miscibility with lubricants, compatibility with materials, less expensive and low flammability with no environmental side effect.

The main requirement which decide whether a substance is applicable as a refrigerant in a certain temperature range or not, is the thermodynamic properties, as will be discussed later. If the thermodynamic properties meet the requirements, the other characters must be taken into consideration and at least to be acceptable as close as possible.

Several alternative refrigerants have been evaluated, HFC-134a was considered as the substitute to R-12 due to its physical and thermodynamic properties similar to those of R-12 and benign environmental effect of ozone. But HFC-134a contains fluorine; these fluorinated substances do not damage the ozone layer, yet have very significant greenhouse warming effects. Nevertheless, several disadvantages of this fluid in connection with its refrigeration oil and remaining substances from manufacturing are evident.

Hydrocarbons (HCs) are an environmentally sound alternative for CFCs and HFCs, the HCs as a refrigerant have been known and used since the beginning of this century. The development of the inert CFCs in the 1930s put the HC technology in the background; CFCs have been applied since then in numerous refrigeration equipments. There is currently little information on the application of hydrocarbon as refrigerant in the refrigerator without modification the refrigerator components.

Global Warming Potentials for propane (R-290), butane (R-600) and R-134a; relative to 1 for CO_2; are 20, 20 and 1000 respectively. This shows the benefits that the environment will get when R-290 and R-600 were used as alternative refrigerants.

The absence of chlorine atoms from hydrocarbons results in no ozone depletion potential. In addition, global warming potential is very low for hydrocarbons, owing to the higher latent heat of hydrocarbons compared with that of R-12 (Hammad and Alsaad, 1999).

Advantages of HCs include the following:

1. No ozone depletion effect.
2. Low global warming effects, which is the most important point.
3. No second conversion, such as the one hanging over all halogen compounds (e.g. HFC-134a), is required in the long run.
4. Energy saving up to over 10% over CFCs and HFC-134a.
5. They are available and easy to produce all over the world with an acceptable cost.
6. The HCs technology is relatively simple to adopt compared to synthetic chemicals, since the same oil and compressor type are used there. This technology will be the future driving force.

The only disadvantage of using HCs as refrigerants is their flammability, but since the mass contents of the HCs mixture in a refrigerator is very small, the risk of an explosion is minimal if happened.

Figures 1.1 and 1.2 show the typical components and a detailed T-s diagram for the vapor compression cycle.

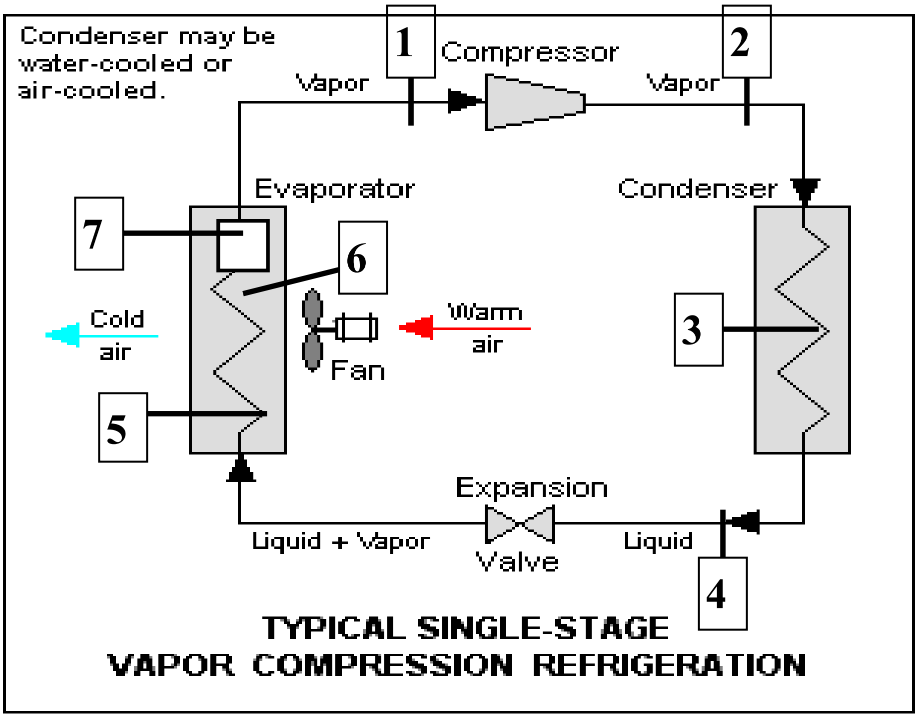

Figure 1.1. Typical vapor compression cycle

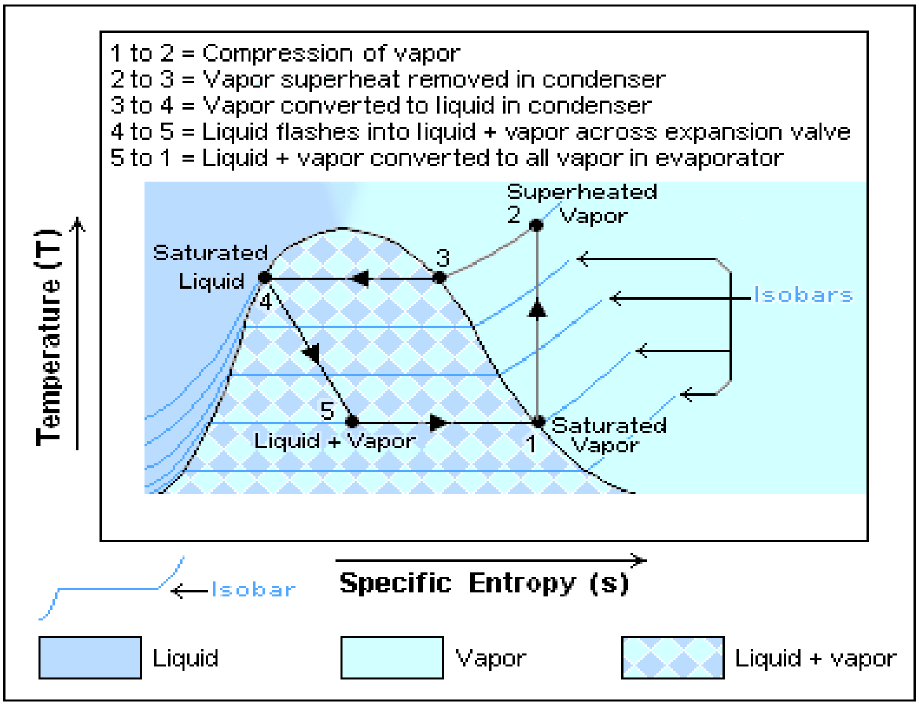

Figure 1.2. Detailed T-s diagram for typical vapor compression cycle

Chapter Two

LITERATURE SURVEY

As of 1989, CFC-based refrigerants were banned via the Montreal Protocol due to the negative effects they have on the ozone layer. The Montreal Protocol was ratified by most CFC producing and consuming nations in Montreal, Quebec, Canada in September 1987. Greenpeace objected to the ratification because the Montreal Protocol instead ratified the use of HFC refrigeration, which are not ozone-depleting but are still powerful global warming gases. Searching for an alternative for home use refrigeration, dkk Scharfenstein (Germany) developed a propane-based CFC as well as an HFC-free refrigerator in 1992 with assistance from Greenpeace. All the previous developments were a direct result of a scientific report released in June 1974.

Scientists and researchers are searching for an environmentally-benign refrigerant for the domestic refrigerator and freezer. Hydrocarbons especially propane, butane and isobutene are proposed as an environmentally-benign refrigerant. Hydrocarbons are free from ozone depletion potential and have negligible global warming potential.

Lee and Su (2002) conducted an experimental study on the use of isobutene as refrigerant in domestic refrigerator. The performance was comparable with those of CFC-12 and HCFC-22 was used as refrigerant.

Akash and Said (2003) studied the performance of LPG from local market (30% propane, 55% n-butane and 15% isobutene by mass) as an alternative refrigerant for CFC-12 in domestic refrigerator with masses of 50g, 80g and 100g. The result showed that a mass charge of 80g gave the best performance.

Devotta et al., (2001) selected HFC-134a, HC-290, R-407C, R-410A, and three blends of HFC-32, HFC-134a and HFC-125 and found that HFC-134a offers the highest COP, but its capacity is the lowest and requires much larger compressors. The characteristics of HC-290 are very close to those of HCFC-22, and compressors require very little modification. Therefore, HC-290 is a potential candidate provided the risk concerns are mitigated as had been accomplished for refrigerators.

Sekhar et al., (2004) investigated an experiment to retrofit a CFC-12 system to eco-friendly system using of HCFC-134a / HC-290 / HC-600a without changing the mineral oil and found that the new mixture could reduce the energy consumption by 4 to 11% and improve the actual COP by 3 to 8% from that of CFC-12.

Sekhar et al., (2005) also investigated refrigerant mixture of HCFC-134a/HC in two low temperature system (domestic refrigerator and deep freezer) and two medium temperature system (vending machine and walk in cooler) and found that the HCFC-134a/HC mixture that contains 9% HC blend (by weight) has better performance resulting in 10-30% and 5-15% less energy consumption (than CFC) in medium and low temperature system respectively.

Driessen et al. (1994) divided their work into two parts. In the first part, they made theoretical analysis for determining the most suitable HC refrigerants to replace R-12 in domestic refrigeration system which showed the performance compared to R-12, and the main impacts of each HC refrigerant on the current R-12 refrigeration systems. In the second part, they made experimental evaluation of the performance of R-600a and a mixture of R-290/R-600a (60/40) as a substitute to R-12 in domestic refrigeration systems which resulted in that R-600a performance could be slightly increased by adjusting the capillary tube. For R-290/R-600a, the necessity of optimizing the evaporator and the capillary tube was evident.

Vollmer and Findessen (1994) calculated the thermodynamic and thermophysical properties of the binary mixture propane/isobutane. They found that the mixture was an acceptable substitute for R-12 apart from the flammability and only minor changes on the refrigerant circuit were necessary to use the mixture in an originally R-12 designed refrigerator with an advantage of higher energetic efficiency compared to R-12.

Richardson and Butterworth (1995) conducted experiments to investigate the performance of hydrocarbon refrigerants in a hermetic vapor compression system, despite their potential flammability. They demonstrated that hydrocarbons could safely be used as a refrigerant in hermetic vapor compression systems, and achieve better COPs than R-12 under similar conditions and design. Mixtures of 50% propane and 50% isobutane have similar saturation characteristics compared with R-12, but COP would seem to improve as the proportion of propane were increased.

Kanbour et al. (1997) did an experimental study to compare the performance of propane (R-290) as a substitute refrigerant for R-12. They concluded that R-290 could be used as a cheap alternative refrigerant in simple domestic refrigerator provided that the charge and capillary tube are varied to yield the same performance as R-12.

Lorentzen (1994) studied the use of natural compounds as refrigerants. He concluded that suitable natural compounds exist to satisfy the requirements for all common applications of refrigeration and heat pumps, three refrigerants would be sufficient to satisfy the normal requirement, which are ammonia, propane and carbon dioxide. They are cheaper and with less power consumption, some changes in current design and practice would certainly be required.

James and Missenden (1992) investigated the use of propane as a substitute to R-12 in domestic refrigerators. Different comparative experiments were done and the most important were the safety tests, which include the leakage inside a refrigerator cabinet and ignition, the leakage near a flame such as a cooker or boiler and the risk in the event of a fire. They concluded that the leakage inside a refrigerator cabinet and ignition was relatively easy to overcome either by placing the evaporator between the insulation and the inner cabinet skin or by placing the light switch and thermostat outside the refrigerated enclosure, in any event the consequences were not catastrophic. To overcome the second problem they advised the user not to place the refrigerator next to the cooker or boiler so in the case of any leakage, the concentration of propane in the room could not by any means reach its lower explosion limit. The fire test showed that the greater hazard in a fire event was the toxic fumes from the cabinet and its insulation, on the other hand propane did not noticeably add to the configuration nor escape catastrophically. The products of combustion from propane were much less dangerous than those of R-12 which were intensely toxic products.

Rivis and Bidone (1994) studied theoretically the performance of a complete range of isobutane and propane mixture in a freezer. They compared it with the two pure gases, and to other traditional refrigerants (R-12 and R-134a) within the evaporation range from -10 to -35°C, and condensation range from 45 to 55°C. They concluded that there is no ideal mixture of isobutane and propane that will provide the best results for all the necessary parameters. Mixtures of approximately (40/60) and (50/50) are the best candidates for replacing R-12 and R-134a, these mixtures have characteristics similar to R-12 and R-134a (mainly pressure and volumetric capacity). However, the temperature glide is at maximum value if the (50/50) mixture is selected, another negative point for the (50/50) mixture is its low coefficient of performance. It was found that from COP point view, the best candidate is pure isobutane.

Habash (1994) studied experimentally the performance of a domestic refrigerator using a Liquefied Petroleum Gas (LPG) as a refrigerant and compared it with that of R-12; he showed that lower evaporating temperatures were obtained using LPG than those of using R-12 for the same condensing temperature, lower refrigeration capacity and slightly lower power consumption, without any change in the design.

Hammad and Alsaad (1999) investigated experimentally the performance of R-12 domestic refrigerator, by replacing R-12 with four mixtures of different ratios of propane, butane and isobutane. The domestic refrigerator was charged and tested with each of the four hydrocarbon mixtures. Their work showed that the hydrocarbon mixture with 50% propane, 38.3% butane and 11.7% isobutane is the most suitable alternative refrigerant with the best performance of all hydrocarbon mixtures investigated, and nearest to R-12 performance.

Ritter and Colbourne (1998) discussed the technique of Quantitative Risk Assessment with respect to its application to flammable refrigerants, specifically hydrocarbons. They used background risks as a basis for comparison of calculated frequencies of fires and fatalities in respect to the use of flammable refrigerants, and constructed to the actual performance of hydrocarbon charged freezer in a fire situation. They concluded that the use of hydrocarbon refrigerants does not significantly increase the potential for fires or fatalities.

All of the previous work was concentrated on finding a suitable alternative refrigerant for R-12 mainly for many equipment running on the same original power source (electrical power).

In this study, the use of a propane and butane mixtures with different ratios to replace R-134a in a domestic refrigerator work on electrical and solar power will be experimentally tested and studied. The performance curves for these new refrigerants are going to be investigated and a comparison of them with those of the traditional R-134a is going to be achieved. There will be no change or modification on the refrigerator components.

Chapter Three

ALTERNATIVE REFRIGERANT PROPERTIES

3.1 Introduction

While it is playing a major role in ozone depletion, it has been proven that R-12 is an ideal refrigerant. The search for an alternative concentrated on thermodynamic, physical and chemical similarity to that of R-12. Notable among these is the hydrofluorocarbon R-134a which is used as a replacement for R-12.

Hydrocarbons offers a cheap, readily available and environmentally acceptable alternative to CFCs, some standard refrigerant designations are listed in Table 3.1 below.

Table 3.1. ASHRAE standard designation of refrigerant (ASHRAE Standard 34-1992, Handbook of Fundamentals, 1993)

Refrigerant No.	**Chemical Name**	**Chemical Formula**
R-12	Dichlorodifluoromethane	$CCl_2 F_2$
R-22	Chlorodifluoromethane	$CHClF_2$
R-134a	Tetrafluoroethane	CF_3CH_2F
R-290	Propane	C_3H_8
R-600	Butane	C_4H_{10}
R-600a	Isobutane	C_4H_{10}

In order to find an alternative for a refrigerant, one must compare the thermodynamic properties of the alternative to that of a chosen Freon, also the processes of condensation and evaporation occurring in the refrigerator heat exchangers demand that the saturated vapor pressure versus temperature for any Freon and its alternative should be close to each other.

Any alternative refrigerants must satisfy some requirements; such as chemical stability under conditions of use is the most important characteristic, safety codes may require a non-flammable refrigerant and low toxicity for application, cost, availability, compatibility with compressor lubricants and materials with which equipment is constructed and also environmentally acceptable. In the next paragraphs the properties and characteristics of the original refrigerant and the alternative (HCs) will be discussed.

3.2 Thermodynamic properties

Thermodynamic properties are the most important properties in selecting refrigerants for any application, the thermodynamic properties of R-12, propane and butane are listed in Table 3.2.

Table 3.2. Thermodynamic properties of refrigerants (ASHRAE Handbook of Fundamentals, 1993)

Properties	Unit	R-134a	R-290	R-600	R-290/R-600 Mixture (50% / 50%)
Boiling point at atmospheric pressure	ºC	-26.3	-42.07	-0.5	-23.8
Freezing point	ºC	-103.3	-187.7	-138.5	-164.8
Critical temperature	ºC	101.1	97	152	121
Critical pressure	MPa	4.06	4.25	3.79	4.05
Latent heat of vaporization	kJ/kg	217.2	423.3	386	404.6

3.2.1 Boiling point

The boiling point of the refrigerant must be low at atmospheric pressure for an efficient refrigerant. Otherwise, it requires operating the compressor at high vacuums, which reduces the capacity of the system. Table 3.2 shows that propane has the lowest boiling point while butane has relatively higher boiling point compared to R-134a. Therefore, the mixture of propane and butane has a boiling temperature close to the boiling point of R-134a.

3.2.2 Freezing point

Also a low freezing temperature of the refrigerant is required because the refrigerant must not solidify during normal operating conditions. The refrigerant must have a freezing point well below the operating evaporator temperatures. All refrigerants in Table 3.2 have a low freezing temperature.

3.2.3 Critical temperature and pressure

The critical temperature of the refrigerant used should be higher than the temperature occurring in the condenser for easy condensation of the refrigerant vapor. Referring to Table 3.2, the critical temperatures of the refrigerants are well above the temperatures occurring in the condenser. Also the critical pressure for the refrigerants is much higher than any pressure experienced in the system.

3.2.4 Latent heat of vaporization

A refrigerant with high latent heat will absorb more heat per kg of refrigerant than a refrigerant with a lower latent heat (higher refrigerating effect). Thus, if a refrigerant with a high latent heat of vaporization is used; lower refrigerant charge mass and/or smaller compressor, condenser and evaporator can be used. As shown in Table 3.2, the latent heat of vaporization for propane and butane are comparatively higher than that of R-134a. The mixture latent heat of vaporization is larger than that of R-134a, this means a lower charge mass of mixture can be used than that of R-134a.

3.2.5 Evaporating and condensing pressure

The operating pressure is one of the major considerations in the selection of refrigerants for the economical working of the refrigeration system. Pressures in the evaporator and condenser should be positive and above atmospheric to prevent air from leaking into the refrigeration system. Also the pressures should not be too high above atmospheric, otherwise expansive piping and equipment will be required.

Also a low compression ratio results in low power consumption. Therefore, the refrigerant with the lowest compression ratios (condenser to evaporator pressure ratio) is desirable.

3.2.6 Coefficient of performance (COP)

Many researchers state that propane and butane have a COP near or slightly high to that of R-134a, so the mixture when used as alternative refrigerant in domestic refrigerators will have higher good values of COP than R-134a under the same operating conditions.

3.2.7 Compressor discharge temperature

A high temperature at the compressor exit could result in oil breakdown, causing excessive wear or reduced life of the discharge valves and compressor overheating. For these reasons, a low discharge temperature is desirable; both propane and butane have slightly higher discharge temperature than R-134a.

3.3 Physical properties

3.3.1 Specific heat

The quantity of heat required to raise 1 kg of a substance 1˚C is the specific heat. Low specific heat of liquid tends to increase the subcooling of liquid (in this case low amount of heat rejection in the condenser is sufficient to lower the liquid temperature considerably), on the other hand, high specific heat of vapor tends to decrease the superheating of vapor. As shown in Table 3.3, both propane and butane have higher specific heats than R-134a.

3.3.2 Thermal conductivity

Thermal conductivity of refrigerant in both liquid and gaseous states must be high, this is desirable for a high heat transfer coefficient, thus more efficient heat transfer in the evaporator and the condenser. As shown in Table 3.3, that propane and butane have considerable high thermal conductivities in both liquid and gaseous states compared to R-134a.

3.3.3 Viscosity

Viscosity is a measure of flowing quality. It is desirable to use refrigerants with low viscosities in both liquid and vapor states for higher heat transfer in the evaporator and condenser, low pumping power and small pressure drops during flow. As shown in Table 3.3, propane and butane have considerably lower viscosity in both liquid and vapor states than R-134a.

Table 3.3. Physical properties of R-134a, propane and butane, at 25ºC and 1 atm.

Properties	Unit	R-134a		R-290		R-600	
		Liquid	Vapor	Liquid	Vapor	Liquid	Vapor
Specific heat	kJ/kg.K	1.42	1.01	2.71	2.03	-	1.72
Thermal conductivity	mw/m.K	81.9	14.06	91.2	19.9	-	17.5
Viscosity	µPa.s	212.9	12.2	111.9	9.116	-	7.9

3.3.4 Specific volume

The low specific volume of the refrigerant at the suction into the compressor is always considerable, because it reduces the size of the compressor for the same refrigeration capacity. Propane and butane have relatively high suction specific volume than R-134a.

3.3.5 Leak tendency and detection:

The leakage of refrigerants should be low; a dense fluid has fewer tendencies to leak than lower density fluid. Also, the detection of a leak should be easy; the greatest drawback of fluorocarbons is the fact that they are odorless. This, sometimes, results in a complete loss of costly gas from leaks without being detected. On the other hand, hydrocarbons leak can be easily detected by their distinct odor.

3.4 Chemical properties

3.4.1 Miscibility with oil

Lubricant oils used in refrigeration have special requirement beyond those of other industrial lubricants. The oil is in contact with the refrigerant and to a greater or lesser extent circulates with it. The oil must be able to circulate freely throughout the system and it must remain fluid at low temperatures so as not to accumulate in the evaporator. Miscibility of oil and the refrigerant is the ability of the refrigerant to mix with oil. Therefore, it is an important characteristic in the selection of any refrigerant. It is desirable to have good miscibility and solubility of the refrigerant/lubricant combination in order to assure efficient oil return and to avoid heat transfer degradation. Another important requirement is that the viscosity of the working fluid is adequate for hydrodynamic lubrication of compressor bearings.

The mineral oils used with CFC refrigerants can be used with propane/butane mixtures. In the case of replacing R-134a by hydrocarbons one must change the original R-134a oil, which is polyolester by mineral oil to avoid any side reactions between the refrigerant and the lubricant oil.

3.4.2 Toxicity

A refrigerant with non-toxic nature is one of the most important properties that make it desirable. The refrigerant may leak from the refrigeration system so the toxic refrigerant has the effect of a poison, which may cause the injury to the human body or death depending upon its percentage in air. The standards classified refrigerants according to the hazard involved in their use. Group A1 refrigerants are the least hazardous, group B3 the most hazardous, in which propane and butane are classified as either non-toxic (group A3) or slightly more toxic than R-134a.

3.4.3 Flammability

Refrigerant should not have any danger of explosion in the presence of air or in association with lubricating oil; R-134a is a non-flammable refrigerant. Propane and butane are hydrocarbons; the most important issue regarding hydrocarbons as a refrigerant is their flammability. Whilst this is an emotive subject, it should be recommended that millions of tons of hydrocarbons are used safely throughout the world every year for cooking, heating and powering vehicles.

In a domestic refrigeration system, the mass content of propane and butane is very small, and then the risk of an explosion does not exist. Thus, if the refrigerant, which is less than 200g, leaks from a refrigerator in the room or the kitchen, an explosion would be impossible. The lower explosion limits of propane and butane in air are 2.3 %, 1.9 %, by volume respectively. To generate a flammable mixture in a room with around 16 m^3, 670g of propane or 810g of butane is necessary, which is a large quantity in comparison to that contained in a refrigerator. Also a portion of the mixture will not be released by the compressor oil in a short period of time.

3.4.4 Water and solubility

Refrigeration system is a closed circuit, once a contaminant enters the system it will stay there until servicing can remove it. Water is the most undesirable contaminant in refrigeration systems, because it may be cause rusting, corrosion, copper plating, refrigerant decomposition, valve damage, oil sludging and general deterioration of the system. If water solubility in the refrigerant is exceeded at low temperatures, ice may formed in the capillary tube and restrict the flow of refrigerant or stop it.

Solubility of water in the refrigerant should be as low as possible, the solubility of water in fluorocarbons in general is low (Solubility of Water in HFC-134a is 0.11% at 25 °C), also water is not soluble in hydrocarbons, and they do not absorb any moisture from air.

3.4.5 Compatibility

The selected refrigerant decides the material to be used for the construction of the refrigeration system. But if a refrigerant is seceding to replace another used refrigerant, then it should have similar effect on the materials as the replaced refrigerant in order to be a successful alternative, without changing the system materials.

Refrigerant must be non-corrosive in order to use more common materials, refrigerants must be chemically inert with their system construction materials as well as they must also remain inert in the presence of water and air, Freon refrigerants are non-corrosive with all metals, but they become acidic with refrigerants as they are readily attacked by acids. Propane and butane, as well as most of the hydrocarbons are non-corrosive with all metals even in the presence of water and air.

3.5 Side properties

One should mention other factors that are not critical in deciding the use of refrigerant, but are fairly important in comparing between alternative refrigerants. These factors are:

3.5.1 Cost

Cost is a critical factor when comparing between alternative refrigerants that have similar performance, especially for developing countries. Propane and butane mixture is a kind of hydrocarbons, which is cheap in general, when compared with other refrigerants especially when the mixture put into mass-production, or when use LPG.

3.5.2 Availability

Availability of the refrigerant used in the refrigeration applications is an important factor, propane and butane can be produced from petroleum natural gas, which is available in enormous quantities, and therefore provides an attractive alternative for R-134a.

3.5.3 Noise

Researchers found that, due to the physical properties of propane and butane, and their relationship with sound waves. This makes the propane and butane mixture as a refrigerant in the refrigerators of less noise than that of Freon. This also can be attributed to lower viscosity of the mixture than Freon, this decrease the viscosity effect on valve opening which decreases the valve flattering.

3.6 Electric vs. solar power

A solar power supply system should be designed to produce enough power to drive the specific application it needs. But, due to variability of solar power with time, it is crucial to check that the design provides enough array size and storage capacity for un-interrupted supply.

In this work the design of the PV array and storage system was actually made and experimentally checked. Minimum number of modules and storage batteries was envisaged to produce stable electric power. This was the major concern in the comparison between electric and solar power.

Chapter Four

EXPERIMENTAL WORK PROCEDURE

4.1 Introduction

A used domestic refrigerator was used in this research. Performance was tested with the usual electrical power and with solar electrical (P.V. generator) power, to ensure close behavior in both conditions.

The original refrigerant (R-12) was replaced by R-134a (with changing the lubricant oil to polyolester oil type), then three different mixtures of propane/butane were installed one by one. The performance tests were carried out for all of the previous charges using both electrical and solar power. For the propane/butane mixtures the lubricant type used was mineral oil, due to the fact that the HCs lubricant oil is the same as that for R-12 systems.

4.2 Refrigerator Specifications

A used simple domestic refrigerator was intentionally used to the aim of conducting the research on a refrigerator that is used or may be used by any person in the real life. This refrigerator contains one compartment with no defrosting or forced air circulation devices. The specifications of the refrigerator are listed in Table 4.1.

Table 4.1. The used refrigerator specifications

MODEL	FR-090C
MANUFACTURER	DAEWOO ELECTRONICS (KOREA)
DAEWOO SERIAL No.	2018
CAPACITY	74 Liters
REFRIGERANT CHARGE MASS	70g
NOMINAL INPUT POWER	80 W
NOMINAL CURRENT/VOLTAGE AC	0.5 A/ 220 V @ 50Hz
REFRIGERANT	R12
DIMENSIONS	45x44x72 cm
COMPRESSOR: MODEL: FN24N45 220/240 V – 50Hz, 1 PH R-12 THERMALLY PROTECTED MATSUSHITA ELECTRIC IND. Co. LTD (JAPAN)	

4.3 Measuring instruments

The following performance parameters of the refrigerator were measured: temperatures, power consumption (current), time, charge mass, water (load) mass, solar intensity, solar current and battery voltage.

4.3.1 Temperature measurement

Copper-Constantan thermocouples type was used to measure the temperatures, at the following points:

1. Compressor inlet, T_1
2. Compressor outlet, T_2
3. Condenser middle point, T_3

4. Condenser outlet, T_4
5. Evaporator, T_5
6. Refrigerator space, T_6
7. Load (hot water), T_7
8. Ambient, T_a

The thermocouples were connected to a data logging system (K-TYPE, MASTECH MS6501 THERMOMETER, RANGE: -50˚C to 150˚C) with an accuracy of ± 0.05 ºC.

4.3.2 Pressure measurement

Due to the complexity and huge data to be measured at the same moment; in this research it was assumed that evaporation pressure (P1) is equal to the saturation pressure at evaporator temperature, and condensation pressure (P2) is equal to the saturation pressure at condenser middle temperature.

4.3.3 Power consumption measurement

In both electrical side of power and solar side a clamp-meter and voltmeter were used to measure the current and voltage during the test period.

4.3.4 Time measurement

Time intervals were measured precisely using a stop watch, and these intervals were taken based on the variation of readings and the aim of that specific reading along the cycle.

4.3.5 Mass measurement

The refrigerant charges mass and load mass was measured using a digital scale of the following specifications:

MANUFACTURER: SARTORIUS AG GOTTINEN, GERMANY

TYPE: QT-000V2

Fabrication No: 10506570

RANGE/ACCURACY:12000g/1g

4.3.6 Solar system measurements

In this research two photovoltaic modules connected in series were used along with a solar charge controller, two storage batteries connected in series and an inverter. These equipment were connected together to form the solar power system. Solar intensity was measured using a pyranometer, which was fitted on the surface of the photovoltaic modules which were oriented to the south. The modules were inclined by an angle of 35º.

Tables 4.2, 4.3 and 4.4 show the specifications of the modules, batteries and the inverter respectively.

Table 4.2. Photovoltaic module specifications

PHOTOVOLTAIC MODULE	
MODEL	KC70
SERIAL NO.	00ZH1A0067
DATE	2000.12
NOMINAL MAXIMUM OUTPUT	70 W
NOMINAL OPEN CIRCUIT VOLTAGE	21.5 V
NOMINAL SHORT CIRCUIT CURRENT	4.35 A
NOMINAL MAXIMUM OUTPUT VOLTAGE	16.9 V
NOMINAL MAXIMUM OUTPUT CURRENT	4.14 A
MAXIMUM SYSTEM VOLTAGE	750 V
NOMINAL MASS	7 kg
DIMENSIONS	85 X 65 cm
MANUFACTURER	KYOCERA CORPORATION MADE IN JAPAN
DIMENSIONS	85 X 65 cm

Table 4.3. Storage batteries specifications

BATTERY	
SUN XTENDER SERIES	
PART NO.	PUX-12100T
NOMINAL VOLTAGE	12 V
AMPERE HOUR CAPACITY @ 24 hr RATE	89 A
CYCLIC APPLICATIONS 2.37 VOLT/CELL @ 77 F°	14.2 VOLTS
FLOAT/STAND BY APPLICATIONS 2.2 to 2.23 VOLTS/CELL @ 77 F°	13.2 to 13.4 VOLTS
TERMINAL TORQUE VALUE	70 inch/Ibs
MANUFACTURED BY	CONCORDE BATTERY CORPORATION, WESTCOVINA, CA, U.S.A

Table 4.4. Inverter specifications

INVERTER	
MASTERVOLT Mass Sine 24/1500 (230 V)	
GENERAL SPECIFICATIONS	
Nominal battery voltage	24V
P30 power Tamb=25°C, cos phi 1	1500 VA
Nom. power Tamb=40°C, cos phi 1	1200 VA
Maximal peak load	2900 VA
Output waveform	true sine
Maximal efficiency	92%
Output voltage	230V (±5%)
Frequency	50Hz (±0.05Hz)
Dimensions (HxWxD)	340x261x130 mm
Weight	6 kg
Minimum battery capacity	>150 Ah
TECHNICAL SPECIFICATIONS	
Technology	HF
Switch off voltage low battery	19V (±0.5V)
Switch on voltage low battery	22V (±0.5V)
Switch off voltage high battery	33V (±0.5V)
Switch on voltage high battery	31V (±0.5V)
Max. allowable ripple on DC	5% RMS
Input current (nominal load)	70A
No load power consumption (off mode)	0 mA
No load power consumption (stand-by mode)	25mA/0.6W
No load power consumption ('low energy' mode - 208V)	180mA/4.5W
No load power consumption ('high power' mode - 230V)	200mA/5W
DC fuse required (slow blow)	100A
Minimum DC cable size	25 mm^2

The readings of solar current and battery voltage was taken from the solar charge controller (PROSTAR, VERSION: PS-30M, MORNING STAR CORPORATION), which was connected between the solar modules and the storage batteries.

Figures 4.1 to 4.4, show the experimental setup, refrigerator interior, photovoltaic modules, storage batteries, charge controller and inverter respectively. In Figure 4.3 only two modules were used out of the six modules.

Figure 4.1. The experimental setup

Figure 4.2. Refrigerator interior

Figure 4.3. Photovoltaic modules

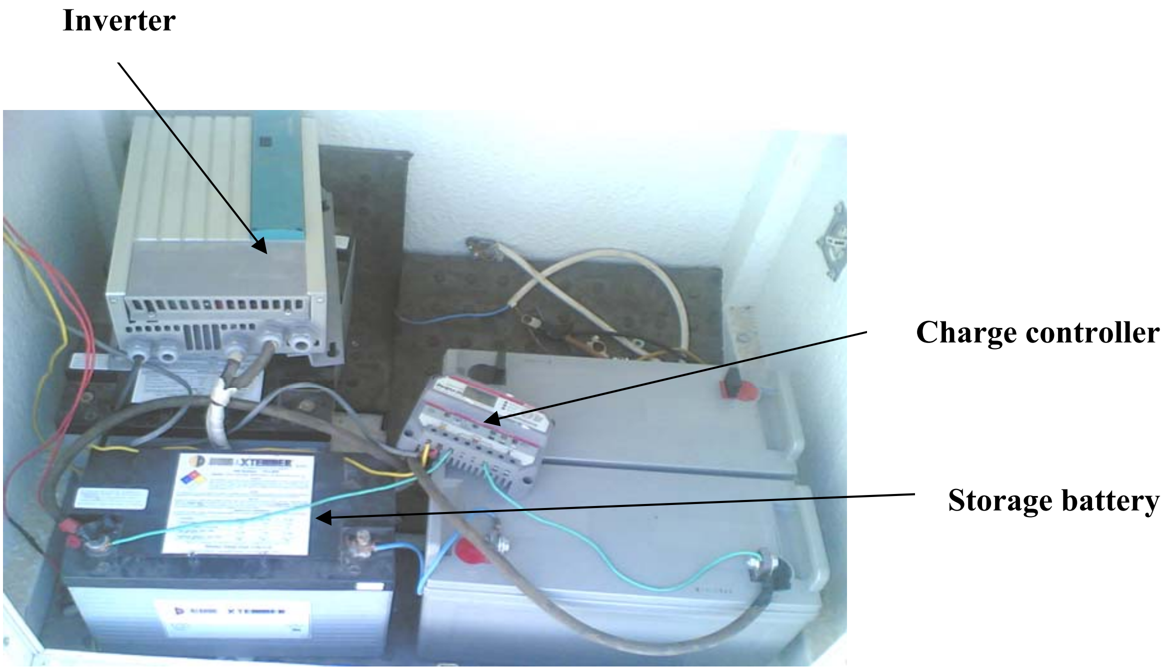

Figure 4.4. Storage batteries, charge controller and inverter

4.4 Hydrocarbons Mixtures

The mixture of propane and butane was achieved by mixing known masses of LPG and pure propane. An LPG bottle (30% propane, 70% butane) for domestic use from Jordan Petroleum Refinery was used. The propane used in this research was taken from a propane bottle contains 400g imported from USA, and has the specifications in Table 4.5 below:

Table 4.5. Properties of the propane

HAZARDOUS INGREDIENTS/IDENTITY INFORMATION	
INGREDIENT	% WEIGHT
PROPANE	85-100
PROPYLENE	0-10
BUTANE & HEAVIER	0-2.5
ETHANE	0-5
ETHYL MERCAPTAN (ODORANT)	<0.1
PHYSICAL/CHEMICAL, FIRE AND EXPLOSION HAZARD DATA	
PROPERTY	VALUE
Appearance and odor	Colorless gas, liquid under pressure. Mercaptan “rotten eggs” odor
Boiling point	- 44 degrees F.
Evaporation rate (Butyl Acetate = 1)	<1 (diffuses readily)
Flash point	-156 degrees F.
Liquid to vapor expansion ratio	1:270
Molecular weight	44.096
Solubility in water	Slight
Specific gravity (liquid)	0.500 - 0.510 (Water = 1)
Specific gravity (vapor)	1.52 (Air = 1)
Vapor pressure (maximum)	208 PSIG @ 100 degrees F.
Flammability limits	2.15% - 9.6% by volume
Auto ignition temperature	940 F.

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4.5 Sizing the solar power system

Number of modules:

Refrigerator power = inverter output voltage * current consumed by refrigerator $= V_{inv} * I_{ref}$ = 230 * 0.52 (in average) = 119.6 Watt.

Refrigerator power consumed per day (assume 14 operational hours / day)

= 119.6 *14 = 1674.4 Whr.

Modules output power required at 7 peak hours per day = 1674.4 / 7

= 239.2 Watt, add 10 % for system inefficiencies (inverter, wiring,…), then it will be 239.2 * 1.1 = 263.12 Watt.

Number of modules required = Modules output power required / nominal output power for each module = 263.12 / 70 = 4 modules.

Number of storage batteries:

Each battery used has 100 Ahr capacity, for maximum battery life it shouldn't discharge more than 80 % of its total storage (i.e 80 Ahr).

Number of batteries required to run the system for 1.5 day (one night + one full day) = [1.5 * peak hours per day * modules output power / battery nominal voltage] / 80 = [(1.5 * 7 * (4 * 70)) / 12] / 80 = 3 batteries.

In addition to the previous a solar charge controller (regulator) that can handle the output current of all modules, is needed to regulate the voltage and current coming from the solar panels going to the battery; most "12 volt" panels output is about 16 to 20 volts, so if there is no regulation the batteries will be damaged from overcharging.

In this experiment two modules and two batteries were used in series, because the inverter used is rated at 24 Volts, two batteries connected in series are needed. Also two modules are needed in series. The minimum number of modules and batteries were used to see the effect of power cut-off.

In this research the refrigerator worked only for half a day without solar power. This was noticeable when the refrigerator went off after one full night working on all mixtures used under solar power source. For that reason the system needed to recharge the batteries again to resume power.

4.6 Work Procedure

4.6.1 Primary Work

The refrigerator used in this research has an R-12 designed refrigerant. The original refrigerant was replaced by R-134a, and consequently the lubricant was changed from mineral oil to polyolester oil type based on the manufacturer instructions for the correct level of the lubricant.

In order to remove air, moisture and any gas dissolved in the lubricant, a purging process was performed before charging the new refrigerant. The refrigerator performance was studied using both mains electrical and solar electrical sources, long experiments were adopted. The following refrigerants were used:

1. R-134a.
2. LPG.
3. 70% propane and 30% butane.
4. 50% propane and 50% butane.
5. Propane.

4.6.2 Experimental Work

All experiments were scheduled to use hot water load as follows:

One kg of hot water at a temperature of 85ºC contained in a tin container (with mass of 0.155 kg and 0.227 kJ/kg.ºC specific heat). A thermocouple was inserted in the load, which was placed inside the refrigerator compartment (the refrigerator thermostat was switched to the maximum value to achieve fast cooling). A rapid increase of T_e was noticed, then slow decrease until load temperature reaches a low limit again.

The refrigerator runs for one day on electrical power and two days on solar power, during each day and at incremental number of minutes; the temperatures at the previously prescribed locations were recorded, in addition to solar intensity, solar current from modules and current consumed by refrigerator.

To determine the optimum charge quantity of the HC mixture required by mass, the refrigerator was charged with six different masses (20, 30, 40, 50, 60, 70g) of LPG in separate experiments. Then COP was calculated at each charge. Figure 4.5 below show that the optimum COP was at 40g charge of LPG, so this charge quantity was taken to be the optimum charge quantity for all refrigerant compositions used in this research.

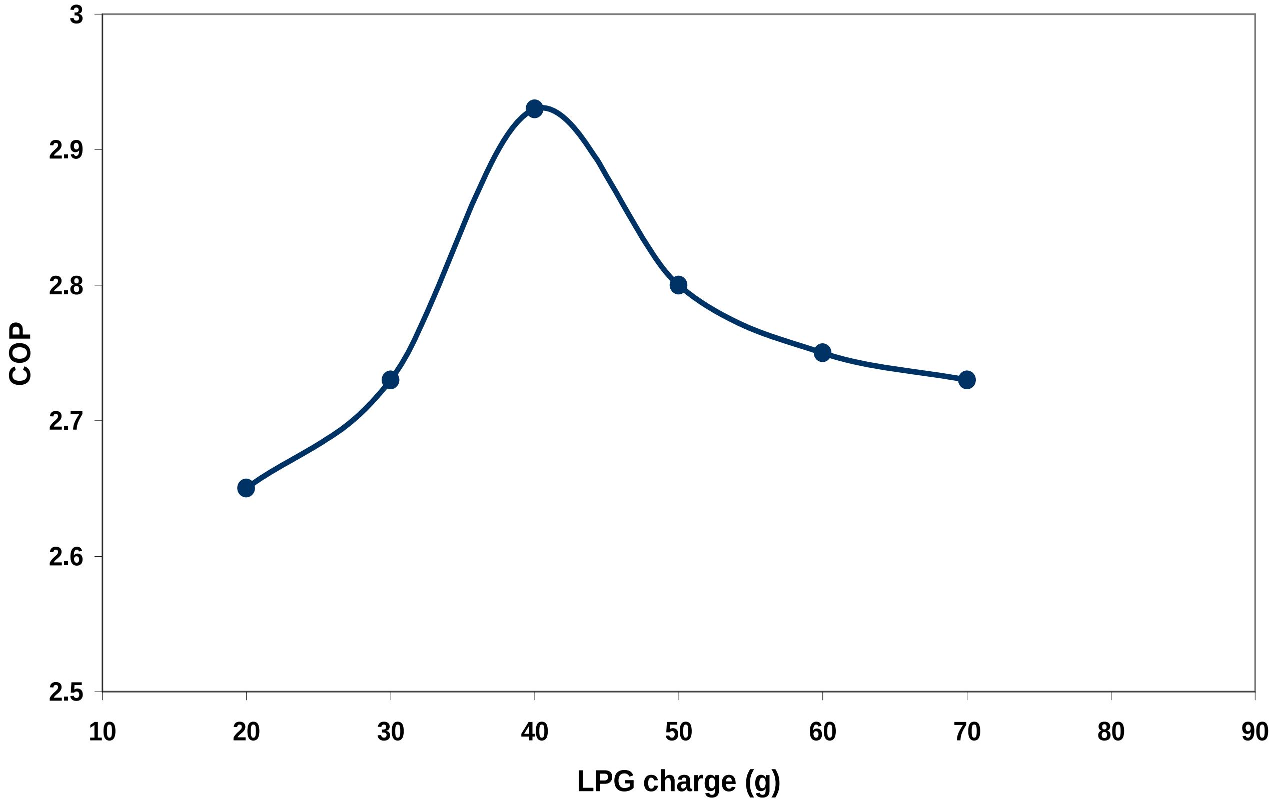

Figure 4.5. Coefficient of performance vs. LPG charge quantity

Chapter Five

MATHEMATICAL ANALYSIS

5.1 Introduction

The vapor compression cycle, shown in Figure 5.1 as T-s diagram includes:

1. Work input compression from compressor inlet point (1) at suction pressure to the discharge pressure at point (2), with certain isentropic efficiency.
2. Heat rejection at nearly constant pressure and condensation to saturated liquid from point (2) to point (3).
3. Expansion with throttling at constant enthalpy from condenser exit point (3) down to the evaporator pressure at point (4).
4. Heat addition at nearly constant pressure leads to complete evaporation and to compressor suction at point (1).

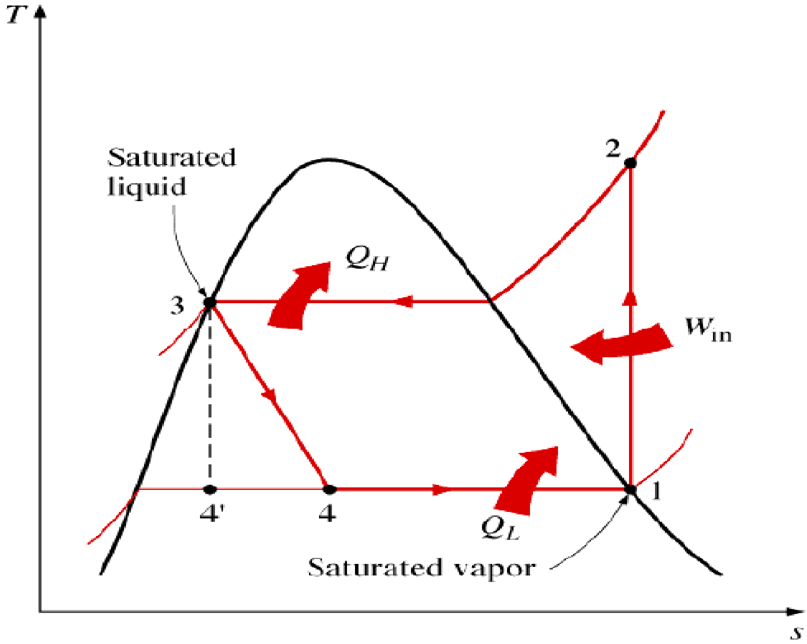

Figure 5.1. T-s diagram of vapor compression cycle

In this cycle the working pressures were determined from the saturation properties of the refrigerant, also mass flow rate can be determined using cooling load and latent heat of evaporation.

The actual vapor compression cycle deviates from the ideal one, due to that the pressure drop of the refrigerant in the condenser, evaporator, piping and valves passages in compressor is mostly due to friction, momentum change, liquid vapor stratification and spring loading of compressor. Also the actual compression process is hardly isentropic due to the losses by friction and heat transfer. To ensure that liquid is at outlet (at elevated ambient temperatures) the condenser is usually oversized; this will sub-cool the liquid.

5.2 Measured data

Appendix A lists all data recorded and calculations results of this work. Temperature readings were in (ºC), pressure readings in (MPa), time readings in (minutes), current readings in (Ampere), voltage readings in (Volts) and solar intensity in W/m².

5.3 Mathematical calculations

Enthalpy calculations

Enthalpies need to be calculated at different locations on the cycle. These locations were compressor inlet and outlet, condenser middle and outlet, and evaporator (at the middle). Pressure and temperature used to state each enthalpy value. The case of the HCs the mixtures treated as ideal gas mixtures (no pressure drop occurs in condenser and evaporator). The propane/butane composition mixture can be described by mass fraction or molar fraction. Table 5.1 shows the mole fractions of the constituents for: LPG (30% propane, 70% butane), 70% propane / 30% butane and 50% propane / 50% butane. For R-134a and propane, one can refer directly to the thermodynamic tables and charts in Appendix B, to get states and enthalpies.

Table 5.1. Components mole fraction for each mixture used

Component	Mass Fraction, mfi	Molecular Weight, mi	Number of Moles, ni	Mole Fraction, yi
40g of LPG (30% propane, 70% butane)				
Propane	0.3	44.1	0.27211	0.36
Butane	0.7	58.12	0.48176	0.64
40g of 70% propane, 30% butane (17g LPG + 23g Propane)				
Propane	0.7	44.1	0.6349	0.75
Butane	0.3	58.12	0.2064	0.25
40g of 50% propane, 50% butane (29g LPG + 11g Propane)				
Propane	0.5	44.1	0.45351	0.57
Butane	0.5	58.12	0.34411	0.43

For propane / butane mixture the mass fraction method was used to find enthalpy (h), at any state as follows:

$$h = mf_p * h_p + mf_b * h_b \tag{5.1}$$

where, h_p and h_b are enthalpies of propane and butane respectively, mf_p and mf_b are mass fractions of propane and butane respectively.

Partial pressures of the constituents were calculated using total pressure by using the mole fraction of each one as follows:

$$P_p = y_p + P \tag{5.2}$$

$$P_b = y_b + P \tag{5.3}$$

where, P_p and P_b are partial pressures of propane and butane respectively, y_p and y_b are mole fractions of propane and butane respectively, P is the total pressure of the mixture which is calculated as that evaporation pressure (P_1) is equal to the saturation pressure at evaporator temperature, and condensation pressure (P_2) is equal to the saturation pressure at condenser middle temperature, the calculation of total pressure P for the mixture is done by using multiplying each component partial pressure (based on the previous assumption) by its mole fraction for that composition, then both components are added together to give total pressure P. Adiabatic throttling process was assumed in the capillary tube so the enthalpy of the mixture at condenser exit is equal to that at evaporator inlet.

Refrigeration effect and capacity calculations

Refrigerant flows as a liquid through the evaporator then it boils by absorbing heat from refrigerator inside space. The quantity of this heat, in kJ per kg of refrigerant circulated, is named refrigeration effect (q_{ref}), which depends on the temperature of the refrigerant leaving the evaporator and that entering the capillary tube (equal to that entering the evaporator as assumed), and given by:

$$q_{ref} = h_1 - h_4 \tag{5.4}$$

where, h_1 and h_4 are the refrigerant enthalpies (kJ/kg) leaving and entering the evaporator respectively.

Refrigeration capacity (Q_{ref}) is the rate of heat removed in (kW) from a refrigerated space by the evaporator, which depend on the mass flow rate of refrigerant ($\dot{m}$) and refrigerating effect, and given by:

$$Q_{ref} = \dot{m} * q_{ref} \tag{5.5}$$

where Q_{ref} is the refrigeration capacity in kW, $\dot{m}$ is the refrigerant mass flow rate in kg/s and q_{ref} is the refrigerating effect (kJ/kg).

Refrigerant mass flow rate calculations

The mass of refrigerant which must be circulated per second, called mass flow rate, and given by:

$$\dot{m} = Q_{ref} / q_{ref} \tag{5.6}$$

where $\dot{m}$ is the refrigerant mass flow rate in kg/s and q_{ref} is the refrigerating effect (kJ/kg), Q_{ref} is calculated here by measuring the heat removed by evaporator from the simulated load (1 kg of hot water in a tin container) in the refrigerator compartment using the equation:

$$Q_{ref} = [(M_w * Cp_w * \Delta T_w) + (M_{co} * Cp_{co} * \Delta T_{co}) + (M_{al} * Cp_{al} * \Delta T_{al}) + (M_A * Cp_A * \Delta T_A)] / \Delta t \tag{5.7}$$

where, M_w, M_{co}, M_{al} and M_A are the masses of water, container, aluminum freezer and air inside the compartment in kg respectively. Cp_w, Cp_{co}, Cp_{al} and Cp_A are the specific heats of water, container, aluminum freezer and air in kJ/kg.ºC respectively. ΔT_w, ΔT_{co}, ΔT_{al} and ΔT_A are the temperature differences of water, container, aluminum freezer and air in ºC respectively. Δt is the time interval in seconds.

Compression work and power consumption calculations

The increase in refrigerant enthalpy during compression process by the compressor known as compression work, and given by:

$$w = h_2 - h_1 \qquad (5.8)$$

where, w is the compression work in kJ/kg and h_1 , h_2 are the refrigerant enthalpies at compressor inlet and exit respectively.

The compressor power consumption is the product of refrigerant mass flow rate and compression work, as follow:

$$W = \dot{m} * w \qquad (5.9)$$

where, W is the compressor power consumption in kW.

Coefficient of Performance (COP) calculations

Coefficient of Performance for a refrigeration system is an expression of the efficiency of the system; it is obtained by dividing the refrigeration capacity over the compressor power consumption, as follow:

$$COP = Q_{ref} / W = q_{ref} / w = (h_1 - h_4)/(h_2 - h_1) \qquad (5.10)$$

5.4 Sample calculation

In this part, sample calculation will be made using readings for specific mixture (LPG) on electrical power; for the solar power side it will be the same procedure. Other mixtures and refrigerant can be treated similarly with minor changes in the case of pure refrigerants.

Readings listed in Table 5.2 are for LPG mixture for the refrigerator running on electrical power; these reading were taken after 30 minutes of inserting 85 ºC, 1 kg of hot water as a load.

Charge quantity of LPG and propane:

Take the 40g of 70% propane, 30% butane as a sample, so the needed

Total mass of propane = 0.7*40 = 28 g.

Total mass of butane = 0.3*40 = 12 g.

To get these quantities, the following charges of LPG and propane must be charged:

LPG charged mass = 17 g (which contains 5 g propane and 12 g butane).

Propane charged mass = 23 g.

Table 5.2. Sample of measured data

Reading (unit)	Symbol	Measured Value
Compressor Inlet Temperature (ºC)	T_1	7
Compressor Outlet Temperature (ºC)	T_2	58
Condenser Middle Temperature (ºC)	T_c	44
Condenser Outlet Temperature (ºC)	T_3	38
Evaporator Temperature (ºC)	T_e	7
Water Temperature Difference (ºC)	ΔT_w	34
Container Temperature Difference (ºC)	ΔT_{co}	36
Aluminum Freezer Temperature Difference (ºC)	ΔT_{al}	2
Air in Compartment Temperature Difference (ºC)	ΔT_A	3
Time Period during the difference (min)	Δt	30

Total and partial pressure calculations (for LPG):

Total Evaporation Pressure: $P_1 = 0.36 P_{1p} + 0.64 P_{1b}$

$P_{1p} = P_{sat}$ at $T_e = 7 + 273 = 280$ K, using propane tables and with interpolation,

$P_{1p} = 0.583$ MPa.

$P_{1b} = P_{sat}$ at $T_c = 44{+}273 = 317$ K, using butane tables and with interpolation,

$P_{1b} = 0.133$ MPa, then

$P_1 = 0.36{*}0.583 + 0.64{*}0.133 = 0.295$ MPa.

Total Condensation Pressure: $P_2 = 0.36 P_{2p} + 0.64 P_{2b}$

$P_{2p} = P_{sat}$ at $T_e = 7 + 273 = 280$ K, using propane tables and with interpolation,

$P_{2p} = 1.5$ MPa.

$P_{2b} = P_{sat}$ at $T_c = 44+273 = 317$ K, using butane tables and with interpolation,

$P_{2b} = 0.423$ MPa, then

$P_2 = 0.36*1.5 + 0.64*0.423 = 0.811$ MPa.

Partial Pressure calculations:

$P_{p1p} = 0.36* P_1 = 0.36*0.295 = 0.11$ MPa (partial pressure for propane at evaporation)

$P_{p1b} = 0.64* P_1 = 0.64*0.295 = 0.18$ MPa (partial pressure for butane at evaporation)

$P_{p2p} = 0.36* P_2 = 0.36*0.811 = 0.29$ MPa (partial pressure for propane at condensation)

$P_{p2b} = 0.64* P_2 = 0.64*0.811 = 0.52$ MPa (partial pressure for butane at condensation)

The refrigerant assumed to be saturated vapor at compressor inlet, superheated at compressor outlet and saturated liquid at condenser outlet (no sub-cooling), also the enthalpy at evaporator inlet h4 assumed to be the equal to that at condenser outlet h3 (adiabatic throttling).

Mixture enthalpies calculation:

$h_1 = 0.3\,h_{1p} + 0.7\,h_{1b}$, for LPG, using tables for propane and butane,

h_{1p} = (hg at $T_e = 280$K) = 906 kJ/kg

h_{1b} = (hg at $T_e = 280$K) = 683.6 kJ/kg, then

$h_1 = 0.3*906 + 0.7*683.6 = 750$ kJ/kg.

$h_2 = 0.3\,h_{2p} + 0.7\,h_{2b}$, using p-h diagrams for propane and butane (superheated),

h_{2p} = (h at $T_2 = 58+273 = 331$ K, with $P_{p2p} = 0.29$ MPa) = 1010 kJ/kg

h_{2b} = (h at $T_2 = 58+273= 331$ K, with $P_{p2b} = 0.52$ MPa) = 760 kJ/kg, then

$h_2 = 0.3*1010 + 0.7*760 = 835$ kJ/kg.

$h_3 = h_4 = 0.3\, h_{3p} + 0.7\, h_{3b}$, using tables for propane and butane,

$h_{3p} = (h_f$ at $T_3 = 38+273 = 311\text{K}) = 624$ kJ/kg

$h_{3b} = (h_f$ at $T_3 = 311\text{K}) = 380$ kJ/kg, then

$h_3 = h_4 = 0.3*624 + 0.7*380 = 453$ kJ/kg.

From eq. (5.7) and with:

$M_w = 1\text{kg}$, $M_c = 0.155\text{kg}$, $M_{al} = \rho_{al} * V_{al} = \rho(L * W * t) = 2700(0.5*0.25*0.003) \approx 1$ kg

and $M_A = \rho_A * V_A = 1.2\ (0.076) = 0.092$ kg, ($V_A = 74$ L ≈ 0.076 m³).

$$Q_{ref} = (((1*4.18*34)+(0.155*0.227*36)+(1*0.9*2)+(0.092*1.004*3))/(30*60))$$

$$= 0.08173 \text{ kW} = 81.73 \text{ Watt.}$$

$q_{ref} = h_1 - h_4 = 750 - 453 = 297$ kJ/kg.

$w = h_2 - h_1 = 835 - 750 = 85$ kJ/kg

$COP = q_{ref} / w = 297 / 85 = 3.49$

$\dot{m} = Q_{ref} / q_{ref} = 81.73 / 297 = 0.28$ g/s

$W = \dot{m} * w = 0.28*85 = 23.39$ Watt.

Compressor - Photovoltaic Module and Total Efficiency:

The readings listed in Table 5.3 below are for R-143a on solar power (day 2), and were taken as a sample to calculate the compressor, photovoltaic module and total efficiencies:

Table 5.3. Sample of measured data for R-134a on solar power (day 2)

Is, solar amperes (Amp)	Solar intensity (W/m2)	Iref, refrigerator amperes (Amp)	W, Compressor Power consumption (Watt)
3.2	805	0.53	34.07
3.4	855	0.53	21.41
3.7	967	0.54	14.26
3.7	1007	0.54	12.67
3.9	1060	0.54	11.65
3.9	1085	0.54	10.44
3.9	1130	0.54	9.27
3.7	1126	0.54	8.33
3.6	1086	0.54	7.74

Two photovoltaic modules total effective area (A) = 2 (length * width)

= 2 (0.765 * 0.45) = 0.69 m²

Photovoltaic modules (PV) efficiency = $(I_s * V_n)$ / (solar intensity*A)

For first line readings in upper table as a sample,

I_s = 3.2 Amp. , V_n = nominal voltage of the modules (average) = 2 (14) = 28 Volt.

Solar intensity = 805 W/m², A = 0.69 m², then

Photovoltaic modules efficiency = (3.2*28) / (805*.69) = 0.16 = 16 %

Compressor efficiency = Compressor Power / $(I_{ref} * V_{inv})$

Compressor power = 34.07 Watt, I_{ref} = 0.53 Amp., V_{inv} = inverter output voltage (to the refrigerator) = 230 Volt.

Compressor efficiency = 34.07 / (0.53*230) = 0.279 = 27.9 %.

Total efficiency = Photovoltaic efficiency * Compressor efficiency

= 0.16*0.279 = 0.045 = 4.5 %.

All calculations are listed in Table 5.4 below.

Table 5.4. Results of sample data for R-134a on solar power (day 2)

Is*Vnom, Watt	Solar intensity*A, Watt	PV efficiency %	Iref*Vinv, Watt	Compressor efficiency %	total efficiency %
89.6	556.7	16.1	121.9	27.9	4.5
95.2	591.3	16.1	121.9	17.6	2.8
103.6	668.7	15.5	124.2	11.5	1.8
103.6	696.4	14.9	124.2	10.2	1.5
109.2	733.1	14.9	124.2	9.4	1.4
109.2	750.3	14.6	124.2	8.4	1.2
109.2	781.5	14.0	124.2	7.5	1.0
103.6	778.7	13.3	124.2	6.7	0.9
100.8	751.0	13.4	124.2	6.2	0.8

The efficiency of the compressor decreases with time because the refrigerant mass flow rate decreases (which in turn decrease the nominator in the compressor efficiency equation), due to the decrease in evaporating temperature, Figure 5.2 below shows those efficiencies versus time.

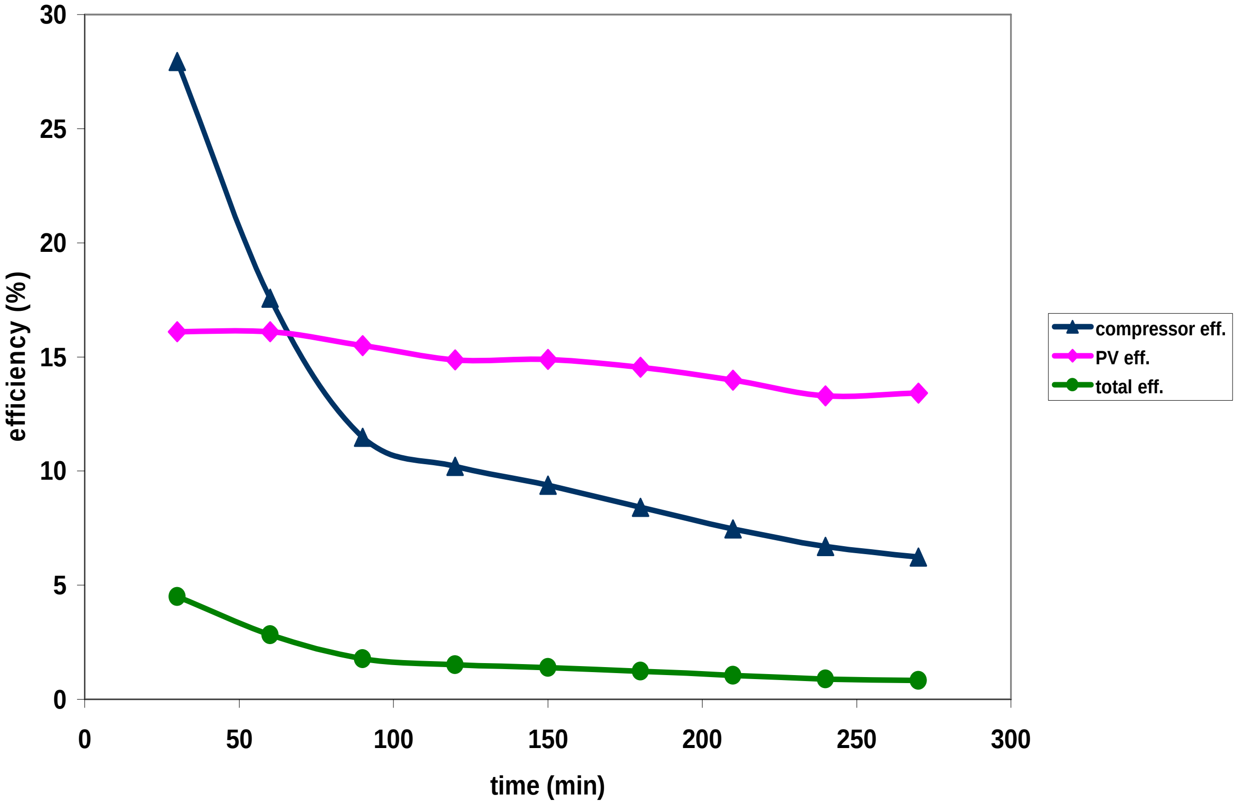

Figure 5.2. Efficiencies vs. time for R-134a using solar power (day 2) at T_a = 27 ºC

Chapter Six

RESULTS AND DISCUSSION

6.1 Introduction

The results of this research and related curves will be presented and discussed in this chapter. As mentioned previously, the best COP was at 40g charge of LPG, and this charge quantity was taken to be the best charge quantity for all refrigerant compositions. The ambient temperature (T_a) was taken to be the average of all ambient temperature readings taken inside the laboratory at each interval and found to be 27 ºC.

The original refrigerant (R-12) quantity was 70 g. This quantity was used for all mixtures, which means that the best charge quantity occurred at 57% (40g/70g) of the original refrigerant quantity.

In this chapter the analysis and discussion will be focused on R-134a and LPG as an alternative refrigerant. Performance of all mixtures will be compared and discussed. The COP, refrigeration capacity, mass flow rate and power consumption will be the parameters for comparison.

6.2 Cooling rate

A simulated load of 1 kg of hot water at temperature of 85 ºC in a container made of tin (with mass of 0.155 kg and specific heat of 0.227 kJ/kg.ºC) was placed inside the refrigerator compartment to study the variation of the load temperature with time for each mixture (on both electrical and solar power), also this will help in finding the refrigerant mass flow rate.

Figures 6.1 to 6.5 below show the load temperatures (load cooling), condensing temperatures, and evaporator temperatures; all versus time in minutes for both electrical and solar power source. On the same Figure the solar intensity during the experiment is presented on another y-axis, to illustrate the solar intensity in the period of experiment running. A rapid increase of T_e was noticed, then it slowly decreases until load temperature reaches a low limit again.

In average for all mixture at both electrical and solar power, the load cools to a temperature of 5 ºC in 315 minutes (5.25 hours), this long time to achieve that temperature is due to the high temperature of the load, and also to the refrigerator specifications.

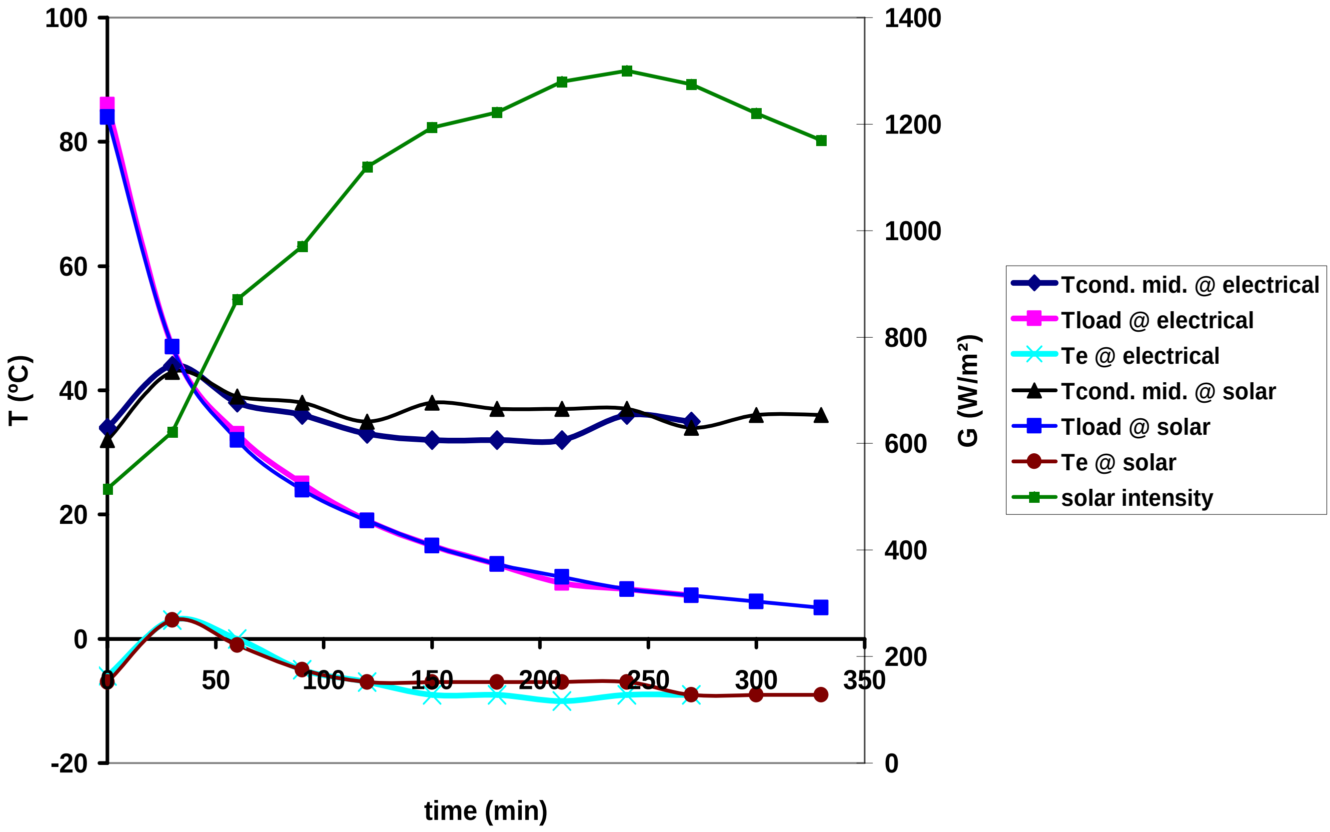

Figure 6.1. Temperature and solar intensity vs. time for R-134a using electrical and solar power (day 1)

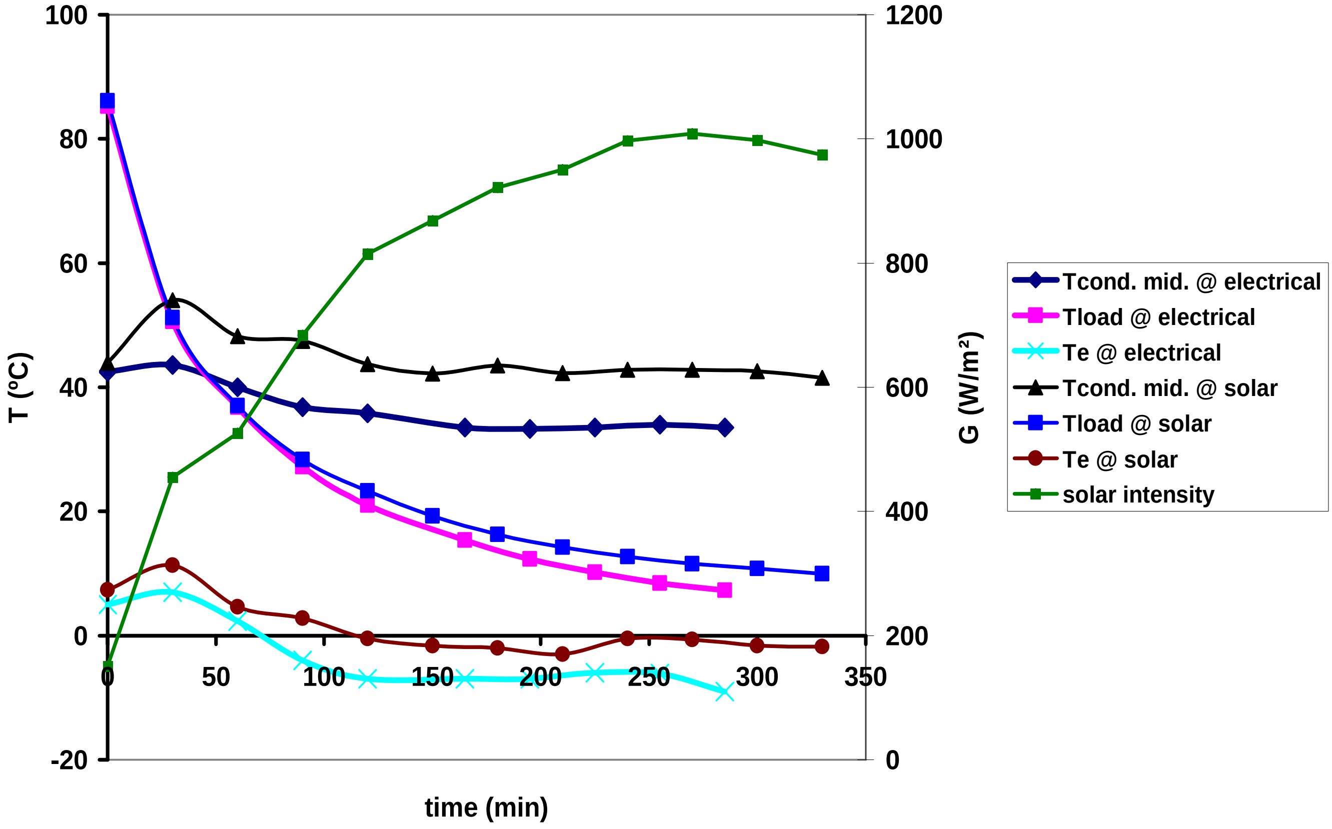

Figure 6.2. Temperature and solar intensity vs. time for LPG using electrical and solar power (day 1)

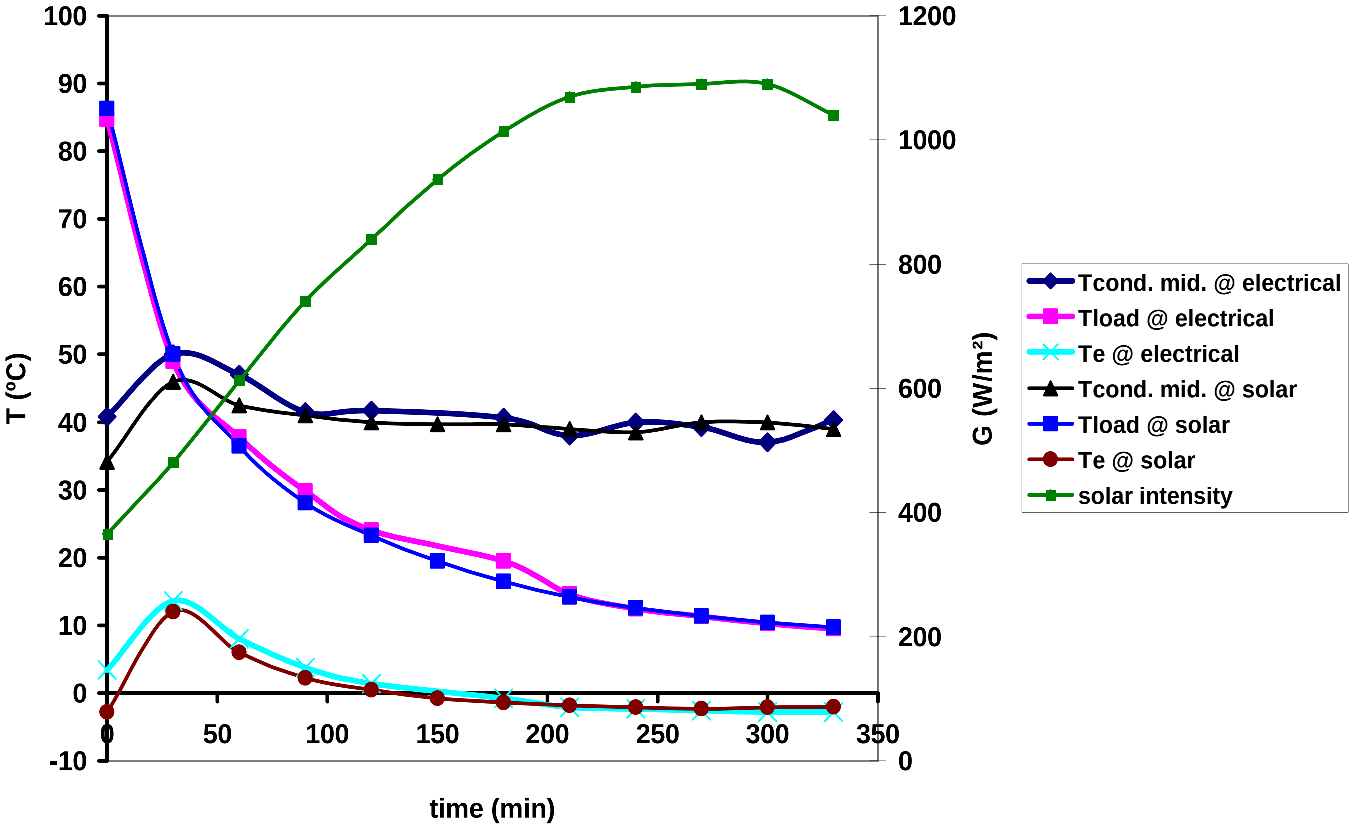

Figure 6.3. Temperature and solar intensity vs. time for 50% propane & 50% butane using electrical and solar power (day 1)

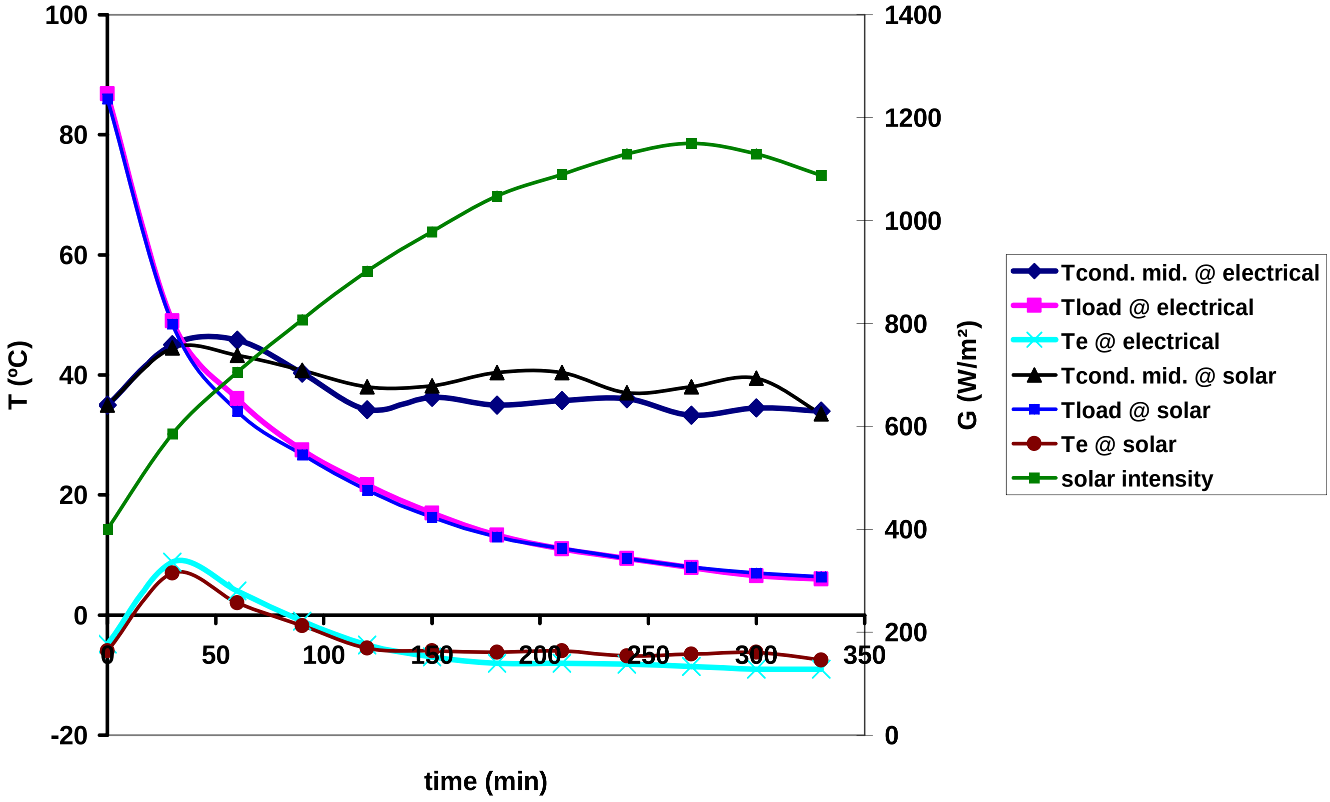

Figure 6.4. Temperature and solar intensity vs. time for 70% propane & 30% butane using electrical and solar power (day 1)

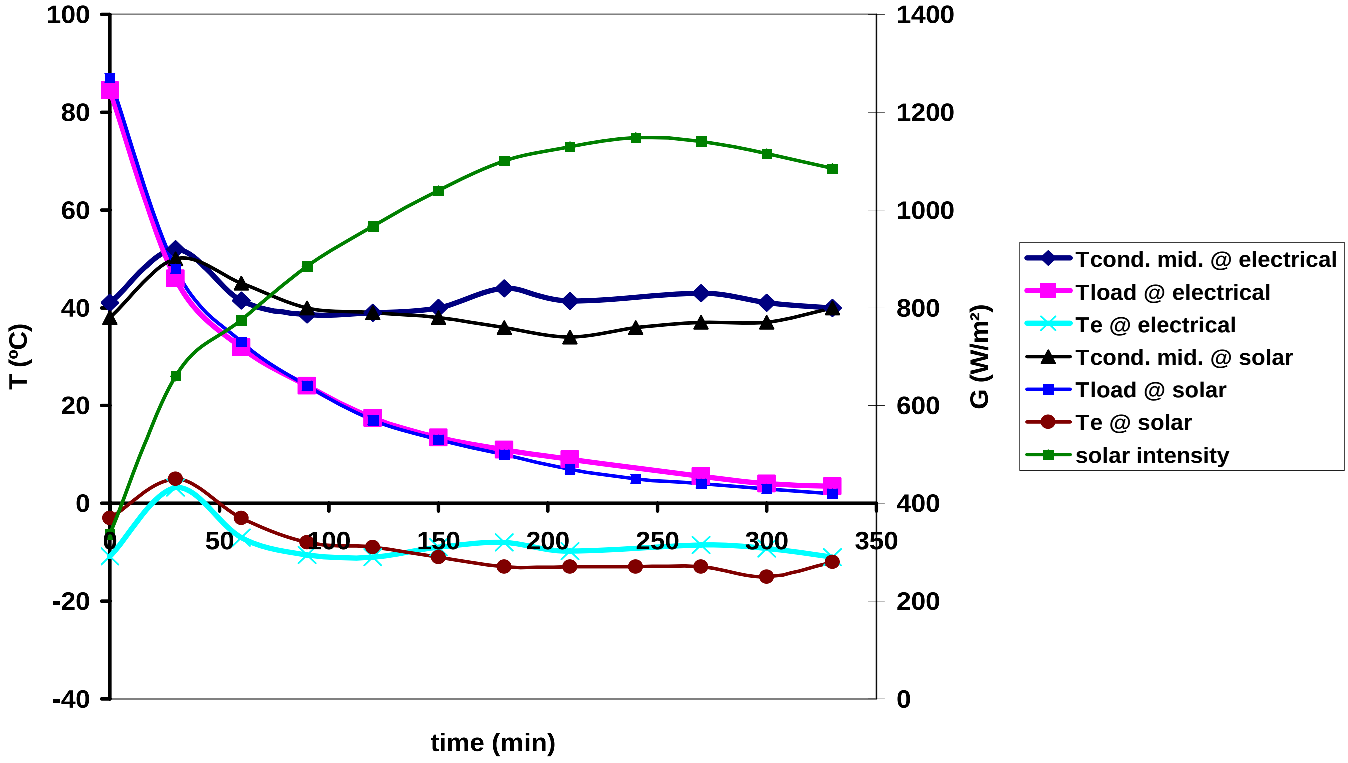

Figure 6.5. Temperature and solar intensity vs. time for propane using electrical and solar power (day 1)

6.3 Power saving and consuming

The electrical power consumed by the refrigerator using electrical power was considered for all mixtures and compared with that of R-134a. It was found that when using R-134a, the refrigerator consumes 0.46 Amp. at 220 Volt. The nominal power was 57.7 Watt. For using LPG it consumes 0.43 Amp. at same voltage with nominal power of 53.9 Watt. Using 50% propane and 50% butane it consumes 0.49 Amp. with nominal power of 61.4 Watt. For 70% propane and 30% butane it consumes 0.5 Amp. with nominal power of 62.7 Watt and for propane it consumes 0.52 Amp. with nominal power of 65.2 Watt.

When comparing the previous values with that of R-134a, the following can be shown:

In case of LPG the refrigerator saves about 7% power, but for 50% propane and 50% butane it consumes 6% power more than that of R-134a, also for 70% propane and 30% butane it consumes 9% power more than that of R-134a, and the highest power consumed was in the case of using propane which consumes 13% more.

This results in that when increasing the percentage of propane in the mixture the power consumption increases until it reaches maximum when using propane, this is due to higher value of saturation pressures of propane, which in turn requires more compressor power to compress. Figure 6.6 below shows the percentage of power saving / consuming of each mixture compared to R-134a (-ve: saving, +ve: consuming more).

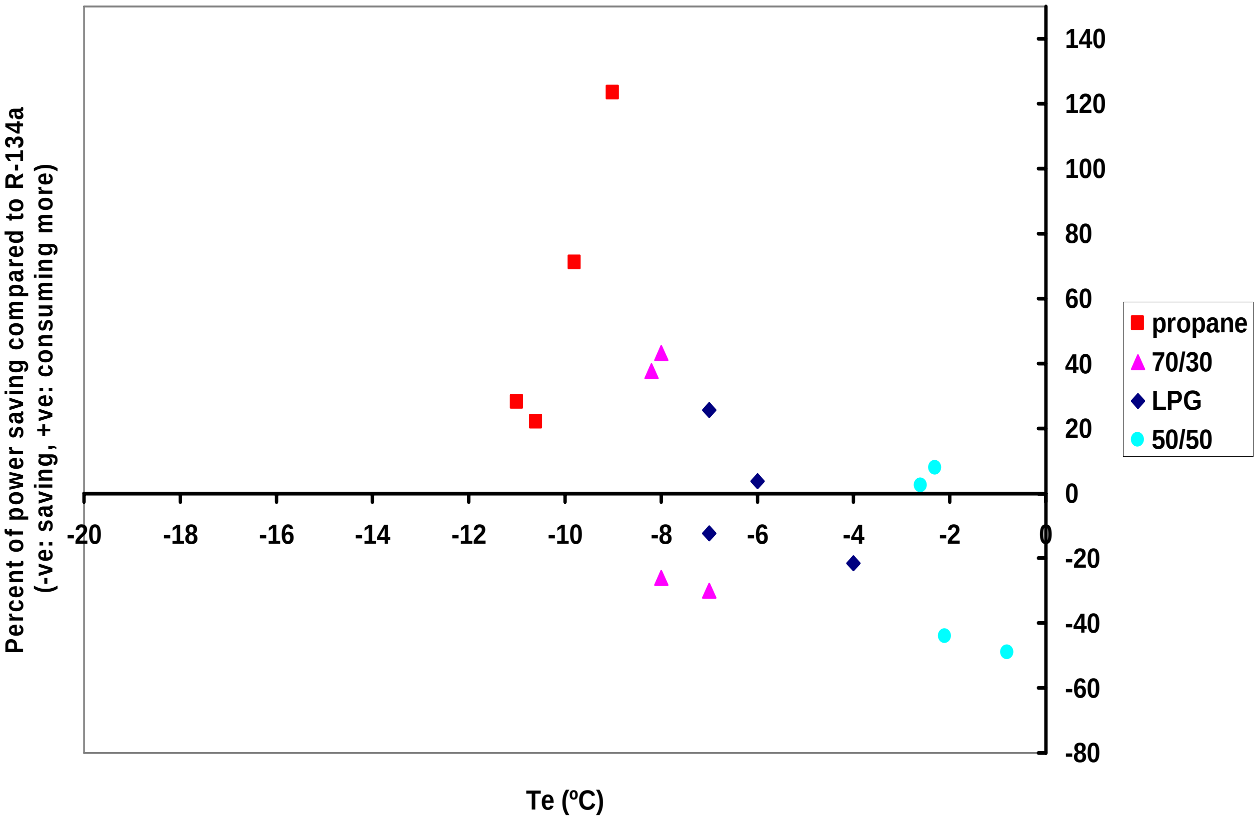

Figure 6.6. Percent of power saving (compared to R-134a) vs. T_e for all mixtures using electrical power at T_c = 37ºC and T_a = 27 ºC

6.4 Performance parameters against Te , for R-134a and LPG

Performance parameters for R-134a and LPG, in this study included the following: COP, refrigeration capacity, mass flow rate and power consumption. These were presented separately and graphically using respective data and results against variable evaporating temperatures, T_e at constant T_c of 37 ºC and constant T_a of 27 ºC.

Those results are presented graphically in Figures 6.7 to 6.22, for R-134a and LPG separately at constant T_c. Other data and results were presented in Appendix A.

Coefficient of performance

As evaporating increases with constant condensing temperature, the COP will increase, this is due to the increase in enthalpy difference across the evaporator, and decrease in enthalpy difference across compressor. An efficient refrigeration system can be determined by COP, which indicate the whole system efficiency (the higher the COP the better the efficiency). These results were indicated by both refrigerants behavior shown by Figure 6.7 and 6.8 for R-134a using electrical and solar power respectively, and Figure 6.9 and 6.10 for LPG using electrical and solar power respectively.

It was found that, the LPG has a COP that is 6% higher compared to that of R-134a at constant T_c.

Refrigeration capacity

It is a measure for heat removal rate in refrigerator compartment, it was noticed that the refrigeration capacity increases as the evaporating temperature increases at a constant condensing temperature, this due to the increase in mass flow rate and enthalpy difference as evaporating temperature increases. These results were indicated by both refrigerants behavior shown by Figure 6.11 and 6.12 for R-134a using electrical and solar power respectively, and Figure 6.13 and 6.14 for LPG using electrical and solar power respectively.

Power consumption

The compressor power increases with increasing the evaporating temperature, because of mass flow rate increasing at a higher rate than of enthalpy decreasing. These results were indicated by both refrigerants behavior shown by Figure 6.15 and 6.16 for

R-134a using electrical and solar power respectively, and Figure 6.17 and 6.18 for LPG using electrical and solar power respectively.

Refrigerant mass flow rate

As evaporating temperature increases, the refrigerant mass flow rate increases at constant condensing temperature. This is due to the decrease in the refrigerant specific volume as evaporating temperature increases, which in turn increases the refrigerant mass flow rate. These results were indicated by both refrigerants behavior shown by Figure 6.19 and 6.20 for R-134a using electrical and solar power respectively, and Figure 6.21 and 6.22 for LPG using electrical and solar power respectively.

6.5 Performance parameters against Tc, for R-134a and LPG

Performance parameters for R-134a and LPG (COP, refrigeration capacity, mass flow rate and power consumption) were presented separately and graphically using respective data and results against variable condensation temperatures, T_c at constant T_e of -9 ºC and constant T_a of 27 ºC.

Those results are presented graphically in Figures 6.23 to 6.38, for R-134a and LPG separately at constant T_e. Other data and results were presented in Appendix A.

6.5.1 Coefficient of performance

When condensing temperature increases at constant evaporating temperature, the enthalpy difference across the evaporator will decrease and across the compressor will increase, this yield in decreasing the COP. These results were indicated by both refrigerants behavior shown by Figure 6.23 and 6.24 for R-134a using electrical and solar power respectively, and Figure 6.25 and 6.26 for LPG using electrical and solar power respectively.

6.5.2 Refrigeration capacity

The refrigeration capacity decreases as condensing temperature increases at constant evaporating temperature. This is due to the increase of saturated liquid enthalpy when increasing the condensing temperature; this will decrease the enthalpy difference across the evaporator and also decreases refrigerant mass flow rate; where the multiplication of mass flow rate and enthalpy difference (state 1 and state 4) is the refrigeration capacity. These results were indicated by both refrigerants behavior shown by Figure 6.27 and 6.28 for R-134a using electrical and solar power respectively, and Figure 6.29 and 6.30 for LPG using electrical and solar power respectively.

6.5.3 Power consumption

When condensing temperature increases at constant evaporating temperature the compression work will increases in a rate higher than the decreasing in the refrigerant mass flow rate; this yield in almost increasing the compressor power consumption. These results were indicated by both refrigerants behavior shown by Figure 6.31 and 6.32 for R-134a using electrical and solar power respectively, and Figure 6.33 and 6.34 for LPG using electrical and solar power respectively.

6.5.4 Refrigerant mass flow rate

As condensing temperature increases at constant evaporating temperature, the refrigerant mass flow rate decreases, because of the decrease in the refrigerant specific volume at the compressor outlet as condensing temperature increases. These results were indicated by both refrigerants behavior shown by Figure 6.35 and 6.36 for R-134a using electrical and solar power respectively, and Figure 6.37 and 6.38 for LPG using electrical and solar power respectively.

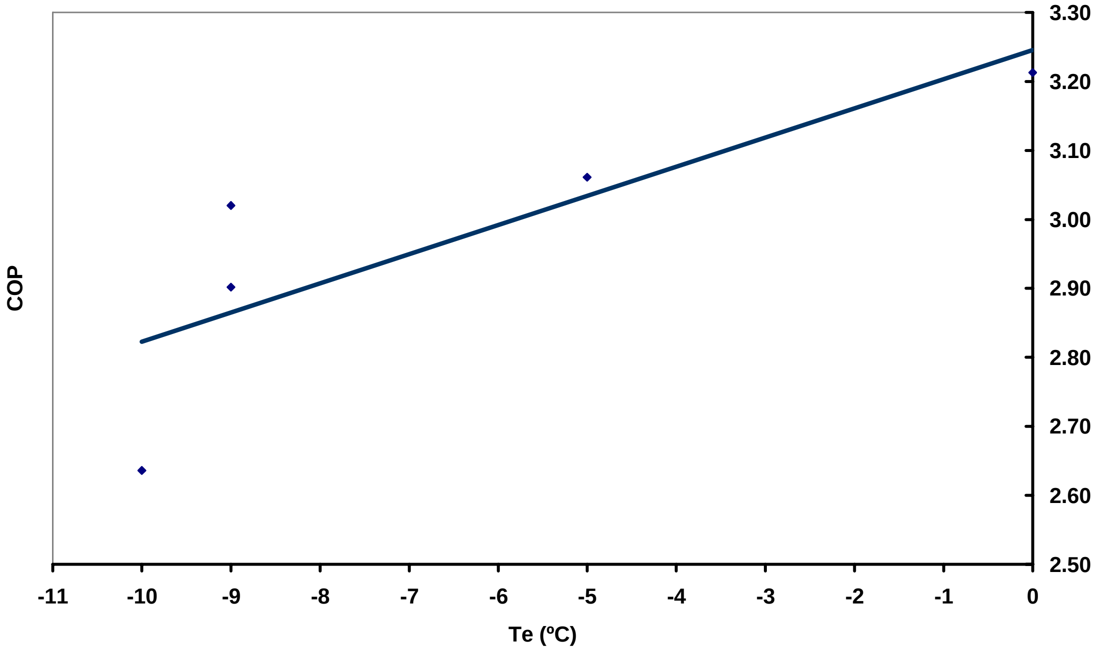

Figure 6.7. COP vs. T_e for R-134a using electrical power at T_c = 37 ºC and T_a = 27 ºC

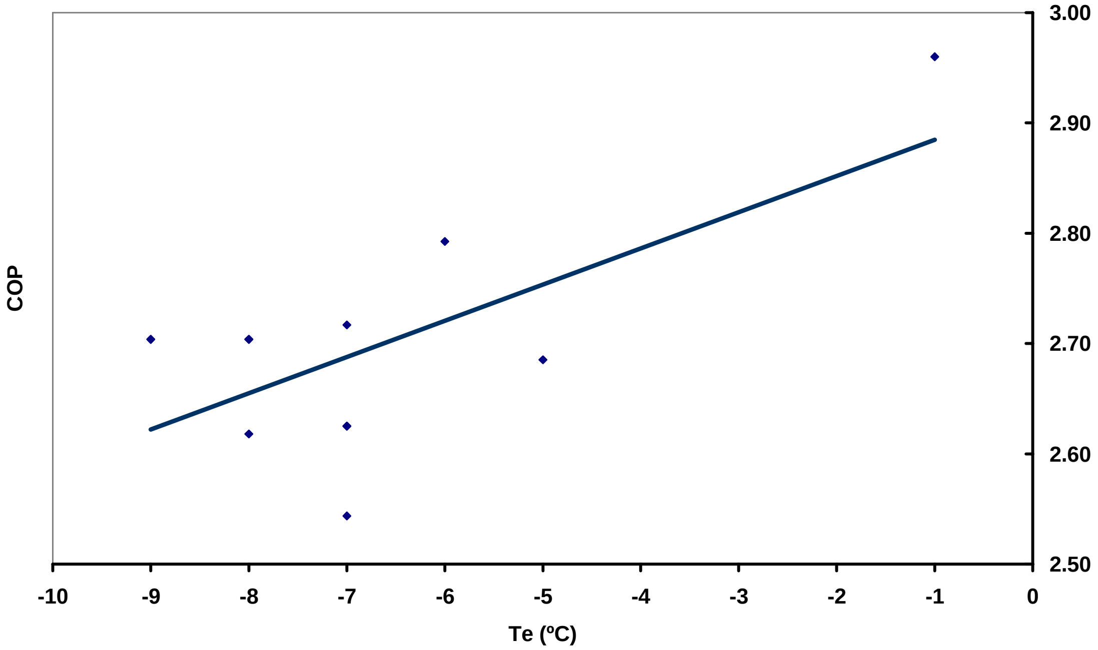

Figure 6.8. COP vs. T_e for R-134a using solar power at T_c = 37 ºC and T_a = 27 ºC

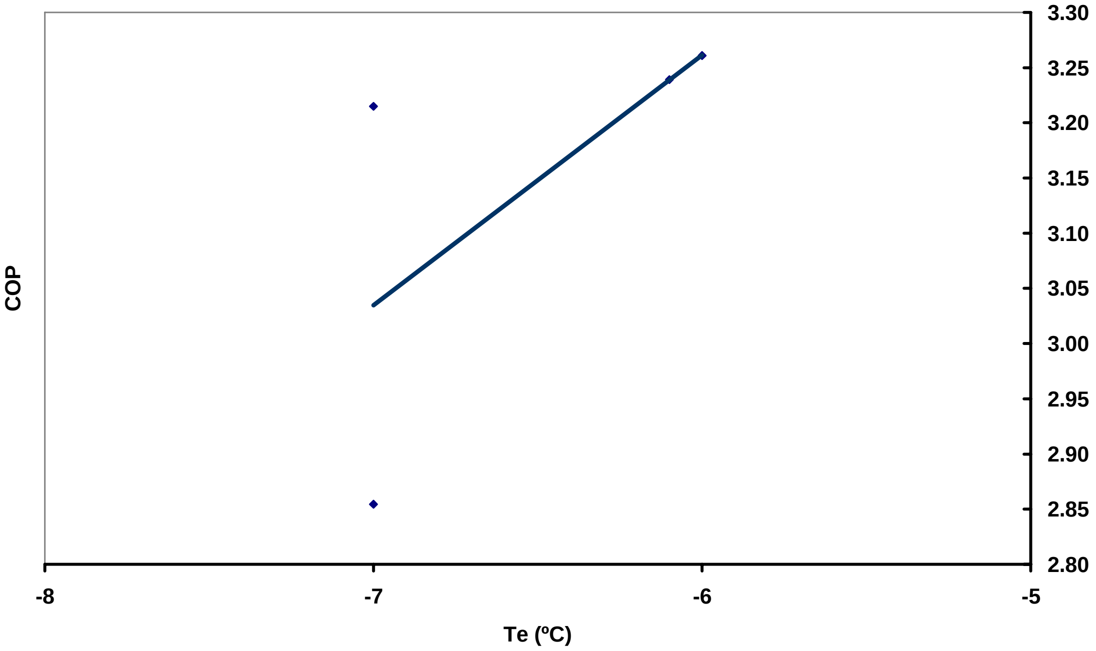

Figure 6.9. COP vs. T_e for LPG using electrical power at T_c = 37 ºC and T_a = 27 ºC

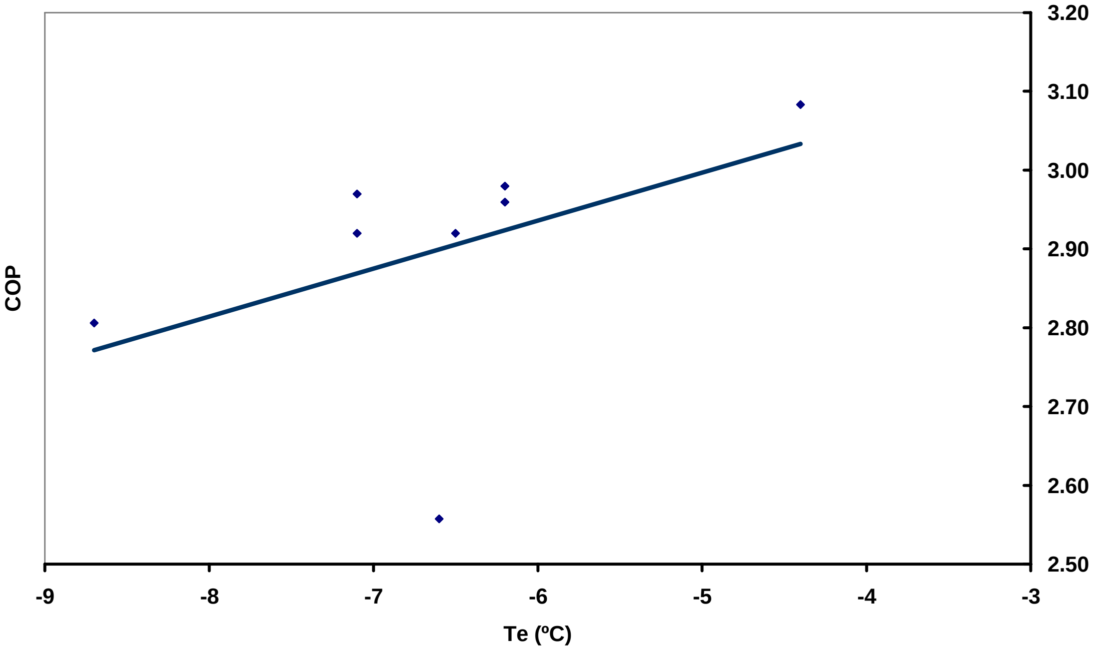

Figure 6.10. COP vs. T_e for LPG using solar power at T_c = 37 ºC and T_a = 27 ºC

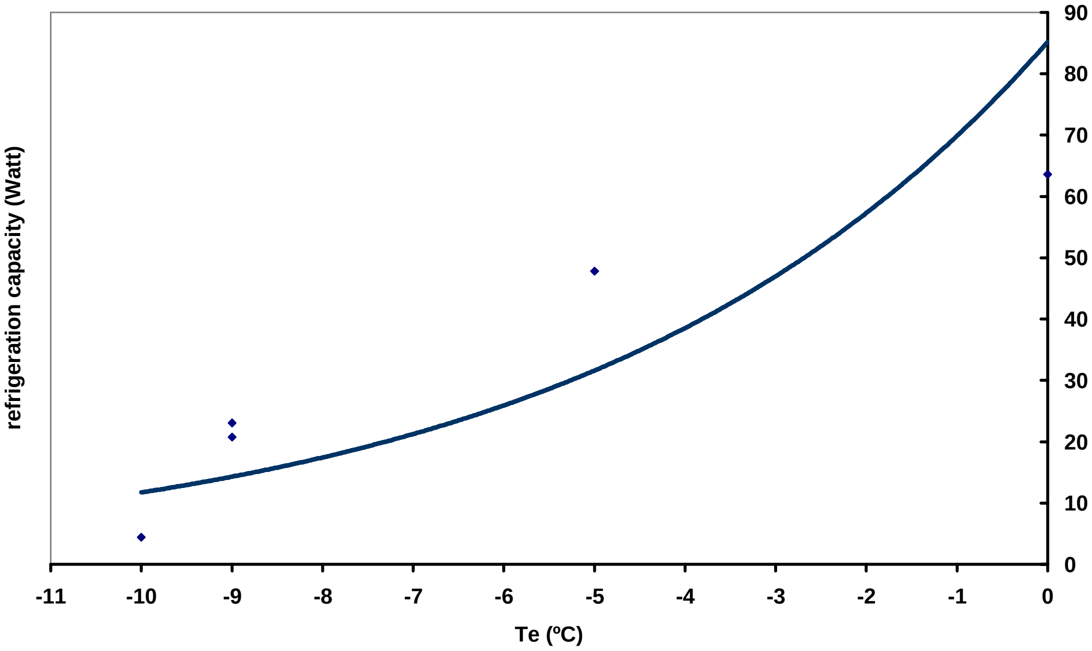

Figure 6.11. Refrigeration capacity vs. T_e for R-134a using electrical power at T_c = 37 ºC and T_a = 27 ºC

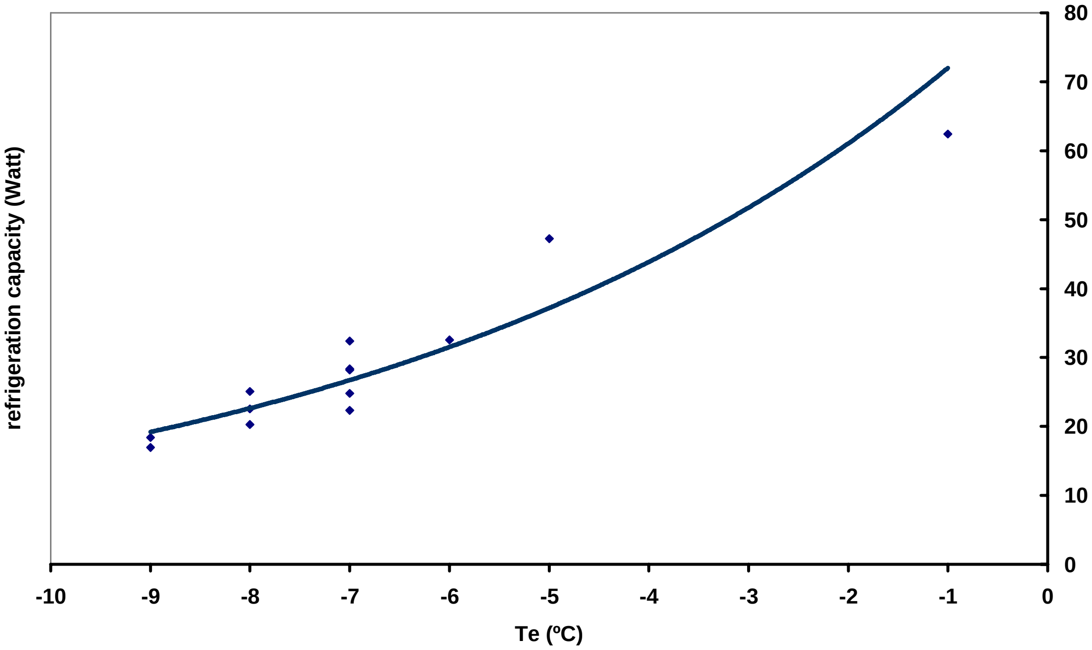

Figure 6.12. Refrigeration capacity vs. T_e for R-134a using solar power at T_c = 37 ºC and T_a = 27 ºC

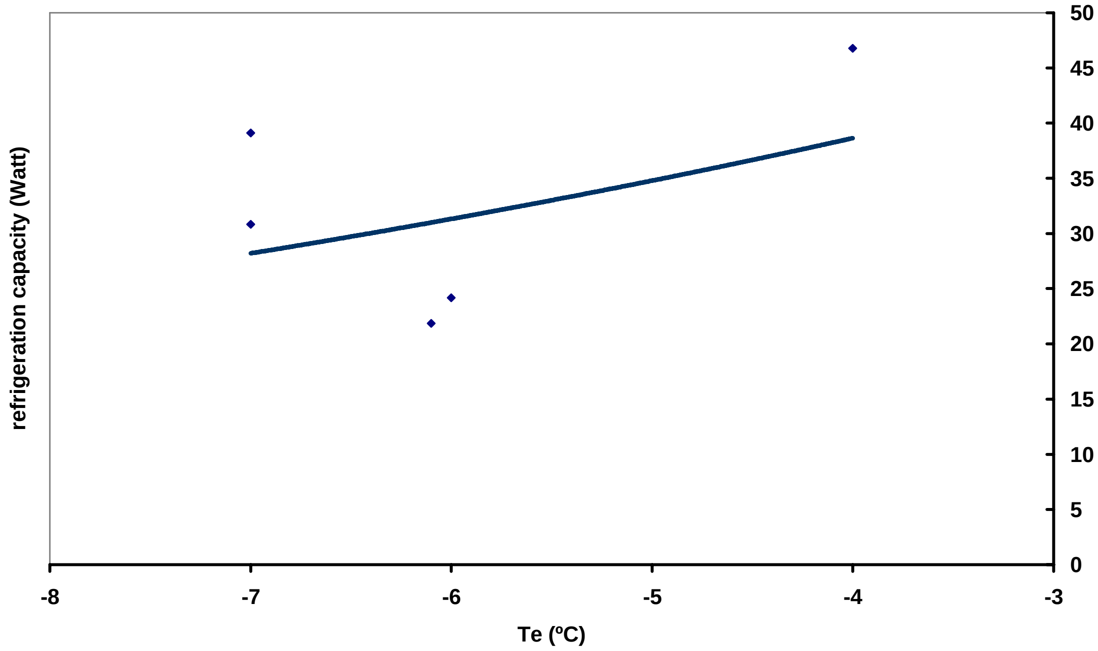

Figure 6.13. Refrigeration capacity vs. T_e for LPG using electrical power at T_c = 37 ºC and T_a = 27 ºC

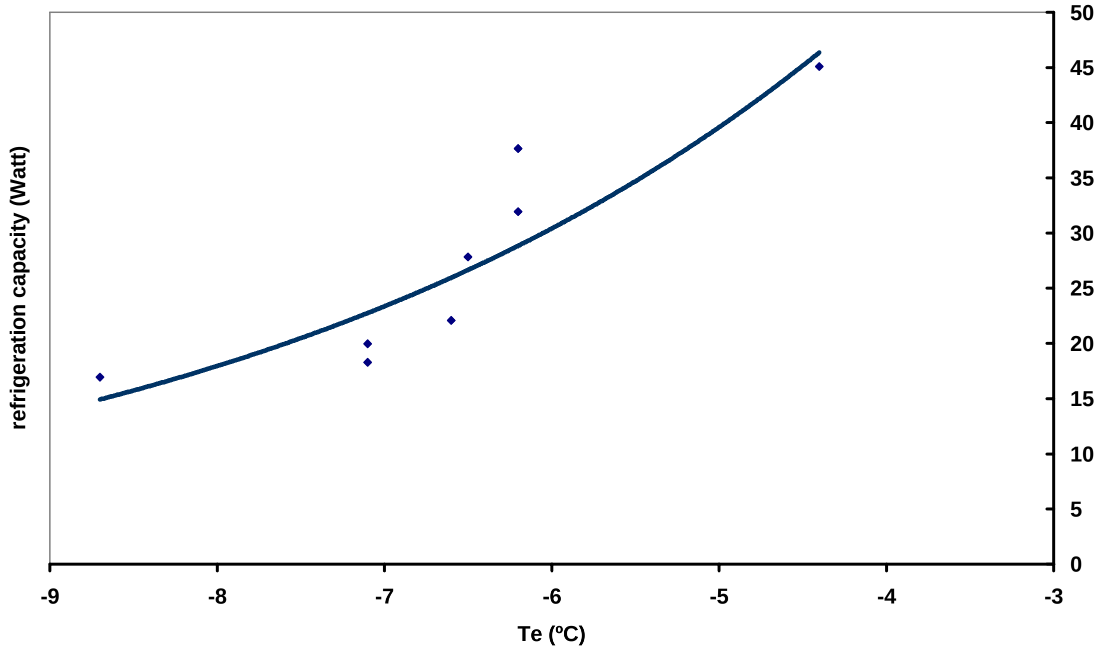

Figure 6.14. Refrigeration capacity vs. T_e for LPG using solar power at T_c = 37 ºC and T_a = 27 ºC

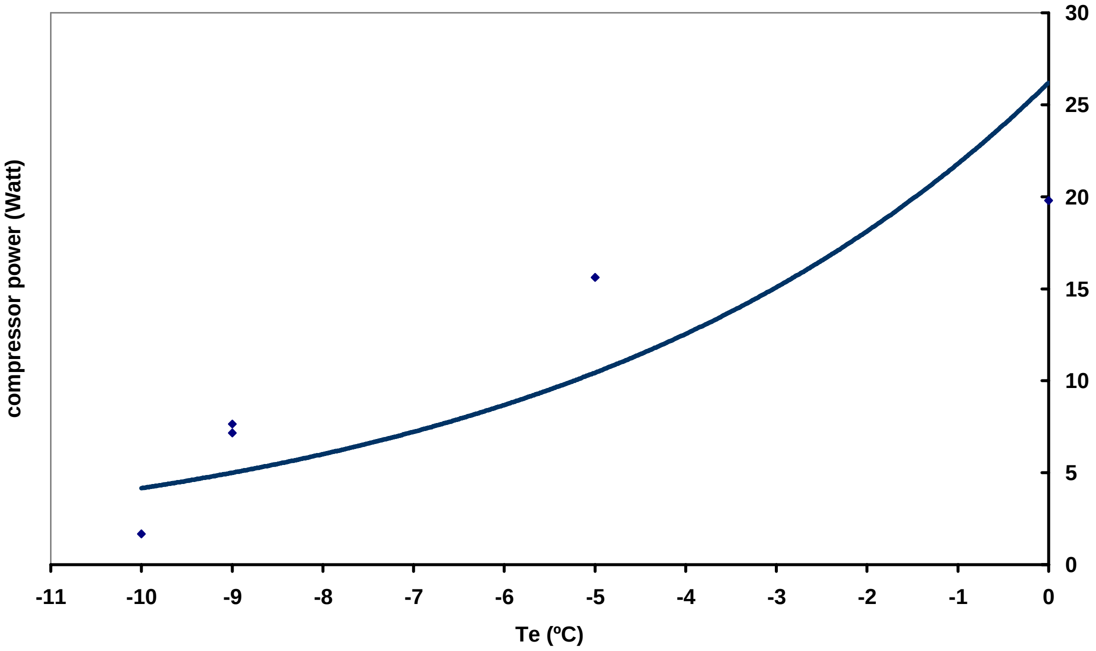

Figure 6.15. Compressor power vs. T_e for R-134a using electrical power at T_c = 37 ºC and T_a = 27 ºC

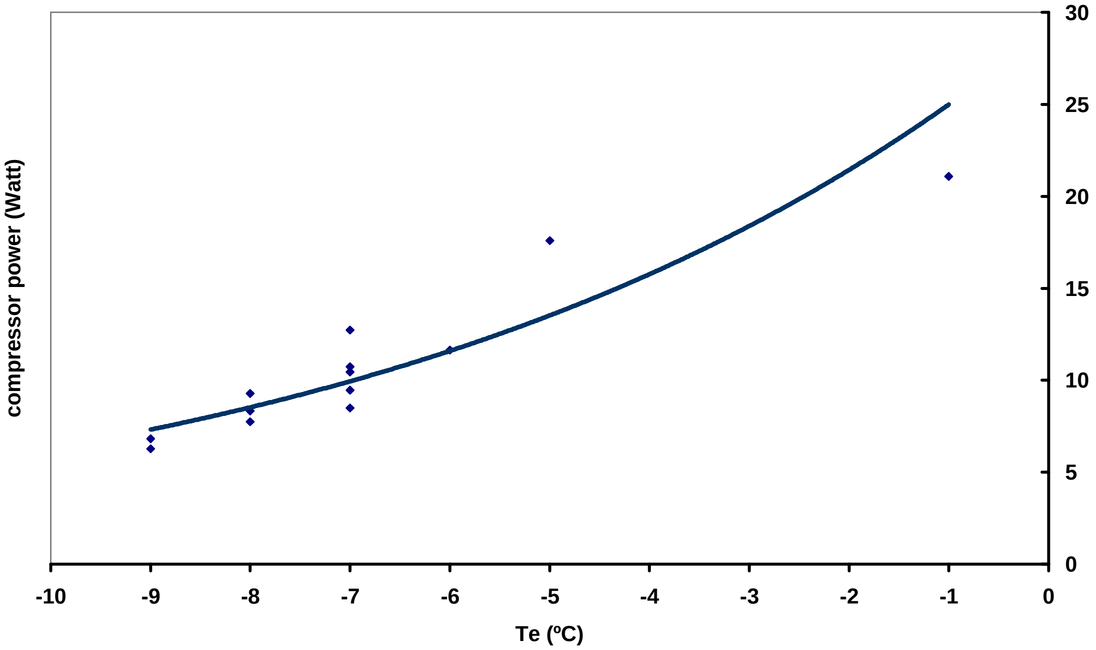

Figure 6.16. Compressor power vs. T_e for R-134a using solar power at T_c = 37 ºC and T_a = 27 ºC

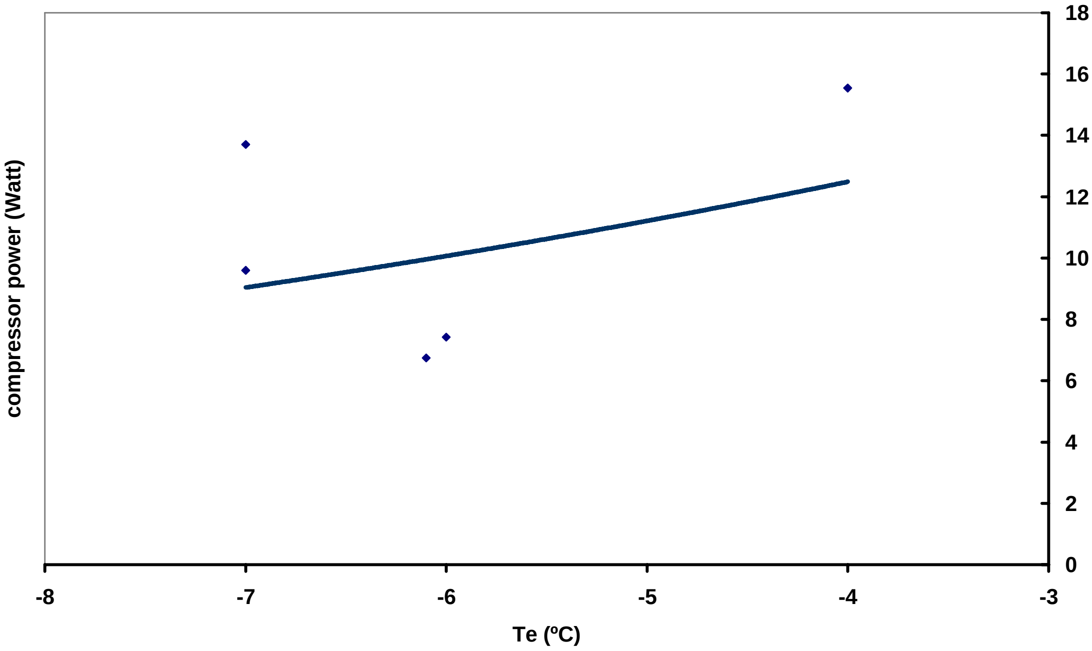

Figure 6.17. Compressor power vs. T_e for LPG using electrical power at

T_c = 37 ºC and T_a = 27 ºC

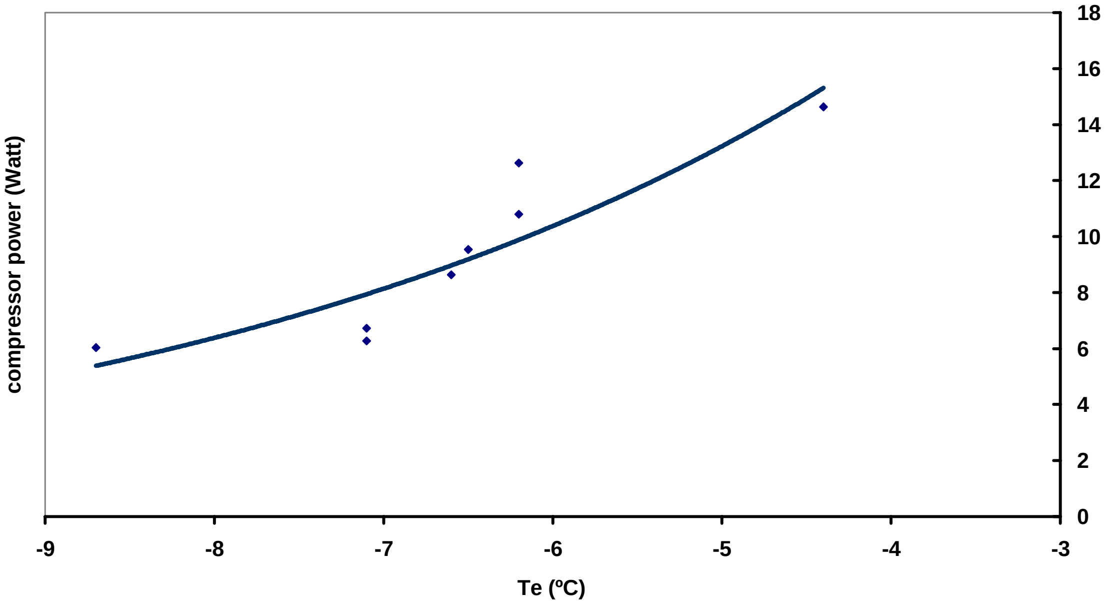

Figure 6.18. Compressor power vs. T_e for LPG using solar power at

T_c = 37 ºC and T_a = 27 ºC

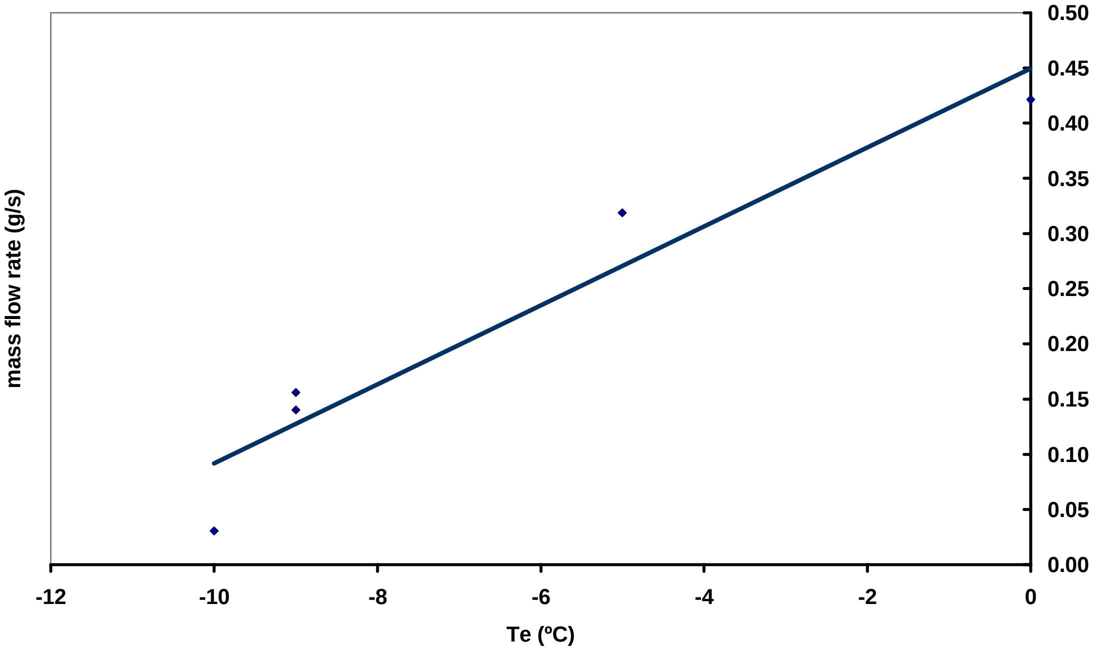

Figure 6.19. Mass flow rate vs. T_e for R-134a using electrical power at T_c = 37 ºC and T_a = 27 ºC

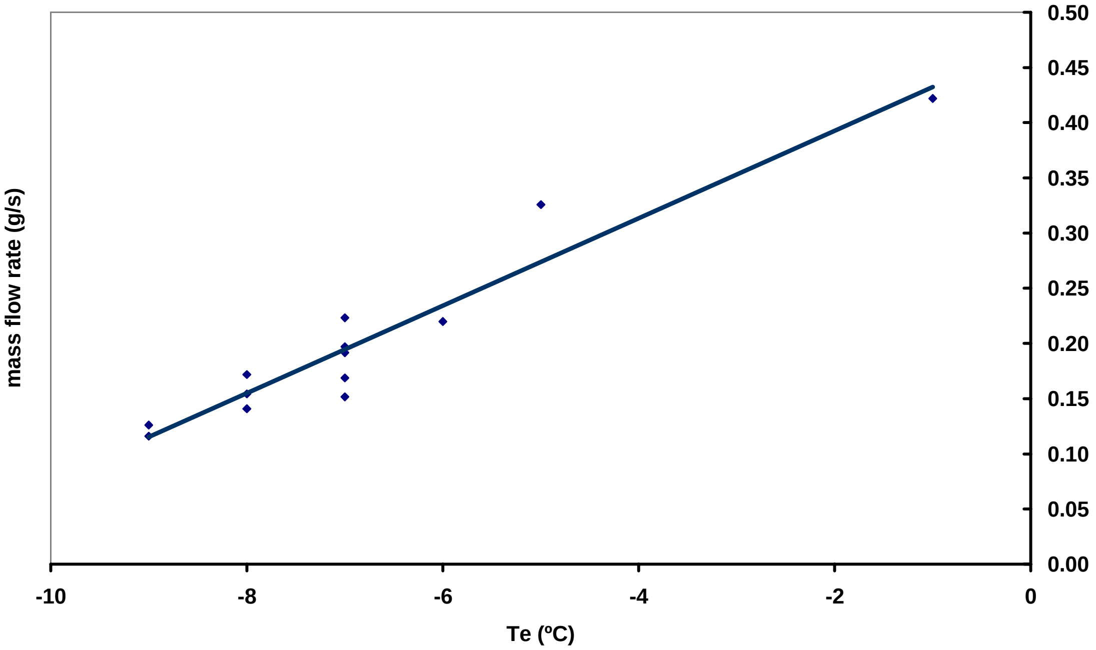

Figure 6.20. Mass flow rate vs. T_e for R-134a using solar power at T_c = 37 ºC and T_a = 27 ºC

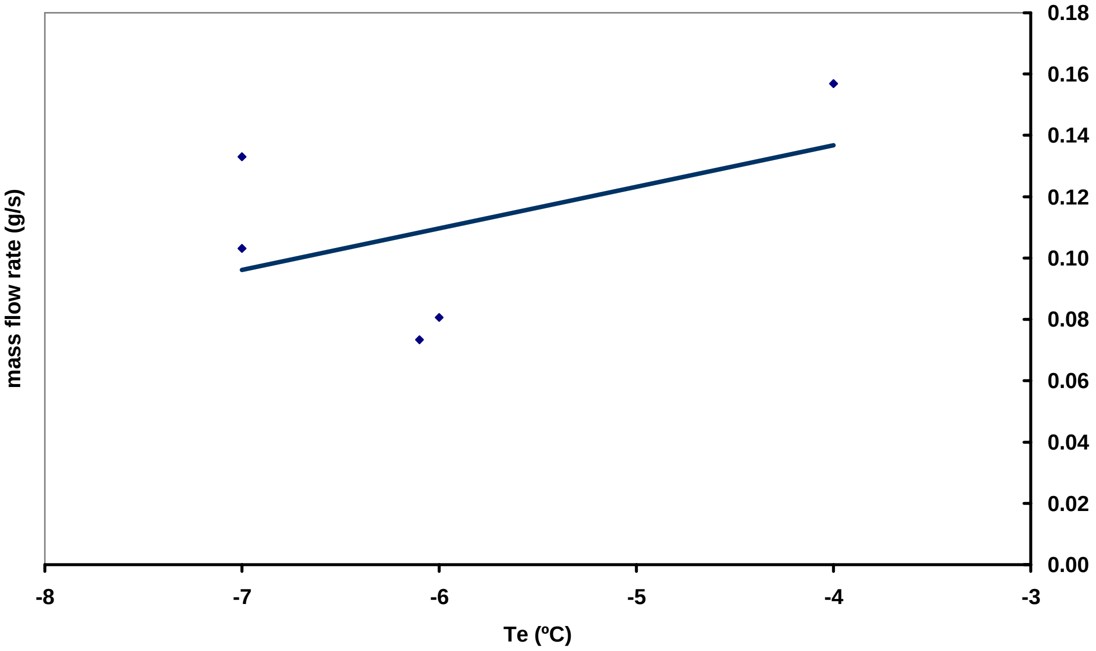

Figure 6.21. Mass flow rate vs. T_e for LPG using electrical power at $T_c = 37$ ºC and $T_a = 27$ ºC

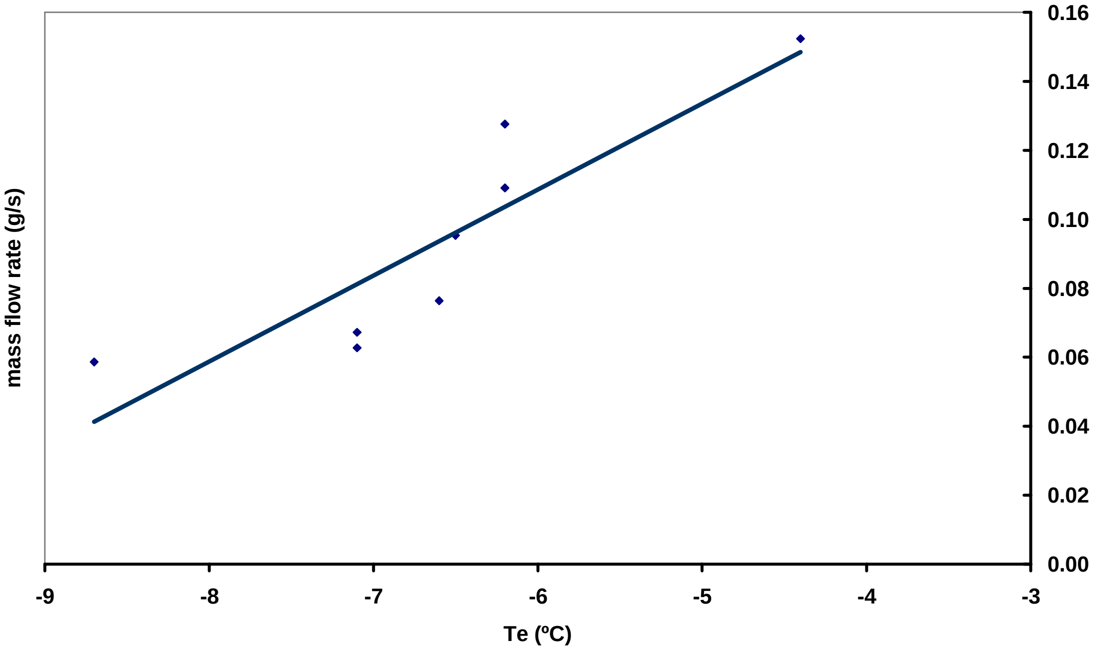

Figure 6.22. Mass flow rate vs. T_e for LPG using solar power at $T_c = 37$ ºC and $T_a = 27$ ºC

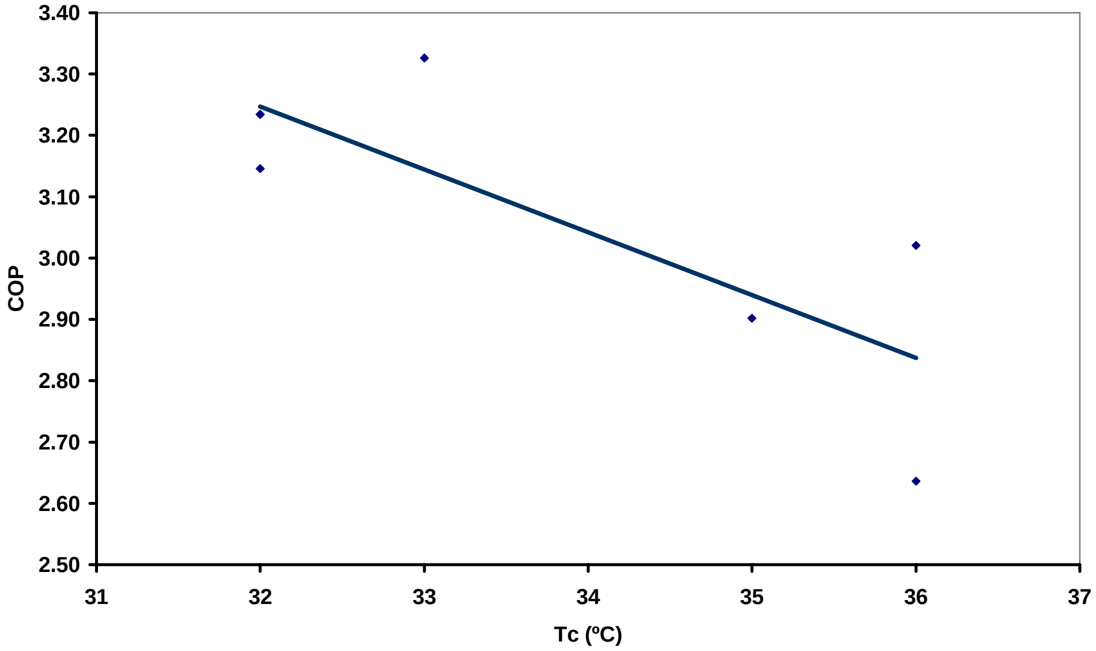

Figure 6.23. COP vs. T_c for R-134a using electrical power at T_e = -9 ºC and T_a = 27 ºC

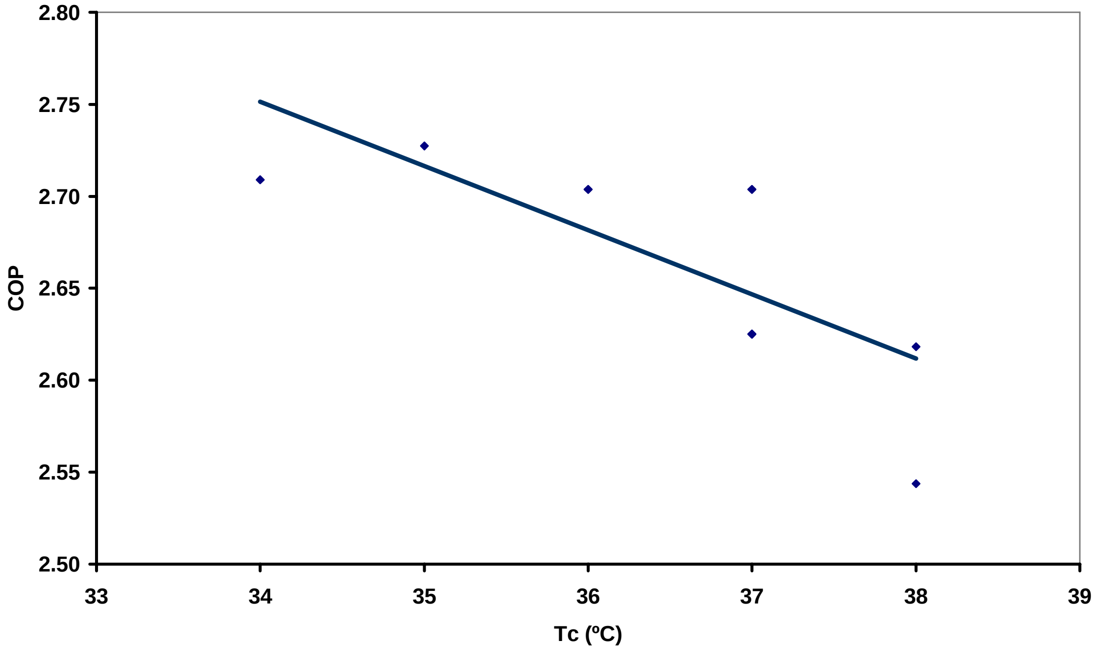

Figure 6.24. COP vs. T_c for R-134a using solar power at T_e = -9 ºC and T_a = 27 ºC

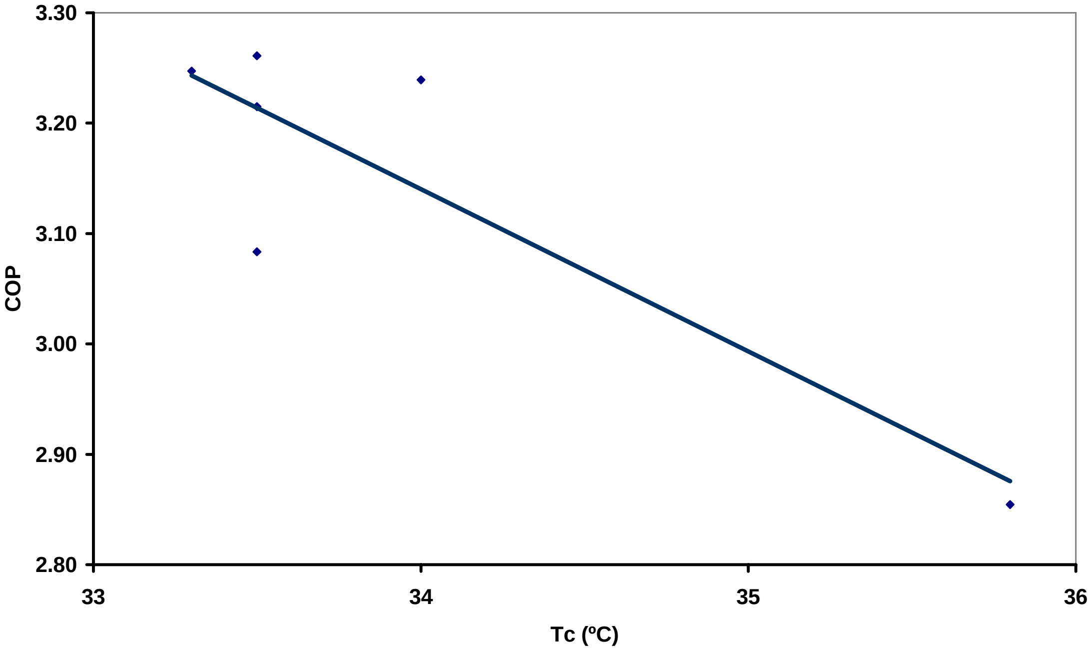

Figure 6.25. COP vs. T_c for LPG using electrical power at T_e = -9 ºC and T_a = 27 ºC

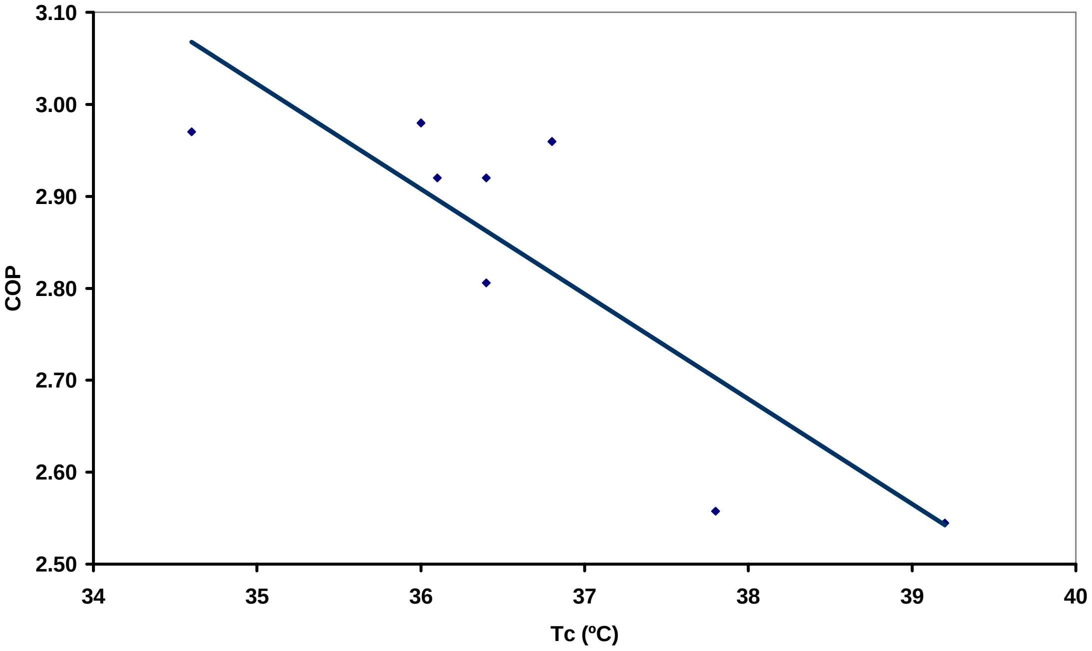

Figure 6.26. COP vs. T_c for LPG using solar power at T_e = -9 ºC and T_a = 27 ºC

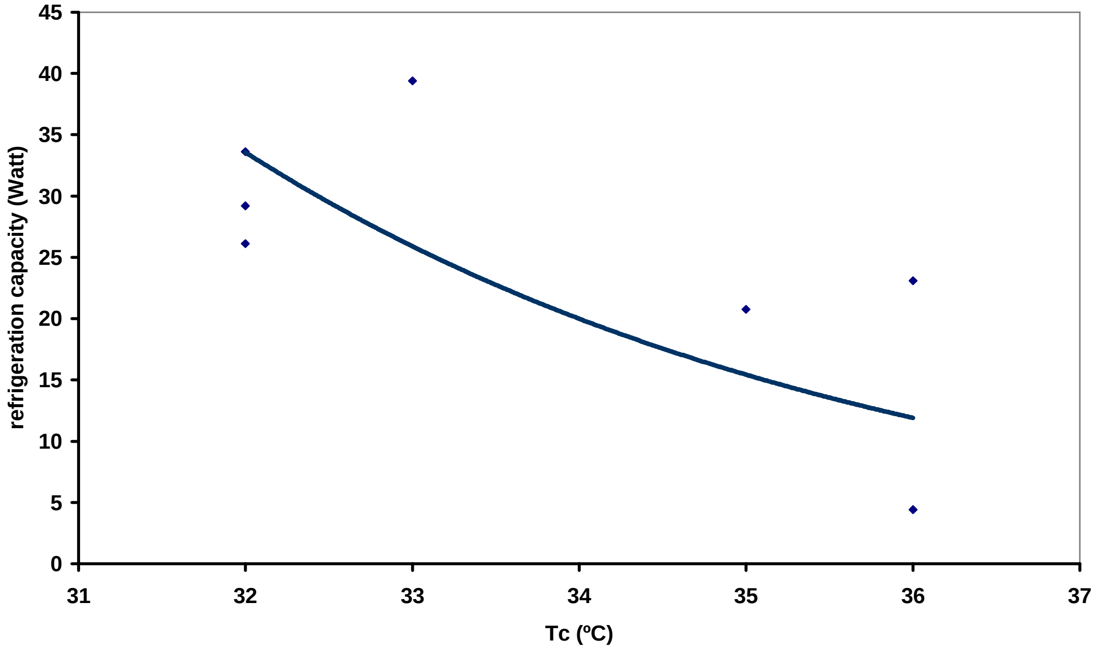

Figure 6.27. Refrigeration capacity vs. T_c for R-134a using electrical power at T_e = -9 ºC and T_a = 27 ºC

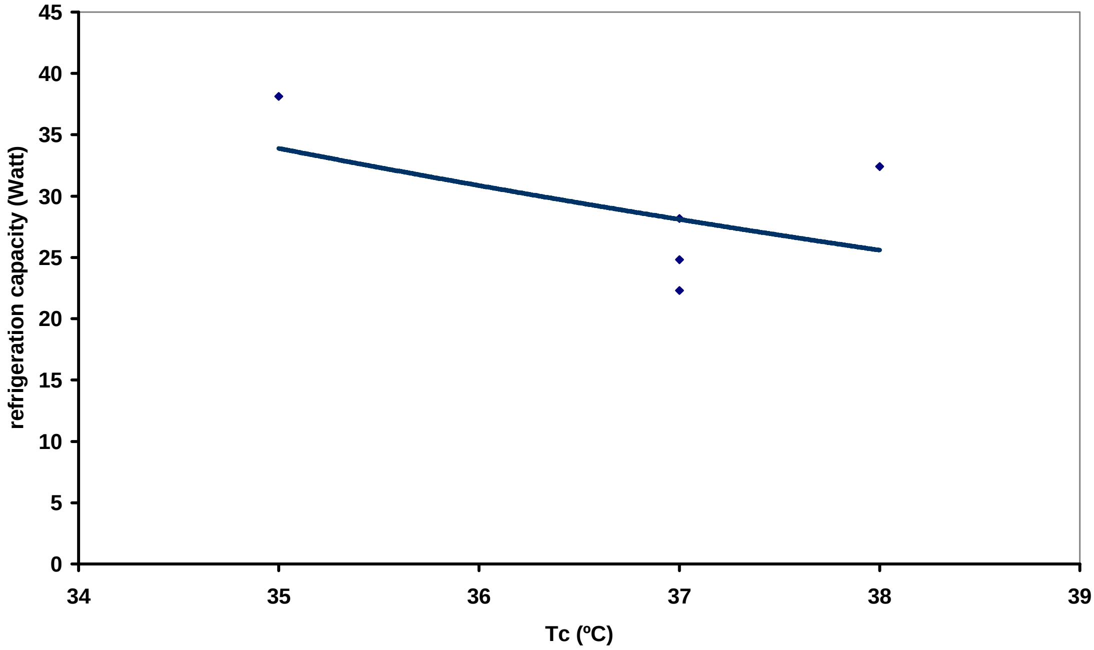

Figure 6.28. Refrigeration capacity vs. T_c for R-134a using solar power at T_e = -9 ºC and T_a = 27 ºC

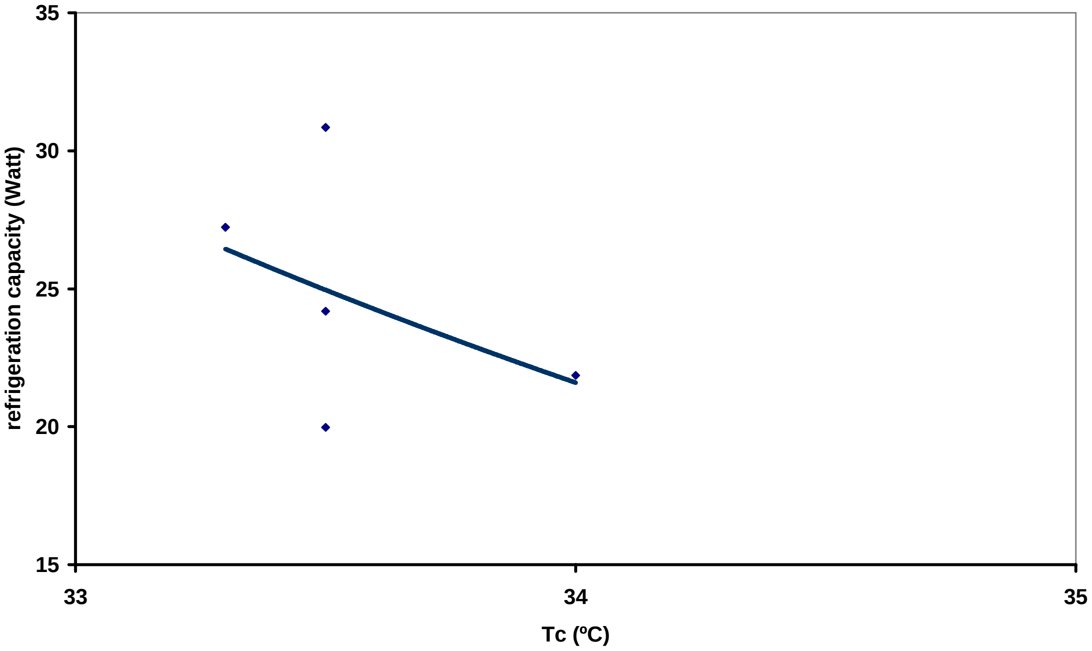

Figure 6.29. Refrigeration capacity vs. T_c for LPG using electrical power at T_e = -9 ºC and T_a = 27 ºC

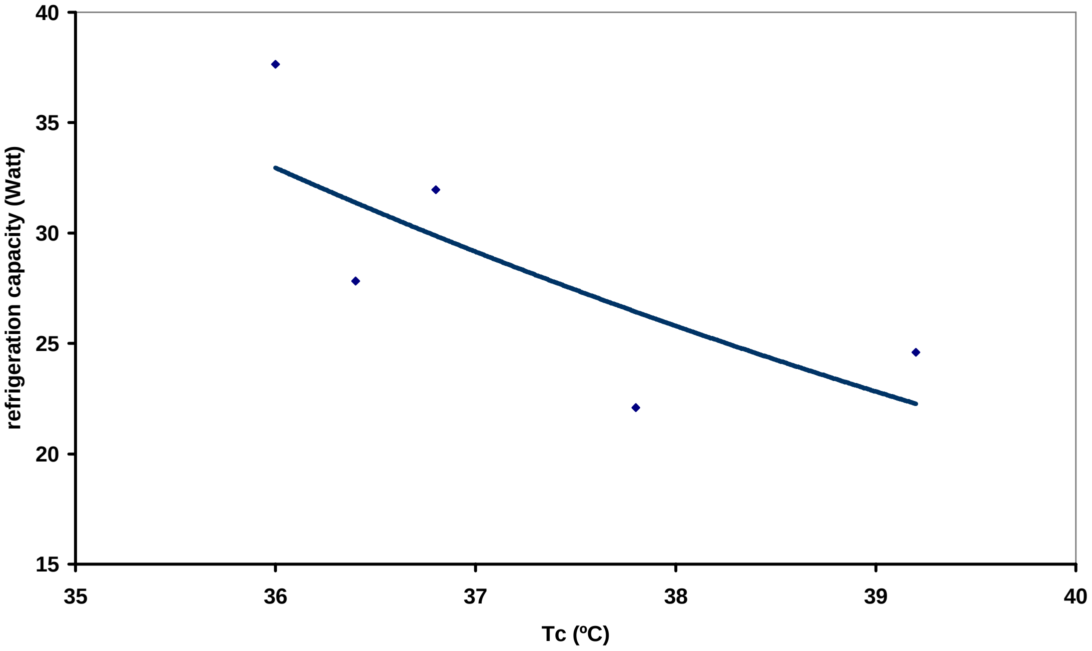

Figure 6.30. Refrigeration capacity vs. T_c for LPG using solar power at T_e = -9 ºC and T_a = 27 ºC

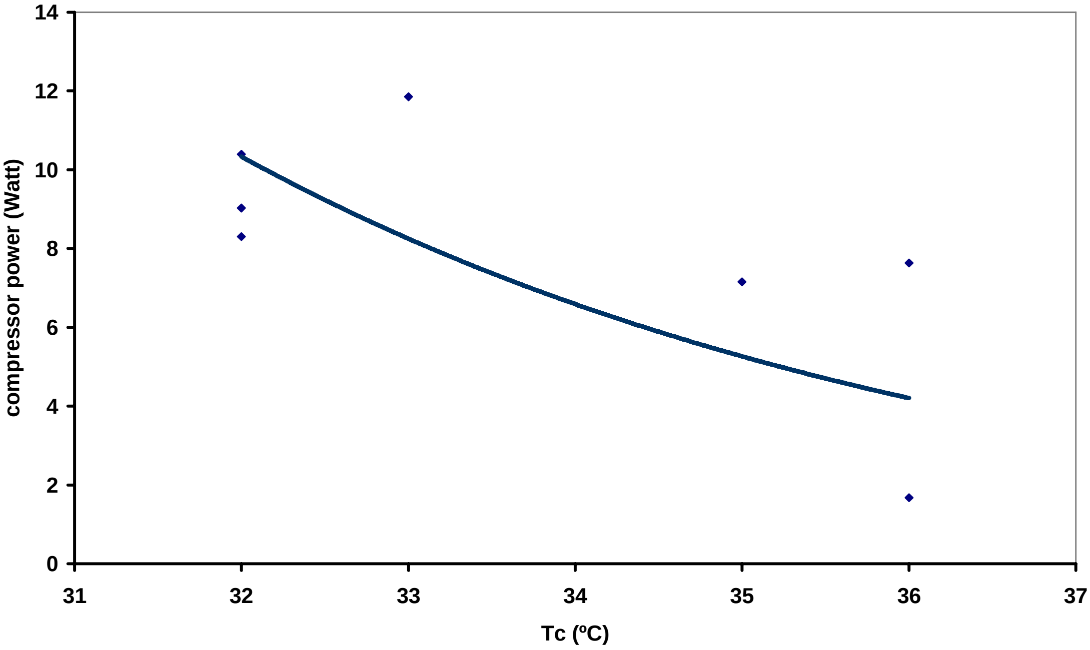

Figure 6.31. Compressor power vs. T_c for R-134a using electrical power at T_e = -9 ºC and T_a = 27 ºC

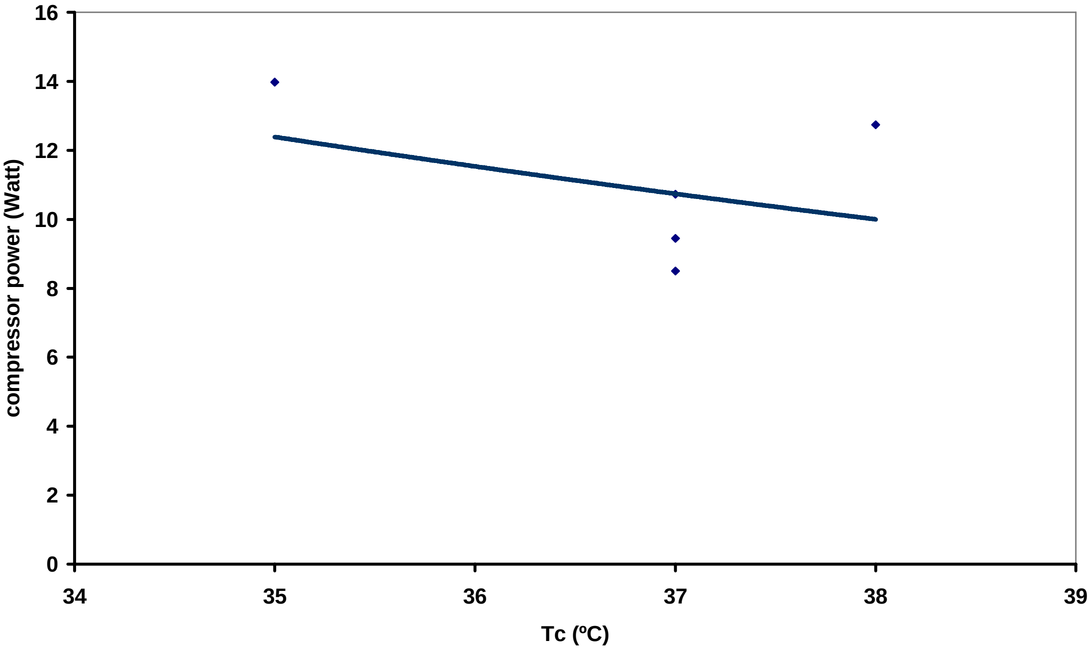

Figure 6.32. Compressor power vs. T_c for R-134a using solar power at T_e = -9 ºC and T_a = 27 ºC

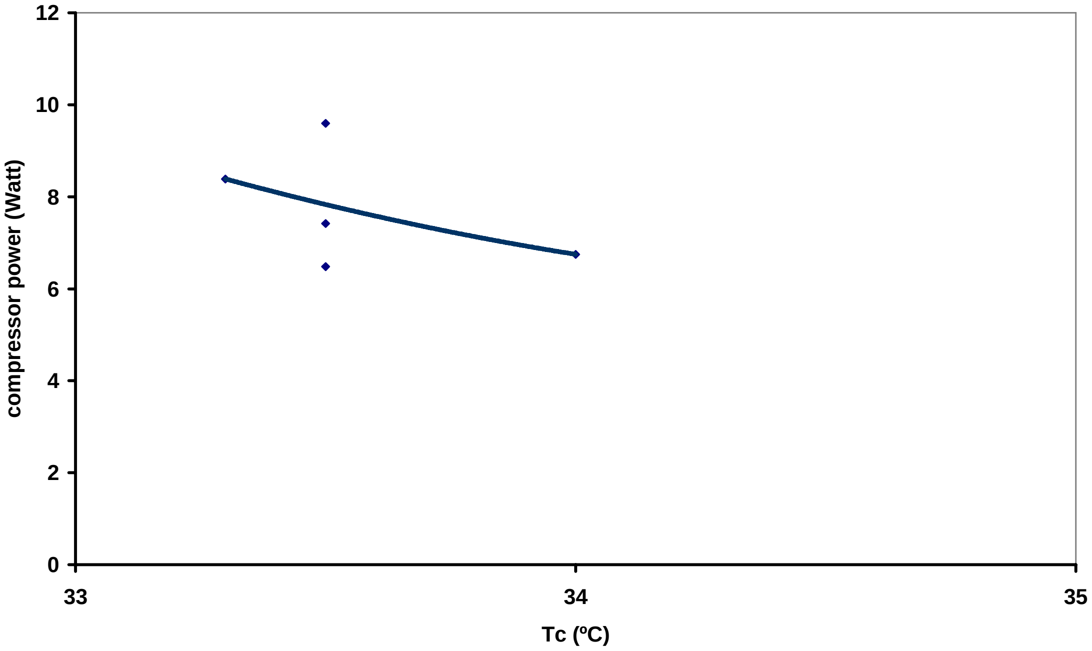

Figure 6.33. Compressor power vs. T_c for LPG using electrical power at T_e = -9 ºC and T_a = 27 ºC

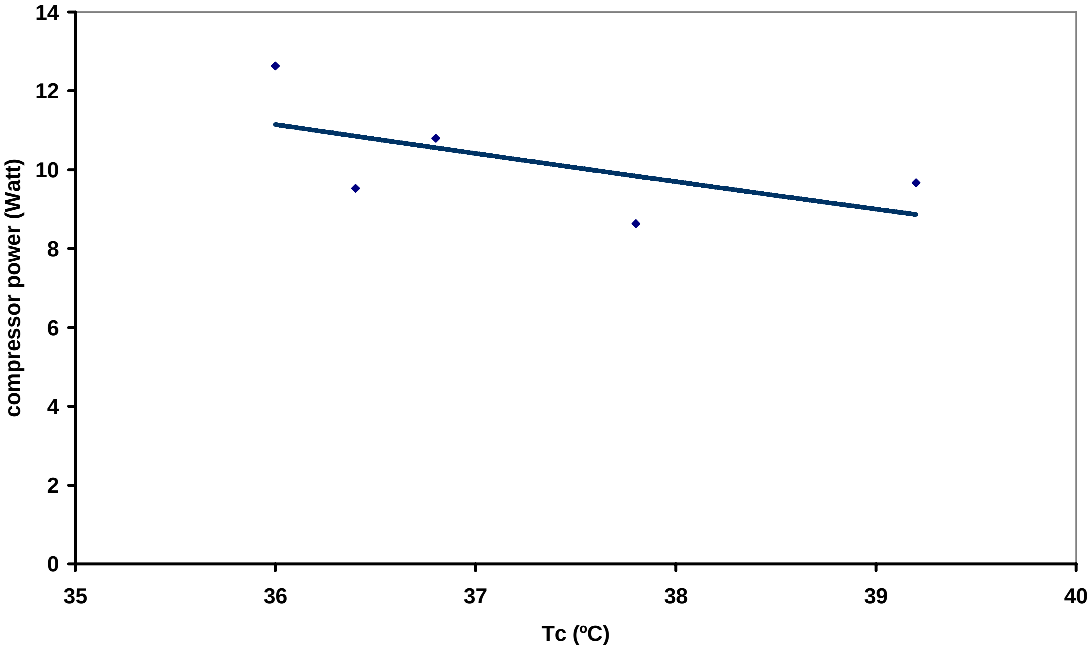

Figure 6.34. Compressor power vs. T_c for LPG using solar power at T_e = -9 ºC and T_a = 27 ºC

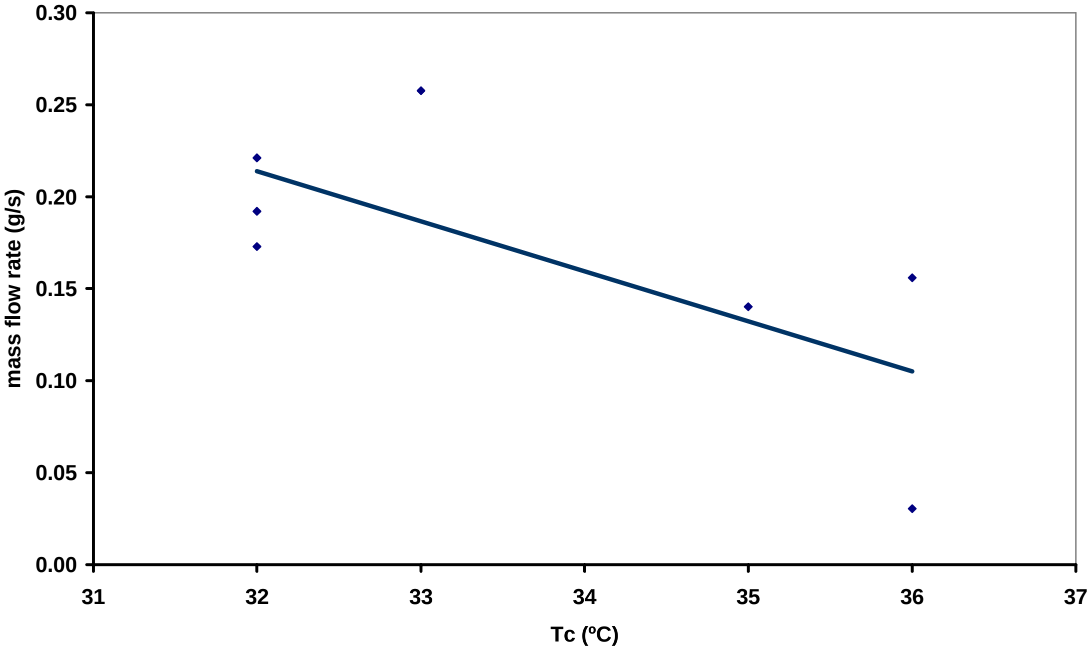

Figure 6.35. Mass flow rate vs. T_c for R-134a using electrical power at T_e = -9 ºC and T_a = 27 ºC

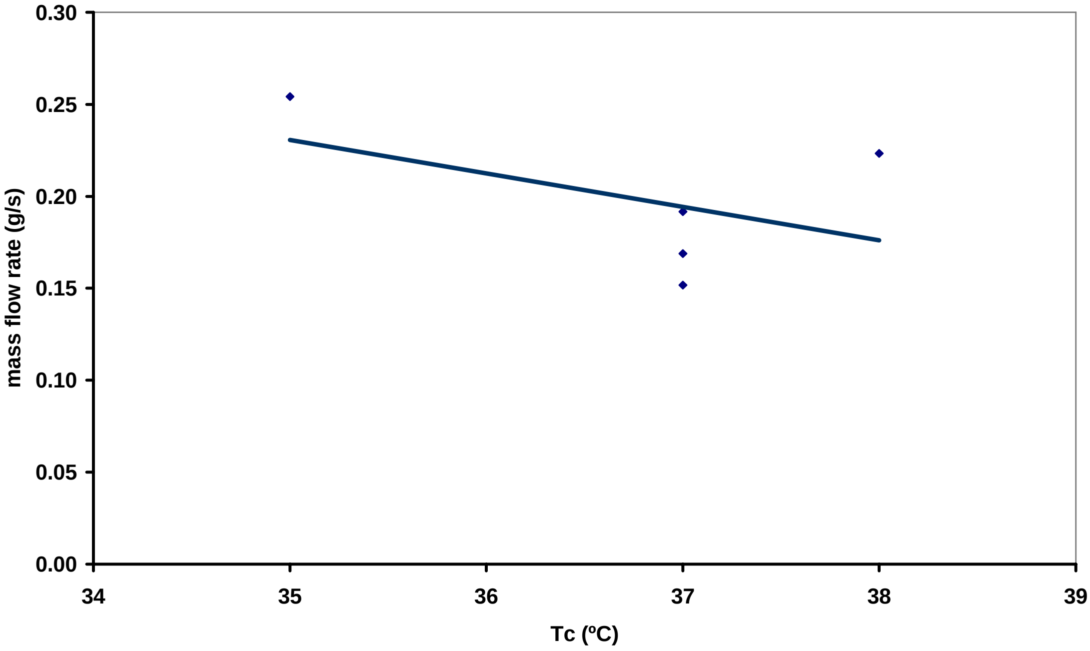

Figure 6.36. Mass flow rate vs. T_c for R-134a using solar power at T_e = -9 ºC and T_a = 27 ºC

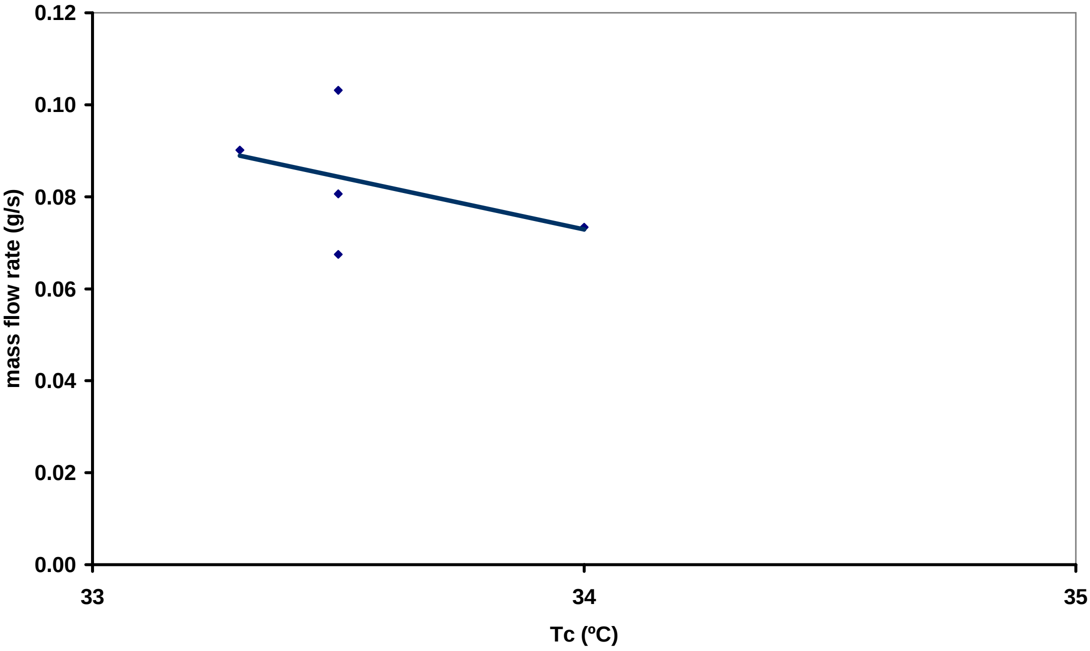

Figure 6.37. Mass flow rate vs. T_c for LPG using electrical power at

T_e = -9 ºC and T_a = 27 ºC

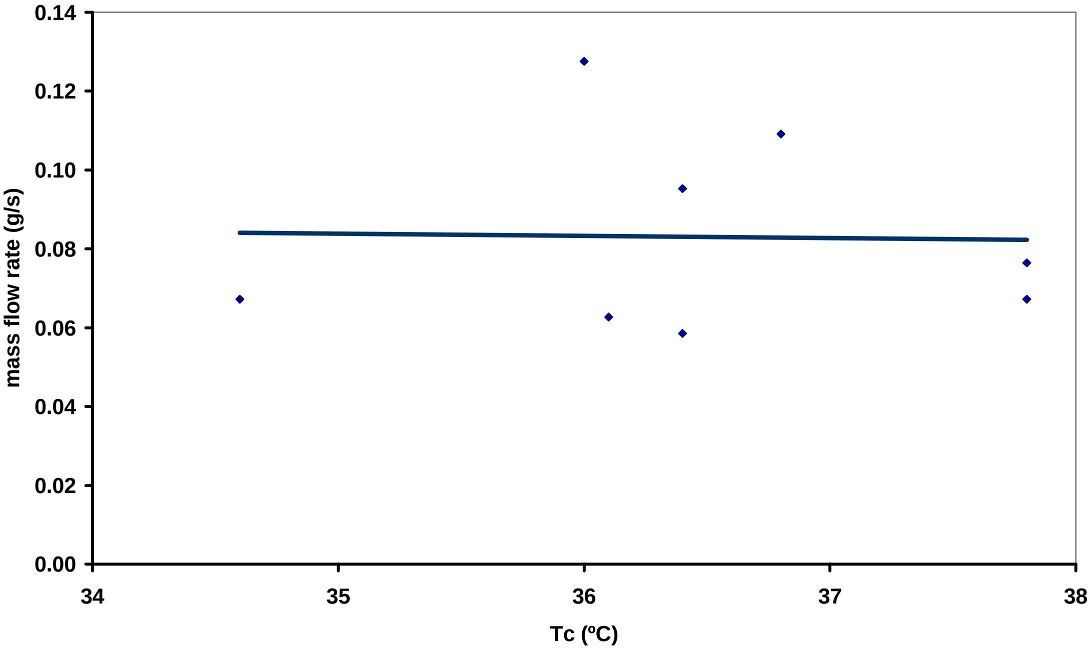

Figure 6.38. Mass flow rate vs. T_c for LPG using solar power at

T_e = -9 ºC and T_a = 27 ºC

6.6 Comparison of the performance of all mixtures with R-134a

For all mixtures the COP, refrigeration capacity, power consumption and refrigerant mass flow rate were presented graphically against evaporation temperature T_e, at constant T_c, when using both electrical and solar power.

The COP is presented in Figure 6.39 and 6.40 against T_e, for electrical and solar power respectively. Refrigeration capacity is presented in Figure 6.41 and 6.42 against T_e, for electrical and solar power respectively. Power consumption is presented in Figure 6.43 and 6.44 against T_e, for electrical and solar power respectively. Refrigerant mass flow rate is presented in Figure 6.45 and 6.46 against T_e, for electrical and solar power respectively.

6.6.1 Coefficient of performance

For all mixtures, it was noticed that as evaporating temperature increases with constant condensing temperature, the COP will increase. These results were indicated by refrigerants behavior shown by Figure 6.39 and 6.40 when using electrical and solar power respectively. From those Figures it can be noticed that the highest COP was for LPG, followed by R-134a, 50% propane / 50% butane, 70% propane / 30% butane and the lowest COP was when using pure propane.

In average and compared to COP of R-134a at constant Tc, the LPG gave a COP about 6% higher, but for 50% propane / 50% butane it was 10% lower, also for 70% propane / 30% butane it was 19% lower, then the lowest COP was when using pure propane which gave 32% lower than R-134a COP.

This yield the result that when increasing the percentage of propane in the mixture the power consumption increases (COP decreases) until reach it maximum when use propane, this is due to the high pressure of propane, which in turn require more compressor power to compress.

6.6.2 Refrigeration capacity

For all mixtures it was noticed that the refrigeration capacity increases as the evaporating temperature increases at a constant condensing temperature. These results were indicated by refrigerants behavior shown by Figure 6.41 and 6.42 when using electrical and solar power respectively. From those Figures it can be noticed that the highest refrigeration capacity was for pure propane, followed 70% propane / 30% butane, R-134a, LPG, and the lowest refrigeration capacity was when using 50% propane / 50% butane.

6.6.3 Power consumption

The compressor power increases with increasing the evaporating temperature, for all mixtures. These results were indicated by refrigerants behavior shown by Figure 6.43 and 6.44 when using electrical and solar power respectively. From those Figures it can be noticed that the highest power consumption was for pure propane, followed 70% propane / 30% butane, R-134a, LPG, and the lowest power consumption was when using 50% propane / 50% butane.

6.6.4 Refrigerant mass flow rate

As evaporating temperature increases, the refrigerant mass flow rate increases at constant condensing temperature, for all mixtures. These results were indicated by refrigerants behavior shown by Figure 6.45 and 6.46 when using electrical and solar power respectively. From those Figures it can be noticed that the highest refrigerant mass flow rate was for R-134a, followed by pure propane, 70% propane / 30% butane, LPG, and the lowest refrigerant mass flow rate was when using 50% propane / 50% butane.

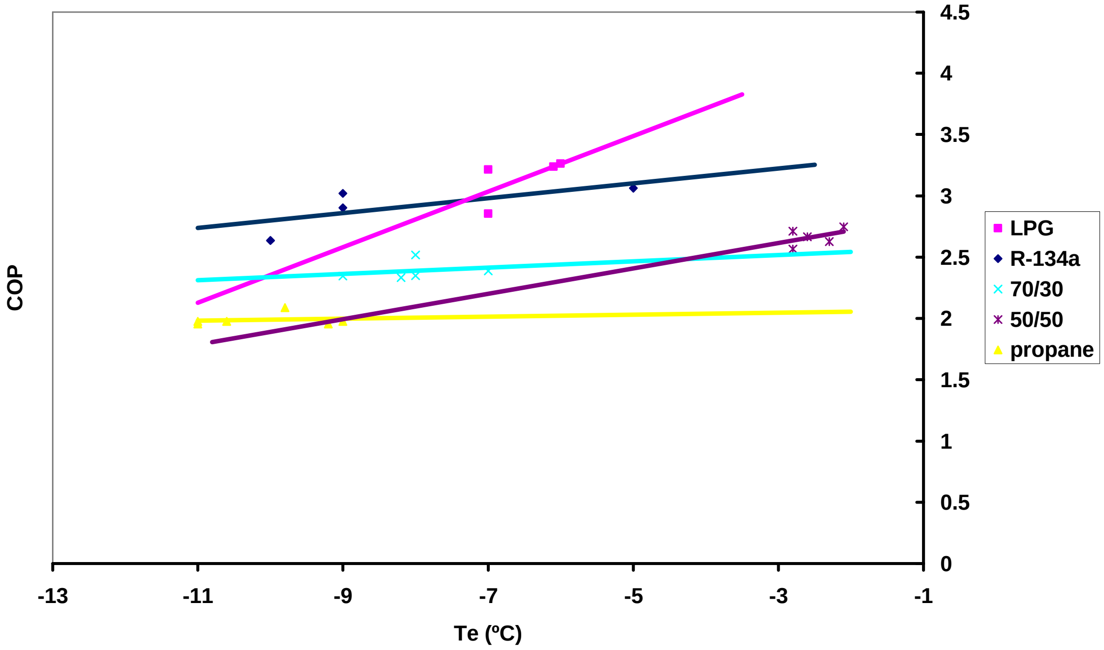

Figure 6.39. COP vs. T_e for all mixtures using electrical power at

T_c = 37 ºC and T_a = 27 ºC

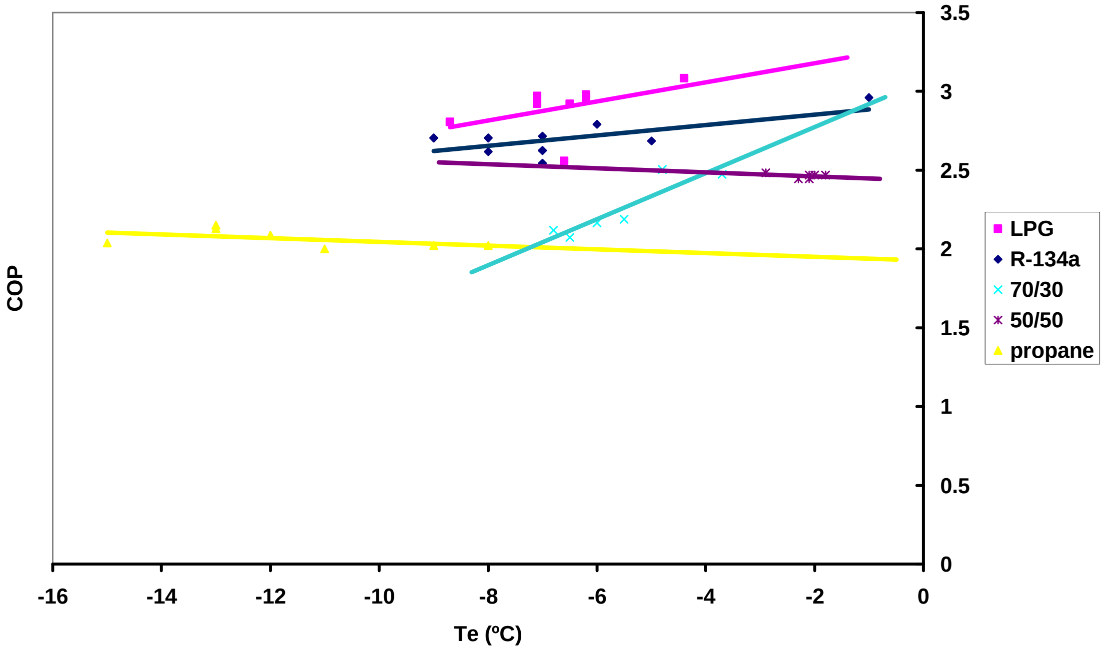

Figure 6.40. COP vs. T_e for all mixtures using solar power at

T_c = 37 ºC and T_a = 27 ºC

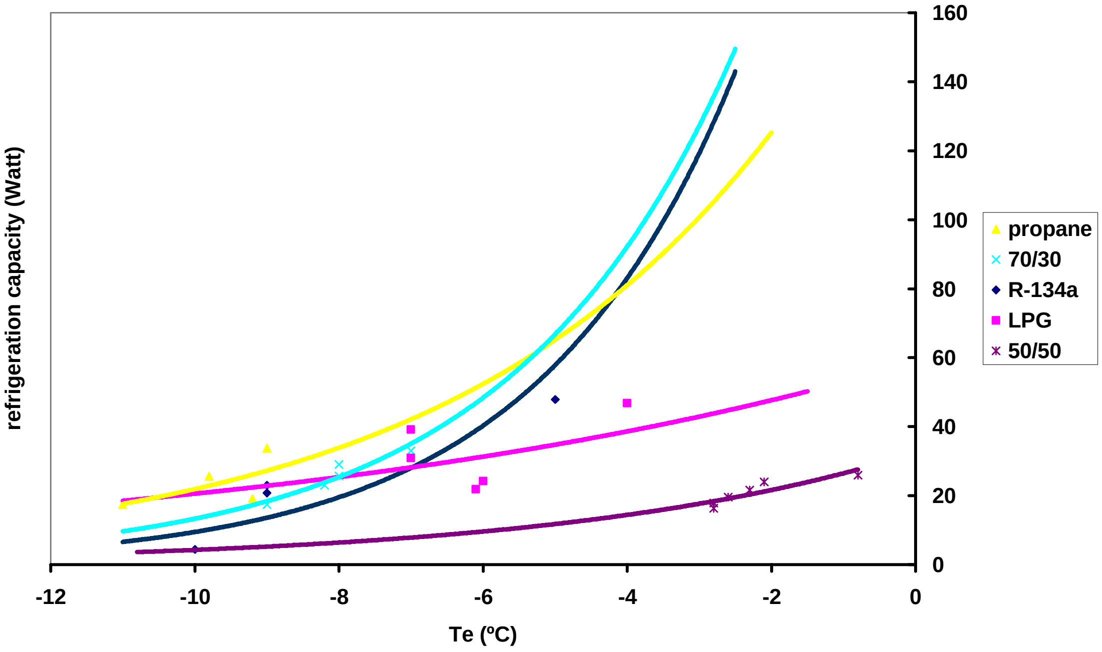

Figure 6.41. Refrigeration capacity vs. T_e for all mixtures using electrical power at $T_c = 37$ ºC and $T_a = 27$ ºC

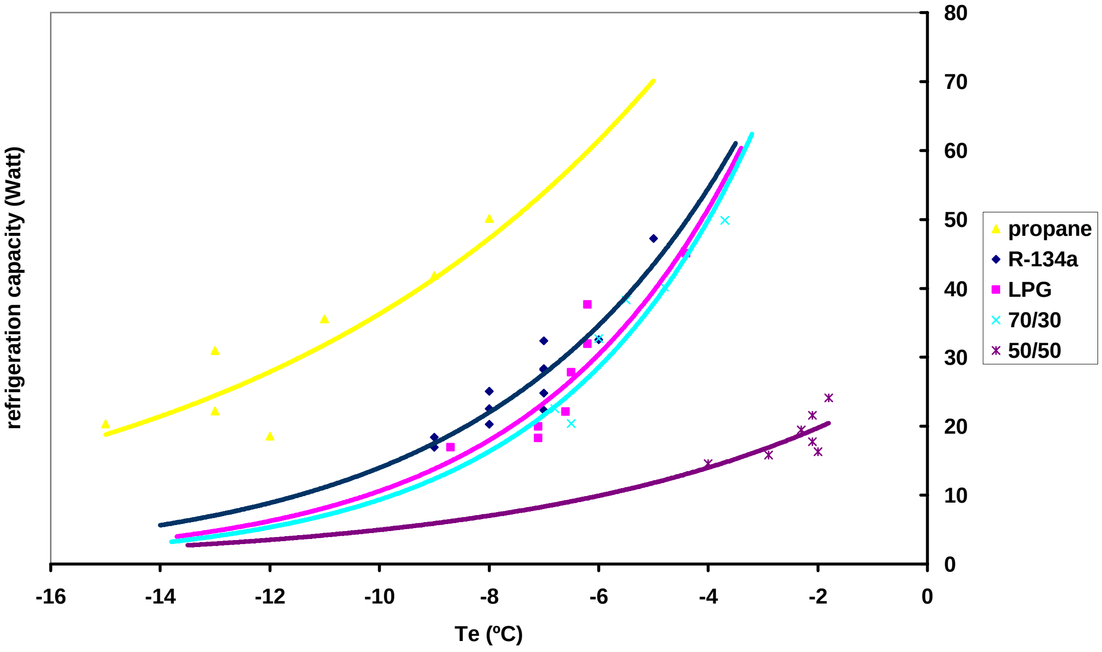

Figure 6.42. Refrigeration capacity vs. T_e for all mixtures using solar power at $T_c = 37$ ºC and $T_a = 27$ ºC

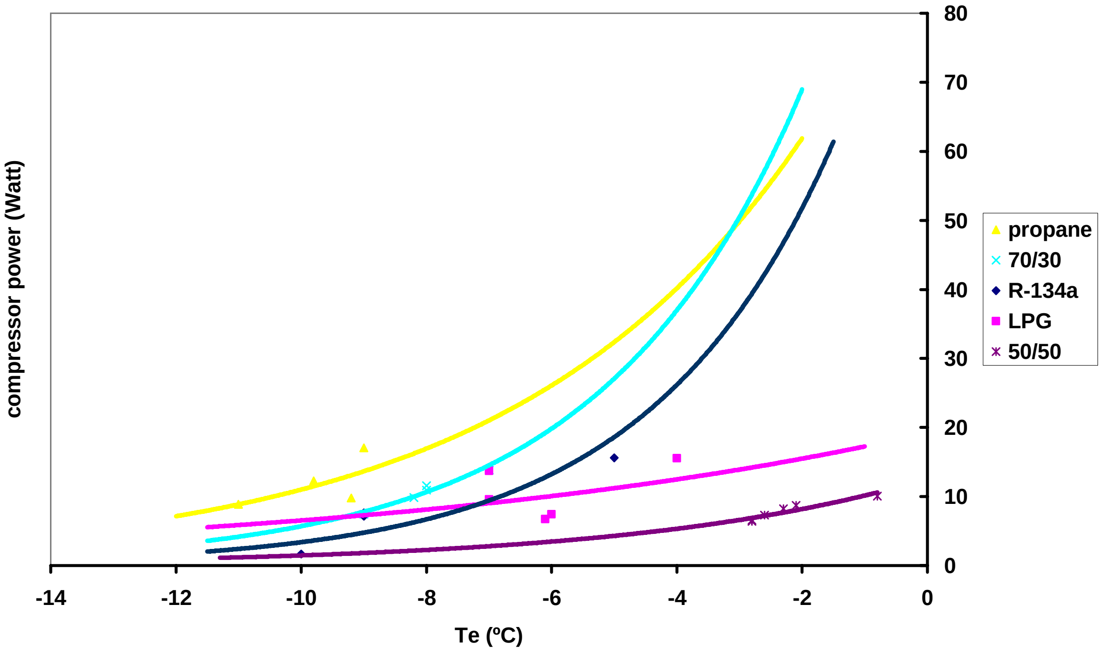

Figure 6.43. Compressor power vs. T_e for all mixtures using electrical power at T_c = 37 ºC and T_a = 27 ºC

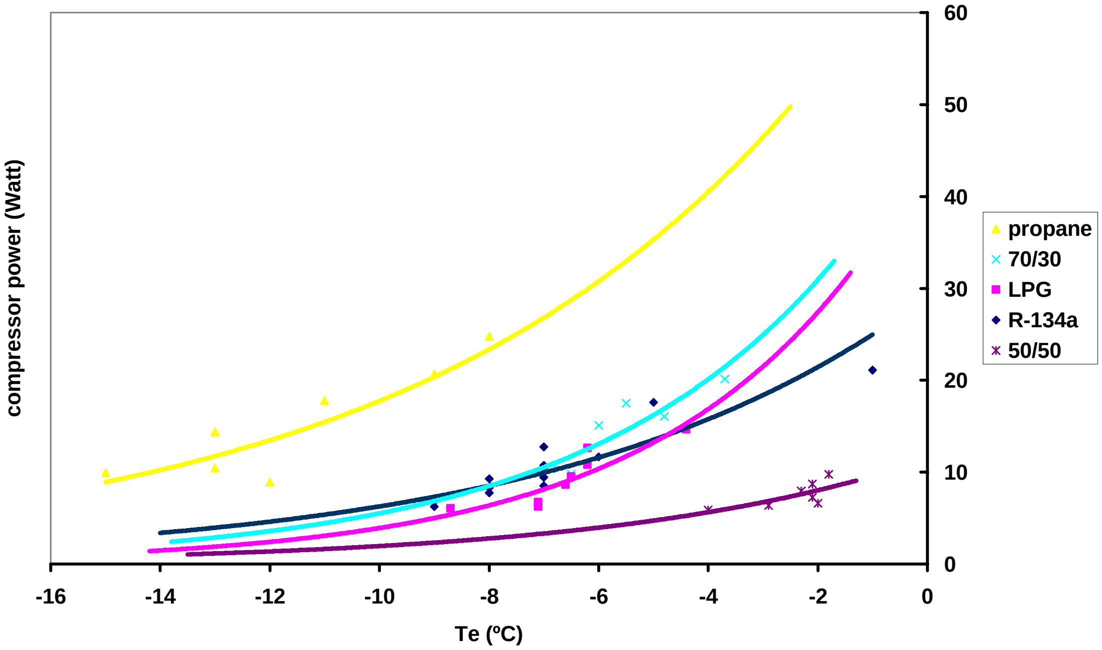

Figure 6.44. Compressor power vs. T_e for all mixtures using solar power at T_c = 37 ºC and T_a = 27 ºC

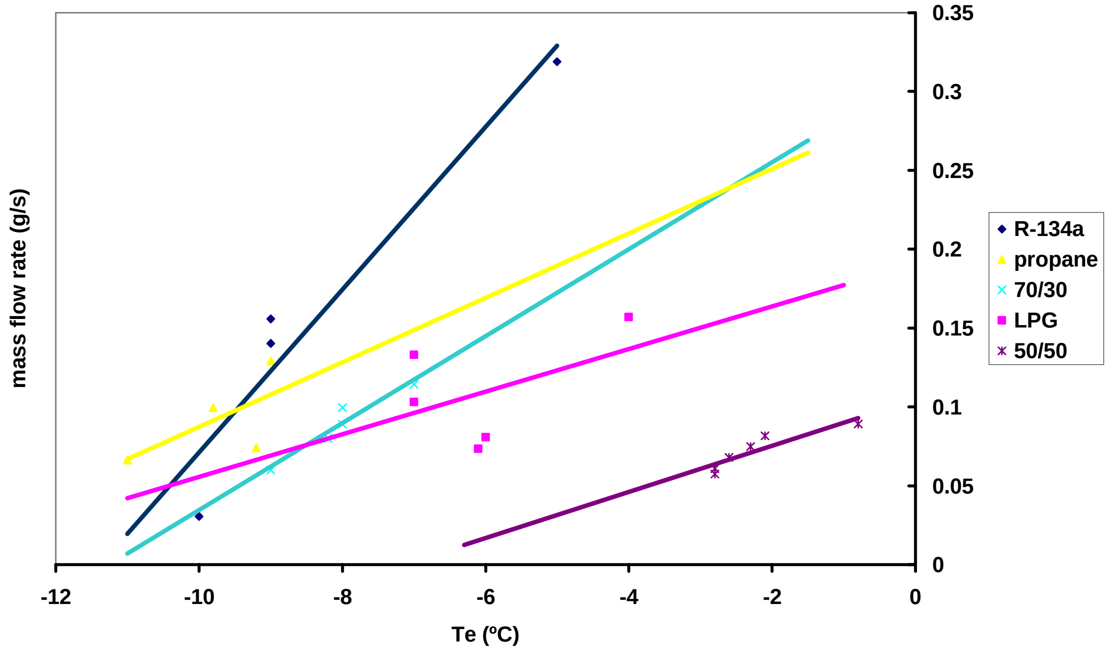

Figure 6.45. Mass flow rate vs. T_e for all mixtures using electrical power at T_c = 37 ºC and T_a = 27 ºC

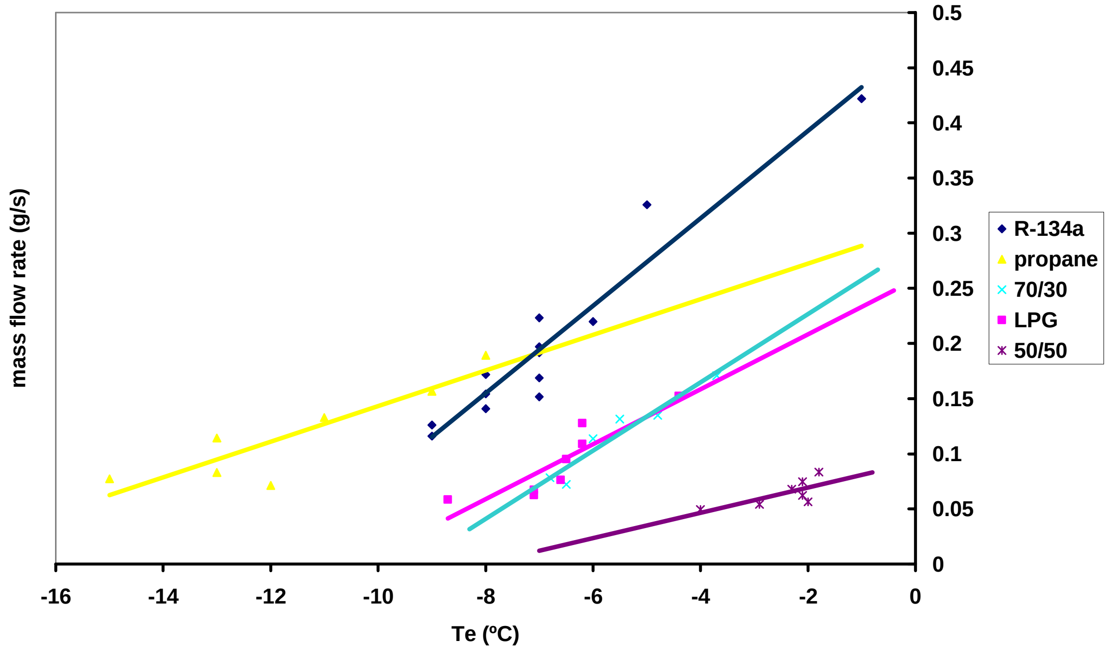

Figure 6.46. Mass flow rate vs. T_e for all mixtures using solar power at T_c = 37 ºC and T_a = 27 ºC

Chapter Seven

CONCLUSIONS AND RECOMMENDATIONS

7.1 Conclusions

In this work the performance study of a solar refrigerator using a mixture of propane and butane with different ratios as a replacement to R-134a refrigerant was studied experimentally.

The mixtures used were LPG, 70% propane and 30% butane, 50% propane and 50% butane and pure propane; the refrigerator was tested without any modifications using electrical and solar power. The performance of the mixtures was compared to that of R-134a, and the following conclusions were deduced:

1. The performance of LPG mixture was fairly close to that of R-134a, then the performance was degraded down while raising the propane percentage in the mixture until the use of pure propane, which gave the lowest performance compared to R-134a.
2. The highest COP value recorded was 3.33, 3.49, 3.13, 3.09 and 2.54 for R-134a, LPG, 50% propane / 50% butane, 70% propane / 30% butane and pure propane respectively.
3. Compared to COP of R-134a at constant Tc, the LPG gave a COP about 6% higher, but 50% propane and 50% butane was 10% lower than that of R-134a, also 70% propane and 30% butane was 19% lower than that in R-134a, then the lowest COP was in the case of propane which gave 32% lower than R-134a COP.

4. The lowest evaporator temperature recorded was -10 ºC, -9 ºC, -4 ºC , -9 ºC and -15 ºC for R-134a, LPG, 50% propane / 50% butane, 70% propane / 30% butane and pure propane respectively.
5. In case of using LPG the refrigerator saves about 7% of power, but for 50% propane and 50% butane it consumes 6% of power more than in R-134a, also for 70% propane and 30% butane it consumes 9% power more than in R-134a, then the most power consumed than in R-134a was in the case of propane which consumes 13% more.
6. It was noticed that after running for 17 hours, an ice formation occurs in the load when only using propane as a refrigerant, the ice layer was about 2 cm in thickness. A faster cooling (high cooling rate) was noticed when using propane as refrigerant, compared to other mixtures, also it gives the lowest evaporator temperature T_e = -15 ºC among all other mixtures.
7. The overall performance when using solar power was close to that when using electrical power, taking into consideration the modules and storage batteries required for such equipment and the period that the system need to run on the batteries only without solar power.
8. The maximum recorded photovoltaic-modules efficiency was 16% which is within the actual range of infield used modules, which depend on the type of each one.
9. The refrigerator needs no modifications or components replacement to run with these mixtures; the only need is to replace the old lubricant oil for R-134a (polyolester) by the mineral oil lubricant type.
10. During the period of running the experiment, no leakage or other effects were detected.

11. Since they have no side effect on ozone layer, also they have low effect on the global warming phenomena; and because they are locally available, low cost and satisfactory efficient; the propane and butane mixtures specially LPG (30% propane and 70% butane) are attractive substitutes to R-134a in domestic refrigerators running on either domestic electrical power or solar power source.

7.2 Recommendations

During the experimental procedures and after data analysis, the following recommendations could be taken into consideration for any future work related to this research topic:

1. The LPG (30% propane and 70% butane) is the recommended mixture between the used mixtures, to replace R-134a in small refrigeration systems.
2. Due to the result that the highest compressor efficiency recorded was 28%, it is recommended to use new refrigerators. To overcome any deficiencies or losses; then to get correct judgments.
3. The use of P.V around peak output hours of solar intensity are relatively high in this part of the world (about 7 hours in summer in average), so the use and utilization of solar power among all applications (especially in-house) is attractive and recommended.
4. Large refrigeration and air-conditioning systems should be tested and investigated using propane / butane mixtures inline with the usage of solar power.
5. Each component efficiency in solar system need to be investigated separately to enhance the whole system performance.

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APPENDICES

APPENDIX A: Data and Results

APPENDIX B: Saturated Properties for R-134a

Superheated Properties for R-134a

Saturated Properties for Propane

Saturated Properties for Butane

Pressure-Enthalpy diagram for Propane

Pressure-Enthalpy diagram for Butane

APPENDIX A

Data and Results

Table A.1 R-134a on electrical power (starting at 09:25 AM on September 23rd) with 1 liter of hot water at 86 °C

DATA									
Δt (min)	T1 (°C)	T2 (°C)	T3 (°C)	T4 (°C)	T5 (°C)	T6 (°C)	T7 (°C)	Ta (°C)	Iref (Amp)
30	3	66	44	39	3	18	47	27	0.46
60	0	62	38	33	0	13	33	26	0.44
90	-5	60	36	32	-5	10	25	26	0.44
120	-7	56	33	30	-7	8	19	26	0.43
150	-9	55	32	29	-9	6	15	25	0.43
180	-9	54	32	29	-9	5	12	25	0.45
210	-10	54	32	29	-10	4	9	25	0.45
240	-9	58	36	32	-9	4	8	25	0.45
270	-9	59	35	32	-9	5	7	25	0.45

RESULTS								
P1 (MPa)	P2 (MPa)	h1 (kJ/kg)	h2 (kJ/kg)	h3 (kJ/kg)	COP	m' (g/s)	W (Watt)	Qref (Watt)
0.33	1.13	249	295	105	3.13	0.67	30.72	96.18
0.29	0.96	247	294	96	3.21	0.42	19.80	63.60
0.24	0.91	244	293	94	3.06	0.32	15.62	47.83
0.23	0.84	244	290	91	3.33	0.26	11.85	39.41
0.21	0.82	242	289	90	3.23	0.22	10.40	33.62
0.21	0.82	242	289	90	3.23	0.19	9.03	29.20
0.2	0.82	241	289	90	3.15	0.17	8.30	26.11
0.21	0.91	242	291	94	3.02	0.16	7.64	23.08
0.21	0.89	242	293	94	2.90	0.14	7.16	20.77

Table A.2 R-134a on solar power (starting at 08:15 AM on September 24th) with 1 liter of hot water at 84 ºC

DATA												
Δt min	T1 ºC	T2 ºC	T3 ºC	T4 ºC	T5 ºC	T6 ºC	T7 ºC	Ta ºC	Iref Amp	Solar Intensity W/m²	Isolar Amp	Battery Voltage Volt
30	3	69	43	38	3	17	47	23	0.51	622	2.6	24.5
60	-1	66	39	35	-1	12	32	23	0.5	871	3.6	24.7
90	-5	66	38	35	-5	9	24	24	0.5	970	3.8	24.8
120	-7	64	35	32	-7	8	19	23	0.49	1120	4	24.4
150	-7	65	38	35	-7	6	15	24	0.49	1194	4.2	24.9
180	-7	66	37	34	-7	6	12	24	0.49	1222	4.4	25
210	-7	66	37	34	-7	6	10	26	0.49	1280	4.4	25.2
240	-7	66	37	34	-7	5	8	26	0.49	1300	4.4	25.2
270	-9	63	34	31	-9	4	7	24	0.49	1275	4.4	25.1
300	-9	63	36	33	-9	3	6	24	0.49	1220	3.5	24.8
330	-9	63	36	33	-9	3	5	25	0.49	1170	3.3	24.6

RESULTS								
P1 MPa	P2 MPa	h1 kJ/kg	h2 kJ/kg	h3 kJ/kg	COP	m' g/s	W Watt	Qref Watt
0.33	1.1	249	301	103	2.81	0.63	32.73	91.89
0.28	0.99	247	297	99	2.96	0.42	21.09	62.43
0.24	0.96	244	298	99	2.69	0.33	17.60	47.25
0.23	0.89	244	299	94	2.73	0.25	13.98	38.13
0.23	0.96	244	301	99	2.54	0.22	12.74	32.40
0.23	0.94	244	300	97	2.63	0.19	10.73	28.17
0.23	0.94	244	300	97	2.63	0.17	9.45	24.81
0.23	0.94	244	300	97	2.63	0.15	8.50	22.30
0.21	0.86	242	297	93	2.71	0.14	7.46	20.20
0.21	0.91	242	296	96	2.70	0.13	6.81	18.42
0.21	0.91	242	296	96	2.70	0.12	6.27	16.96

Table A.3 R-134a on solar power (starting at 08:55 AM on September 25th) with 1 liter of hot water at 83 ºC

DATA												
Δt min	T1 ºC	T2 ºC	T3 ºC	T4 ºC	T5 ºC	T6 ºC	T7 ºC	Ta ºC	Iref Amp	Solar Intensity W/m²	Isolar Amp	Battery Voltage Volt
30	3	63	45	41	3	15	36	26	0.53	805	3.2	24.2
60	0	64	40	37	0	12	30	27	0.53	855	3.4	24.4
90	1	62	42	37	1	11	24	27	0.54	967	3.7	24.5
120	-3	63	40	36	-3	8	21	26	0.54	1007	3.7	24.6
150	-6	64	37	33	-6	6	15	26	0.54	1060	3.9	24.7
180	-7	65	39	36	-7	5	12	26	0.54	1085	3.9	24.8
210	-8	64	37	34	-8	4	10	26	0.54	1130	3.9	24.8
240	-8	64	37	34	-8	4	8	26	0.54	1126	3.7	24.8
270	-8	65	38	35	-8	4	7	26	0.54	1086	3.6	24.8

RESULTS								
P1 MPa	P2 MPa	h1 kJ/kg	h2 kJ/kg	h3 kJ/kg	COP	m' g/s	W Watt	Qref Watt
0.33	1.16	249	292	108	3.28	0.79	34.07	111.70
0.29	1.02	247	297	102	2.90	0.43	21.41	62.10
0.3	1.07	248	293	102	3.24	0.32	14.26	46.27
0.26	1.02	245	295	100	2.90	0.25	12.67	36.75
0.23	0.94	244	297	96	2.79	0.22	11.65	32.53
0.23	0.99	244	297	100	2.72	0.20	10.44	28.37
0.22	0.94	243	297	97	2.70	0.17	9.27	25.06
0.22	0.94	243	297	97	2.70	0.15	8.33	22.52
0.22	0.96	243	298	99	2.62	0.14	7.74	20.28

Table A.4 LPG on electrical power (starting at 08:27 AM on September 9th) with 1 liter of hot water at 85 °C

DATA

Δt (min)	T1 (°C)	T2 (°C)	T3 (°C)	T4 (°C)	T5 (°C)	T6 (°C)	T7 (°C)	Ta (°C)	Iref (Amp)
30	7	58	44	38	7	23	51	26	0.45
60	2	57	40	35	2	17	37	27	0.46
90	-4	56	37	32	-4	12	27	25	0.46
120	-7	55	36	32	-7	9	21	26	0.44
165	-7	52	34	30	-7	8	15	26	0.44
195	-7	52	33	29	-7	6	12	26	0.44
225	-6	53	34	30	-6	6	10	27	0.43
255	-6	53	34	31	-6	5	8	26	0.43
285	-9	52	34	30	-9	4	7	26	0.43

RESULTS

P1 (MPa)	P2 (MPa)	h1 (kJ/kg)	h2 (kJ/kg)	h3 (kJ/kg)	COP	m' (g/s)	W (Watt)	Qref (Watt)
0.295	0.811	750	835	453	3.49	0.28	23.39	81.73
0.252	0.735	744	835	446	3.27	0.19	17.47	57.22
0.208	0.681	736	835	438	3.01	0.16	15.54	46.77
0.187	0.67	732	835	438	2.85	0.13	13.70	39.11
0.187	0.633	732	825	433	3.22	0.10	9.59	30.85
0.187	0.62	732	825	430	3.25	0.09	8.39	27.23
0.193	0.633	733	825	433	3.26	0.08	7.42	24.19
0.193	0.633	733	825	435	3.24	0.07	6.75	21.85
0.174	0.633	729	825	433	3.08	0.07	6.48	19.98

Table A.5 LPG on solar power (starting at 08:15 AM on September 7th) with 1 liter of hot water at 86 °C

DATA												
Δt min	T1 °C	T2 °C	T3 °C	T4 °C	T5 °C	T6 °C	T7 °C	Ta °C	Iref Amp	Solar Intensity W/m²	Isolar Amp	Battery Voltage Volt
30	11	62	54	49	11	26	51	31	0.55	455	1.8	25.4
60	5	66	48	44	5	20	37	31	0.54	526	2.1	25.5
90	3	69	48	44	3	17	28	31	0.54	684	2.7	25.6
120	-1	67	44	40	-1	14	23	31	0.53	815	3	26
150	-2	67	42	39	-2	12	19	32	0.54	868	3.2	26.4
180	-2	68	44	40	-2	12	16	31	0.53	922	3.3	26.6
210	-3	67	42	39	-3	11	14	32	0.53	951	3.3	26.7
240	-1	68	43	39	-1	11	13	32	0.53	997	3.4	26.7
270	-1	68	43	40	-1	10	12	32	0.53	1009	3.3	26.8
300	-2	67	43	39	-2	10	11	32	0.53	998	3.2	26.7
330	-2	66	42	38	-2	9	10	32	0.53	974	3.1	26.7

RESULTS								
P1 (MPa)	P2 (MPa)	h1 (kJ/kg)	h2 (kJ/kg)	h3 (kJ/kg)	COP	m' (g/s)	W (Watt)	Qref (Watt)
0.33	1.03	756	838	483	3.33	0.31	25.18	83.84
0.28	0.89	748	854	469	2.63	0.21	22.07	58.08
0.26	0.89	745	854	469	2.53	0.17	18.11	45.86
0.23	0.81	740	854	459	2.46	0.13	15.32	37.77
0.23	0.77	738	854	456	2.43	0.11	13.25	32.22
0.23	0.81	738	854	459	2.41	0.10	11.67	28.06
0.21	0.77	737	854	456	2.40	0.09	10.34	24.83
0.23	0.79	740	854	456	2.49	0.08	8.83	22.01
0.23	0.79	740	854	456	2.49	0.07	7.97	19.86
0.23	0.79	738	854	456	2.43	0.06	7.45	18.11
0.23	0.77	738	854	453	2.46	0.06	6.78	16.65

Table A.6 LPG on solar power (starting at 08:15 AM on September 8th) with 1 liter of hot water at 85 °C

DATA												
Δt min	T1 °C	T2 °C	T3 °C	T4 °C	T5 °C	T6 °C	T7 °C	Ta °C	Iref Amp	Solar Intensity W/m²	Isolar Amp	Battery Voltage Volt
30	5	63	42	36	5	19	49	29	0.54	515	2.1	24.4
60	1	59	39	34	1	15	36	28	0.54	618	2.5	24.4
90	-4	57	37	33	-4	12	28	28	0.54	735	2.8	24.5
120	-6	57	36	32	-6	10	22	28	0.54	835	3.2	24.6
150	-6	59	37	33	-6	9	18	28	0.54	903	3.3	24.8
180	-7	59	36	33	-7	8	15	29	0.53	966	3.5	24.9
210	-6	61	39	36	-6	7	12	29	0.52	1014	3.6	25
240	-7	60	38	34	-7	7	11	29	0.52	1061	3.6	25.1
270	-7	56	35	31	-7	7	9	29	0.52	1074	3.6	25.1
300	-7	57	36	33	-7	7	8	28	0.52	1071	3.5	25.1
330	-9	57	36	33	-9	6	7	28	0.52	1052	3.3	25

RESULTS								
P1 (MPa)	P2 (MPa)	h1 (kJ/kg)	h2 (kJ/kg)	h3 (kJ/kg)	COP	m' (g/s)	W (Watt)	Qref (Watt)
0.28	0.77	748	845	448	3.09	0.30	28.77	88.97
0.25	0.72	742	832	443	3.32	0.20	17.68	58.73
0.21	0.68	736	832	440	3.08	0.15	14.63	45.10
0.19	0.67	733	832	438	2.98	0.13	12.63	37.65
0.19	0.68	733	832	440	2.96	0.11	10.80	31.96
0.185	0.67	732	832	440	2.92	0.10	9.53	27.83
0.19	0.72	733	845	448	2.54	0.09	9.67	24.59
0.185	0.7	732	845	443	2.56	0.08	8.64	22.09
0.185	0.65	732	832	435	2.97	0.07	6.73	19.98
0.185	0.67	732	832	440	2.92	0.06	6.27	18.31
0.175	0.67	729	832	440	2.81	0.06	6.03	16.93

Table A.7 50% propane/50% butane on electrical power (starting at 08:15 AM on September 17th) 1 liter of hot water at 85°C

DATA									
Δt (min)	T1 (°C)	T2 (°C)	T3 (°C)	T4 (°C)	T5 (°C)	T6 (°C)	T7 (°C)	Ta (°C)	Iref (Amp)
30	14	68	50	41	14	26	49	29	0.5
60	8	68	47	39	8	20	38	29	0.5
90	4	66	42	34	4	16	30	31	0.5
120	1	66	42	36	1	13	24	30	0.49
180	-1	65	41	35	-1	12	20	28	0.49
210	-2	64	38	33	-2	10	15	29	0.49
240	-2	64	40	35	-2	9	12	29	0.48
270	-3	64	39	35	-3	9	11	29	0.48
300	-3	62	37	33	-3	8	10	30	0.48
330	-3	65	40	36	-3	8	10	30	0.48

RESULTS								
P1 (MPa)	P2 (MPa)	h1 (kJ/kg)	h2 (kJ/kg)	h3 (kJ/kg)	COP	m' (g/s)	W (Watt)	Qref (Watt)
0.48	1.19	804	898	510	3.13	0.31	28.76	89.94
0.4	1.11	796	898	505	2.85	0.19	19.82	56.54
0.36	1	791	898	491	2.80	0.14	15.44	43.30
0.32	1	787	898	497	2.61	0.12	13.78	36.01
0.3	0.97	785	898	494	2.58	0.09	10.08	25.96
0.29	0.9	783	890	489	2.75	0.08	8.73	23.99
0.29	0.94	783	893	494	2.63	0.07	8.24	21.66
0.28	0.92	782	890	494	2.67	0.07	7.33	19.56
0.28	0.88	782	890	489	2.71	0.06	6.58	17.85
0.28	0.94	782	893	497	2.57	0.06	6.39	16.40

Table A.8 50% propane and 50% butane on solar power (starting at 08:15 AM on September 15th) 1 liter of hot water at 86 ºC

DATA												
Δt min	T1 ºC	T2 ºC	T3 ºC	T4 ºC	T5 ºC	T6 ºC	T7 ºC	Ta ºC	Iref Amp	Solar Intensity W/m²	Isolar Amp	Battery Voltage Volt
30	12	69	46	37	12	22	50	26	0.53	480	2.4	25.4
60	6	69	43	36	6	18	37	27	0.53	612	2.8	25.5
90	2	70	41	36	2	15	28	27	0.53	740	3.2	25.9
120	1	68	40	35	1	13	23	27	0.53	840	3.5	26.5
150	-1	69	40	35	-1	12	20	28	0.53	936	3.7	26.9
180	-1	69	40	35	-1	11	17	28	0.52	1014	3.7	27.8
210	-2	68	39	35	-2	10	14	29	0.52	1070	3.5	28.3
240	-2	68	39	35	-2	10	13	29	0.52	1086	3.4	28.3
270	-2	68	40	36	-2	10	11	29	0.52	1090	3.3	28.3
300	-2	69	40	36	-2	9	10	30	0.52	1090	3.3	28.3
330	-2	68	39	35	-2	9	10	30	0.52	1040	3.3	27.3

RESULTS								
P1 (MPa)	P2 (MPa)	h1 (kJ/kg)	h2 (kJ/kg)	h3 (kJ/kg)	COP	m' (g/s)	W (Watt)	Qref (Watt)
0.45	1.09	801	900	499	3.05	0.31	30.28	92.36
0.37	1	794	900	497	2.80	0.20	21.55	60.38
0.33	0.97	790	900	497	2.66	0.16	17.31	46.12
0.32	0.94	787	900	494	2.59	0.13	14.33	37.17
0.31	0.94	785	900	494	2.53	0.11	12.40	31.37
0.31	0.94	785	900	494	2.53	0.09	10.78	27.27
0.29	0.92	783	900	494	2.47	0.08	9.77	24.12
0.29	0.92	783	900	494	2.47	0.07	8.73	21.56
0.29	0.94	783	900	497	2.44	0.07	7.96	19.47
0.29	0.94	783	900	497	2.44	0.06	7.27	17.77
0.29	0.92	783	900	494	2.47	0.06	6.60	16.31

Table A.9 50% propane and 50% butane on solar power (starting at 08:25 AM on September 16th) 1 liter of hot water at 79 ºC

DATA												
Δt min	T1 ºC	T2 ºC	T3 ºC	T4 ºC	T5 ºC	T6 ºC	T7 ºC	Ta ºC	Iref Amp	Solar Intensity W/m²	Isolar Amp	Battery Voltage Volt
30	10	72	47	39	10	22	48	28	0.56	555	2.5	24.2
60	6	71	43	36	6	19	36	29	0.56	664	2.8	24.3
90	3	70	43	38	3	15	28	29	0.55	788	3.2	24.4
120	1	70	42	37	1	14	23	29	0.55	890	3.5	24.6
150	0	70	40	36	0	13	20	30	0.55	986	3.7	24.7
180	0	70	42	37	0	12	17	30	0.55	1004	3.7	24.8
210	-1	70	41	37	-1	12	15	30	0.5	1045	3.7	24.9
240	-1	70	42	37	-1	11	14	30	0.5	1080	3.8	24.9
270	-1	70	42	37	-1	11	12	30	0.5	1075	3.6	24.9
300	-3	65	37	33	-3	10	12	30	0.5	1060	3.6	24.9
330	-4	64	36	32	-4	9	11	30	0.5	1026	3.4	24.8

RESULTS								
P1 (MPa)	P2 (MPa)	h1 (kJ/kg)	h2 (kJ/kg)	h3 (kJ/kg)	COP	m' (g/s)	W (Watt)	Qref (Watt)
0.43	1.11	799	908	505	2.70	0.27	29.69	80.09
0.37	1	794	908	497	2.61	0.18	20.57	53.58
0.35	1	790	908	502	2.44	0.14	16.81	41.02
0.32	1	787	908	499	2.38	0.12	14.07	33.48
0.31	0.94	786	908	497	2.37	0.10	11.94	28.29
0.31	1	786	908	499	2.35	0.09	10.46	24.60
0.31	0.97	785	908	499	2.33	0.08	9.31	21.65
0.31	1	785	908	499	2.33	0.07	8.34	19.38
0.31	1	785	908	499	2.33	0.06	7.53	17.51
0.29	0.88	782	900	489	2.48	0.05	6.38	15.83
0.28	0.86	781	900	486	2.48	0.05	5.87	14.56

Table A.10 70% propane and 30% butane on electrical power (starting at 08:17AM on September 10th) 1 liter of hot water at 87 ºC

DATA									
Δt (min)	T1 (ºC)	T2 (ºC)	T3 (ºC)	T4 (ºC)	T5 (ºC)	T6 (ºC)	T7 (ºC)	Ta (ºC)	Iref (Amp)
30	9	75	45	35	9	22	49	27	0.53
60	4	76	46	38	4	16	36	27	0.52
90	-1	71	40	34	-1	13	28	27	0.5
120	-5	65	34	29	-5	10	22	27	0.49
150	-7	65	36	32	-7	8	17	26	0.49
180	-8	64	35	30	-8	7	13	26	0.49
210	-8	66	36	31	-8	6	11	27	0.49
240	-8	65	36	32	-8	5	9	26	0.49
270	-9	63	33	30	-9	4	8	27	0.48
300	-9	64	35	30	-9	4	7	27	0.48
330	-9	65	34	30	-9	4	6	28	0.48

RESULTS								
P1 (MPa)	P2 (MPa)	h1 (kJ/kg)	h2 (kJ/kg)	h3 (kJ/kg)	COP	m' (g/s)	W (Watt)	Qref (Watt)
0.5	1.26	842	961	543	2.51	0.32	38.33	96.31
0.43	1.29	836	961	551	2.28	0.22	27.21	62.04
0.37	1.12	830	958	540	2.27	0.16	20.81	47.15
0.32	0.97	825	944	527	2.50	0.13	15.29	38.29
0.3	1.02	823	944	534	2.39	0.11	13.84	33.06
0.3	1	821	937	529	2.52	0.10	11.55	29.08
0.3	1.02	821	944	532	2.35	0.09	10.94	25.70
0.3	1.02	821	944	534	2.33	0.08	9.85	22.98
0.29	0.95	820	934	529	2.55	0.07	8.16	20.84
0.29	1	820	934	529	2.55	0.07	7.49	19.11
0.29	0.97	820	944	529	2.35	0.06	7.45	17.48

Table A.11 70% propane and 30% butane on solar power (starting at 08:13 AM on September 11th)1 liter of hot water at 86 ºC

DATA												
Δt min	T1 ºC	T2 ºC	T3 ºC	T4 ºC	T5 ºC	T6 ºC	T7 ºC	Ta ºC	Iref Amp	Solar Intensity W/m²	Isolar Amp	Battery Voltage Volt
30	7	75	45	35	7	21	49	27	0.58	585	2.2	24.4
60	2	76	43	36	2	15	34	27	0.58	705	2.7	24.4
90	-2	75	41	35	-2	12	27	27	0.57	808	3	24.5
120	-6	73	38	32	-6	10	21	27	0.56	902	3.3	24.5
150	-6	72	38	33	-6	8	16	27	0.56	978	3.6	24.6
180	-6	74	40	36	-6	7	13	27	0.56	1048	3.7	24.6
210	-6	75	40	36	-6	7	11	28	0.56	1090	3.8	24.7
240	-7	71	37	32	-7	6	9	28	0.56	1130	3.8	24.7
270	-7	72	38	34	-7	6	8	28	0.56	1150	3.7	24.7
300	-6	74	40	35	-6	5	7	28	0.56	1130	3.6	24.7
330	-8	69	34	30	-8	5	6	28	0.56	1088	3.5	24.6

RESULTS								
P1 (MPa)	P2 (MPa)	h1 (kJ/kg)	h2 (kJ/kg)	h3 (kJ/kg)	COP	m' (g/s)	W (Watt)	Qref (Watt)
0.47	1.26	839	961	543	2.43	0.32	39.05	94.74
0.41	1.2	833	961	545	2.25	0.22	27.98	62.96
0.36	1.15	829	961	543	2.17	0.16	21.70	47.02
0.31	1.07	825	958	534	2.19	0.13	17.50	38.29
0.31	1.07	825	958	537	2.17	0.11	15.10	32.70
0.31	1.12	825	961	545	2.06	0.10	13.87	28.56
0.31	1.12	825	961	545	2.06	0.09	12.19	25.11
0.3	1.04	822	958	534	2.12	0.08	10.63	22.52
0.3	1.07	822	958	540	2.07	0.07	9.82	20.37
0.31	1.12	825	961	543	2.07	0.07	8.95	18.55
0.3	0.97	821	951	529	2.25	0.06	7.59	17.05

Table A.12 70% propane and 30% butane on solar power (starting at 08:25 AM on September 14th) 1 liter of hot water at 87 °C

DATA												
Δt min	T1 °C	T2 °C	T3 °C	T4 °C	T5 °C	T6 °C	T7 °C	Ta °C	Iref Amp	Solar Intensity W/m²	Isolar Amp	Battery Voltage Volt
30	12	67	47	37	12	23	51	24	0.61	634	2.3	25.3
60	2	68	39	32	2	16	36	24	0.59	731	2.7	25.5
90	-4	68	37	32	-4	11	25	24	0.58	842	3.2	25.6
120	-5	66	34	29	-5	9	20	25	0.58	952	3.3	25.7
150	-6	67	34	29	-6	8	16	25	0.58	1018	3.6	25.9
180	-7	67	34	29	-7	7	12	24	0.58	1073	3.6	26.1
210	-8	66	33	29	-8	6	9	24	0.58	1124	3.7	26.4
240	-8	66	34	29	-8	5	8	24	0.58	1142	3.7	26.4
270	-8	67	35	30	-8	5	6	25	0.58	1134	3.6	26.4
300	-8	66	32	28	-8	5	5	25	0.58	1118	3.4	26.2
330	-9	64	31	27	-9	4	4	25	0.58	1060	3.4	26.2

RESULTS								
P1 (MPa)	P2 (MPa)	h1 (kJ/kg)	h2 (kJ/kg)	h3 (kJ/kg)	COP	m' (g/s)	W (Watt)	Qref (Watt)
0.54	1.32	845	941	548	3.09	0.31	29.37	90.87
0.4	1.13	833	941	534	2.77	0.20	21.61	59.84
0.34	1.04	826	944	534	2.47	0.17	20.15	49.86
0.33	0.97	825	944	527	2.50	0.13	16.05	40.18
0.31	0.97	825	944	527	2.50	0.11	13.68	34.26
0.3	0.97	822	944	527	2.42	0.10	12.44	30.08
0.3	0.95	821	944	527	2.39	0.09	11.24	26.86
0.3	0.97	821	944	527	2.39	0.08	10.02	23.95
0.3	1	821	944	529	2.37	0.07	9.12	21.66
0.3	0.92	821	944	524	2.41	0.07	8.20	19.79
0.29	0.91	820	934	521	2.62	0.06	6.94	18.20

Table A.13 Propane on electrical power (starting at 08:20 AM on September 18th) with 1 liter of hot water at 85 °C

DATA

Δt (min)	T1 (°C)	T2 (°C)	T3 (°C)	T4 (°C)	T5 (°C)	T6 (°C)	T7 (°C)	Ta (°C)	Iref (Amp)
30	3	89	52	49	3	17	46	28	0.64
60	-7	79	42	39	-7	12	32	27	0.53
90	-11	75	39	37	-11	9	24	27	0.5
120	-11	74	39	37	-11	7	18	28	0.49
150	-9	75	40	39	-9	6	14	27	0.49
180	-8	74	44	41	-8	6	11	28	0.51
210	-10	73	41	40	-10	4	9	27	0.49
270	-9	75	43	42	-9	4	6	29	0.48
300	-9	74	41	40	-9	3	4	27	0.47
330	-11	74	40	38	-11	3	4	28	0.47

RESULTS

P1 (MPa)	P2 (MPa)	h1 (kJ/kg)	h2 (kJ/kg)	h3 (kJ/kg)	COP	m' (g/s)	W (Watt)	Qref (Watt)
0.39	1.79	902	1030	657	1.91	0.40	51.58	98.72
0.38	1.43	891	1020	627	2.05	0.24	30.83	63.09
0.33	1.34	886	1020	621	1.98	0.18	24.15	47.76
0.33	1.34	886	1020	621	1.98	0.15	20.02	39.60
0.36	1.37	888	1020	627	1.98	0.13	17.07	33.76
0.37	1.5	889	1020	633	1.95	0.11	14.94	29.19
0.34	1.4	887	1010	630	2.09	0.10	12.24	25.58
0.36	1.47	888	1020	636	1.91	0.08	10.93	20.87
0.36	1.4	888	1020	630	1.95	0.07	9.78	19.11
0.33	1.37	886	1020	624	1.96	0.07	8.90	17.40

Table A.14 Propane on solar power (starting at 08:30 AM on September 21st) with 1 liter of hot water at 87 ºC

DATA												
Δt min	T1 ºC	T2 ºC	T3 ºC	T4 ºC	T5 ºC	T6 ºC	T7 ºC	Ta ºC	Iref Amp	Solar Intensity W/m²	Isolar Amp	Battery Voltage Volt
30	5	77	50	48	5	18	48	25	0.57	660	2.7	25.2
60	-3	80	45	43	-3	12	33	25	0.53	775	3.1	25.4
90	-8	77	40	38	-8	9	24	26	0.51	885	3.4	25.5
120	-9	75	39	37	-9	7	17	25	0.51	967	3.7	25.6
150	-11	74	38	36	-11	5	13	24	0.51	1040	3.9	25.8
180	-13	70	36	34	-13	3	10	25	0.51	1100	4	26.1
210	-13	66	34	32	-13	3	7	25	0.51	1130	4	26.2
240	-13	68	36	33	-13	2	5	26	0.51	1148	4	26.3
270	-13	70	37	35	-13	1	4	26	0.51	1140	3.8	26.2
300	-15	70	37	36	-15	1	3	25	0.51	1115	3.6	26
330	-12	73	40	38	-12	1	2	25	0.51	1085	3.5	25.9

RESULTS								
P1 (MPa)	P2 (MPa)	h1 (kJ/kg)	h2 (kJ/kg)	h3 (kJ/kg)	COP	m' (g/s)	W (Watt)	Qref (Watt)
0.55	1.71	904	1010	654	2.36	0.38	40.48	95.47
0.43	1.53	895	1020	639	2.05	0.25	30.93	63.35
0.37	1.37	889	1020	624	2.02	0.19	24.79	50.14
0.36	1.34	888	1020	621	2.02	0.16	20.69	41.86
0.33	1.31	886	1020	618	2.00	0.13	17.79	35.58
0.31	1.25	884	1010	613	2.15	0.11	14.42	31.00
0.31	1.19	884	1000	607	2.39	0.10	11.55	27.58
0.31	1.25	884	1000	610	2.36	0.09	10.47	24.72
0.31	1.28	884	1010	616	2.13	0.08	10.46	22.24
0.29	1.28	881	1010	618	2.04	0.08	9.98	20.35
0.32	1.37	885	1010	624	2.09	0.07	8.90	18.58

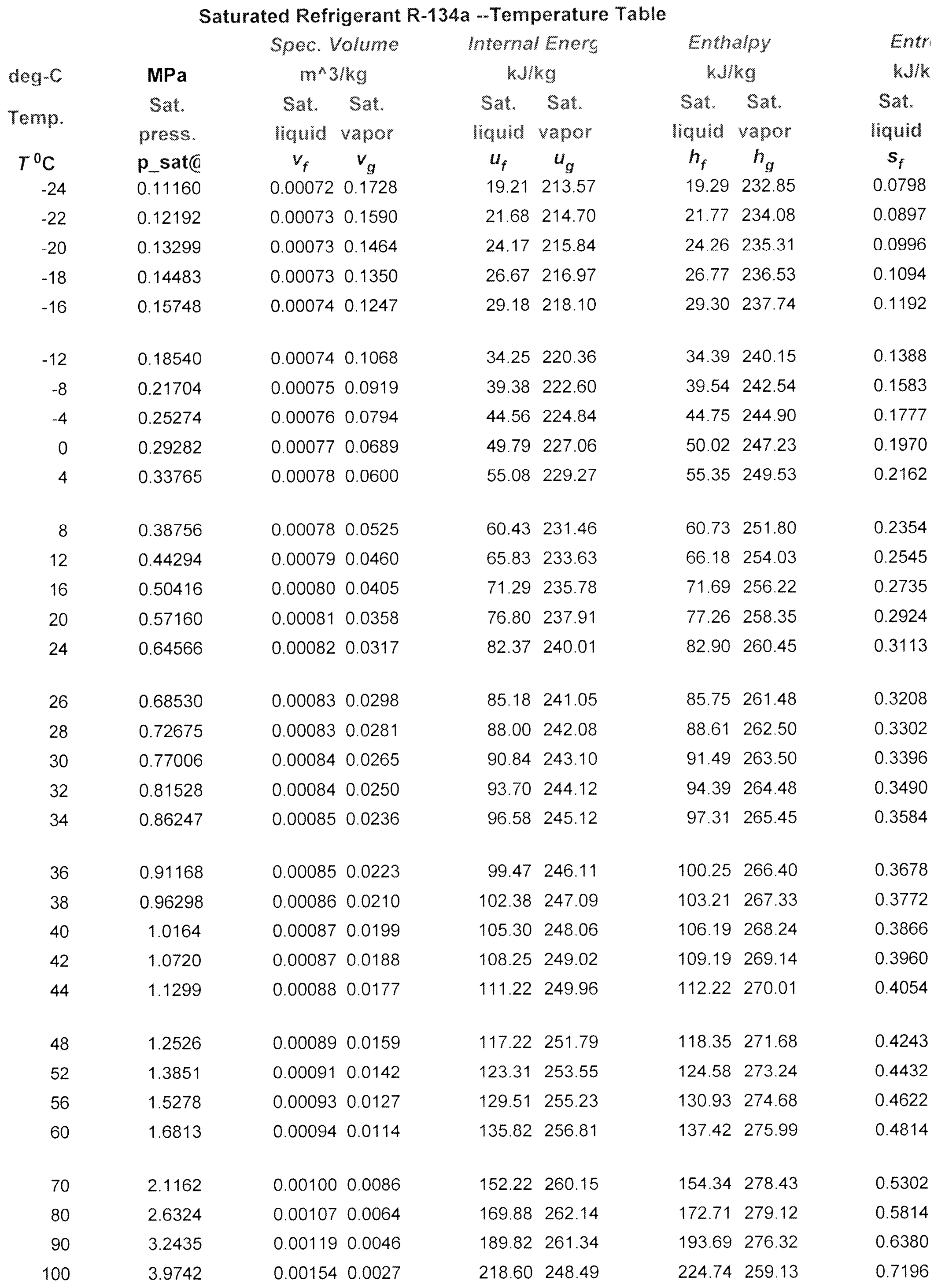
Table A.15 Propane on solar power (starting at 10:00 AM on September 22nd) with 1 liter of hot water at 75 ºC

DATA												
Δt min	T1 ºC	T2 ºC	T3 ºC	T4 ºC	T5 ºC	T6 ºC	T7 ºC	Ta ºC	Iref Amp	Solar Intensity W/m²	Isolar Amp	Battery Voltage Volt
40	10	77	58	56	10	24	45	29	0.68	937	3.6	20.5
50	5	82	54	52	5	20	40	30	0.63	952	3.7	19.4
60	3	86	53	50	3	16	36	30	0.63	979	3.7	17.8
100	4	76	54	52	4	16	27	29	0.63	1025	3.8	21.7
110	-1	78	49	47	-1	13	25	30	0.6	1028	3.8	21
120	-7	82	50	48	-7	11	23	29	0.59	1000	3.7	20.7
150	-10	82	45	43	-10	8	18	29	0.56	1084	3.9	20.2
180	-12	82	43	41	-12	7	14	29	0.56	1061	3.7	19.3

RESULTS								
P1 (MPa)	P2 (MPa)	h1 (kJ/kg)	h2 (kJ/kg)	h3 (kJ/kg)	COP	m' (g/s)	W (Watt)	Qref (Watt)
0.64	2	909	1000	678	2.54	0.24	21.89	55.58
0.55	1.87	904	1020	666	2.05	0.21	24.30	49.86
0.39	1.83	902	1030	660	1.89	0.19	24.19	45.74
0.53	1.87	903	1010	666	2.21	0.14	15.31	33.91
0.46	1.68	897	1010	650	2.19	0.13	14.90	32.56
0.34	1.71	891	1025	654	1.77	0.13	17.98	31.79
0.34	1.53	887	1025	639	1.80	0.11	15.64	28.11
0.32	1.47	885	1025	633	1.80	0.10	13.98	25.16

APPENDIX B

Table B.1 Saturated Properties for R-134a



Saturated Refrigerant R-134a --Temperature Table

		Spec. Volume		*Internal Energ*		*Enthalpy*		*Entr*
deg-C	MPa	m^3/kg		kJ/kg		kJ/kg		kJ/k
Temp.	Sat. press.	Sat. liquid	Sat. vapor	Sat. liquid	Sat. vapor	Sat. liquid	Sat. vapor	Sat. liquid
T °C	p_sat@	v_f	v_g	u_f	u_g	h_f	h_g	s_f
-24	0.11160	0.00072	0.1728	19.21	213.57	19.29	232.85	0.0798
-22	0.12192	0.00073	0.1590	21.68	214.70	21.77	234.08	0.0897
-20	0.13299	0.00073	0.1464	24.17	215.84	24.26	235.31	0.0996
-18	0.14483	0.00073	0.1350	26.67	216.97	26.77	236.53	0.1094
-16	0.15748	0.00074	0.1247	29.18	218.10	29.30	237.74	0.1192
-12	0.18540	0.00074	0.1068	34.25	220.36	34.39	240.15	0.1388
-8	0.21704	0.00075	0.0919	39.38	222.60	39.54	242.54	0.1583
-4	0.25274	0.00076	0.0794	44.56	224.84	44.75	244.90	0.1777
0	0.29282	0.00077	0.0689	49.79	227.06	50.02	247.23	0.1970
4	0.33765	0.00078	0.0600	55.08	229.27	55.35	249.53	0.2162
8	0.38756	0.00078	0.0525	60.43	231.46	60.73	251.80	0.2354
12	0.44294	0.00079	0.0460	65.83	233.63	66.18	254.03	0.2545
16	0.50416	0.00080	0.0405	71.29	235.78	71.69	256.22	0.2735
20	0.57160	0.00081	0.0358	76.80	237.91	77.26	258.35	0.2924
24	0.64566	0.00082	0.0317	82.37	240.01	82.90	260.45	0.3113
26	0.68530	0.00083	0.0298	85.18	241.05	85.75	261.48	0.3208
28	0.72675	0.00083	0.0281	88.00	242.08	88.61	262.50	0.3302
30	0.77006	0.00084	0.0265	90.84	243.10	91.49	263.50	0.3396
32	0.81528	0.00084	0.0250	93.70	244.12	94.39	264.48	0.3490
34	0.86247	0.00085	0.0236	96.58	245.12	97.31	265.45	0.3584
36	0.91168	0.00085	0.0223	99.47	246.11	100.25	266.40	0.3678
38	0.96298	0.00086	0.0210	102.38	247.09	103.21	267.33	0.3772
40	1.0164	0.00087	0.0199	105.30	248.06	106.19	268.24	0.3866
42	1.0720	0.00087	0.0188	108.25	249.02	109.19	269.14	0.3960
44	1.1299	0.00088	0.0177	111.22	249.96	112.22	270.01	0.4054
48	1.2526	0.00089	0.0159	117.22	251.79	118.35	271.68	0.4243
52	1.3851	0.00091	0.0142	123.31	253.55	124.58	273.24	0.4432
56	1.5278	0.00093	0.0127	129.51	255.23	130.93	274.68	0.4622
60	1.6813	0.00094	0.0114	135.82	256.81	137.42	275.99	0.4814
70	2.1162	0.00100	0.0086	152.22	260.15	154.34	278.43	0.5302
80	2.6324	0.00107	0.0064	169.88	262.14	172.71	279.12	0.5814
90	3.2435	0.00119	0.0046	189.82	261.34	193.69	276.32	0.6380
100	3.9742	0.00154	0.0027	218.60	248.49	224.74	259.13	0.7196

Source: ASHRAE Transc. Vol. 94, (1988). pp. 2095-118.

Table B.2 Superheated Properties for R-134a

	p = 0.5 MPa (T_{sat} = 15.74 C)				p = 0.60 MPa (T_{sat} =21.58 C)				p = 0.70 MPa (T_{sat} = 26.72 C)			
	v	*u*	*h*	*s*	*v*	*u*	*h*	*s*	*v*	*u*	*h*	*s*
Sat.	0.0408	253.64	256.07	0.9117	0.0340	238.74	259.19	0.9097	0.0291	241.42	261.85	0.9080
20	0.0418	239.40	260.34	0.9264								
30	0.0441	248.20	270.28	0.9597	0.0358	246.41	267.89	0.9388	0.0297	244.51	265.37	0.9197
40	0.0463	256.99	280.16	0.9918	0.0377	255.45	278.09	0.9719	0.0315	253.83	275.93	0.9539
50	0.0484	265.83	290.04	1.0229	0.0395	264.48	288.23	1.0037	0.0332	263.08	286.35	0.9867
60	0.0504	274.73	299.95	1.0531	0.0413	273.54	298.35	1.0346	0.0348	272.31	296.69	1.0182
70	0.0524	283.72	309.92	1.0825	0.0430	282.66	308.48	1.0645	0.0363	281.57	307.01	1.0487
80	0.0543	292.80	319.96	1.1114	0.0446	291.86	318.67	1.0938	0.0378	290.88	317.35	1.0784
90	0.0562	302.00	330.10	1.1397	0.0463	301.14	328.93	1.1225	0.0392	300.27	327.74	1.1074
100	0.0580	311.31	340.33	1.1675	0.0479	310.53	339.27	1.1505	0.0406	309.74	338.19	1.1358
110	0.0598	320.74	350.68	1.1949	0.0494	320.03	349.70	1.1781	0.0420	319.31	348.71	1.1637
120	0.0616	330.30	361.14	1.2218	0.0509	329.64	360.24	1.2053	0.0433	328.98	359.33	1.1910
130	0.0634	339.98	371.72	1.2484	0.0525	339.38	370.88	1.2320	0.0446	338.76	370.04	1.2179
140	0.0652	349.79	382.42	1.2746	0.0540	349.23	381.64	1.2584	0.0459	348.66	380.86	1.2444
150					0.0555	359.21	392.52	1.2844	0.0472	358.68	391.79	1.2706
160					0.0569	369.32	403.51	1.3100	0.0485	368.82	402.82	1.2963

	p = 0.80 MPa (T_{sat} = 31.33 ^{0}C				p = 0.90 MPa (T_{sat} = 35.53 ^{0}C				p = 1.00 MPa (T_{sat} = 39.33 ^{0}C			
	v	*u*	*h*	*s*	*v*	*u*	*h*	*s*	*v*	*u*	*h*	*s*
Sat.	0.0254	243.78	264.15	0.9066	0.0225	245.88	266.18	0.9054	0.0202	247.77	267.97	0.9043
40	0.0269	252.13	273.66	0.9374	0.0232	250.32	271.25	0.9217	0.0202	248.39	268.68	0.9066
50	0.0284	261.62	284.39	0.9711	0.0247	260.09	282.34	0.9566	0.0217	258.48	280.19	0.9428
60	0.0299	271.04	294.98	1.0034	0.0260	269.72	293.21	0.9897	0.0230	268.35	291.36	0.9768
70	0.0313	280.45	305.50	1.0345	0.0273	279.30	303.94	1.0214	0.0242	278.11	302.34	1.0093
80	0.0326	289.89	316.00	1.0647	0.0286	288.87	314.62	1.0521	0.0253	287.82	313.20	1.0405
90	0.0339	299.37	326.52	1.0940	0.0298	298.46	325.28	1.0819	0.0264	297.53	324.01	1.0707
100	0.0351	308.93	337.08	1.1227	0.0309	308.11	335.96	1.1109	0.0275	307.27	334.82	1.1000
110	0.0364	318.57	347.71	1.1508	0.0320	317.82	346.68	1.1392	0.0285	317.06	345.65	1.1286
120	0.0376	328.31	358.40	1.1784	0.0331	327.62	357.47	1.1670	0.0295	326.93	356.52	1.1567
130	0.0388	338.14	369.19	1.2055	0.0342	337.52	368.33	1.1943	0.0305	336.88	367.46	1.1841
140	0.0399	348.09	380.07	1.2321	0.0352	347.51	379.27	1.2211	0.0315	346.92	378.46	1.2111
150	0.0411	358.15	391.05	1.2584	0.0363	357.61	390.31	1.2475	0.0325	357.06	389.56	1.2376
160	0.0422	368.32	402.14	1.2843	0.0373	367.82	401.44	1.2735	0.0334	367.31	400.74	1.2638
170	0.0434	378.61	413.33	1.3098	0.0383	378.14	412.68	1.2992	0.0343	377.66	412.02	1.2895
180	0.0445	389.02	424.63	1.3351	0.0393	388.57	424.02	1.3245	0.0352	388.12	423.40	1.3149

	p = 1.20 MPa (T_{sat} = 46.32 ^{0}C				p = 1.40 MPa (T_{sat} = 52.43 ^{0}C				p = 1.60 MPa (T_{sat} = 57.92 ^{0}C			
	v	*u*	*h*	*s*	*v*	*u*	*h*	*s*	*v*	*u*	*h*	*s*
Sat.	0.0166	251.03	270.99	0.9023	0.0140	253.74	273.40	0.9003	0.0120	256.00	275.33	0.8982
50	0.0171	254.98	275.52	0.9164								
60	0.0183	265.42	287.44	0.9527	0.0149	262.17	283.10	0.9297	0.0123	258.48	278.20	0.9069
70	0.0194	275.59	298.96	0.9868	0.0160	272.87	295.31	0.9658	0.0134	269.89	291.33	0.9457
80	0.0205	285.62	310.24	1.0192	0.0170	283.29	307.10	0.9997	0.0143	280.78	303.74	0.9813
90	0.0215	295.59	321.39	1.0503	0.0179	293.55	318.63	1.0319	0.0152	291.39	315.72	1.0148
100	0.0224	305.54	332.47	1.0804	0.0187	303.73	330.02	1.0628	0.0160	301.84	327.46	1.0467
110	0.0233	315.50	343.52	1.1096	0.0196	313.88	341.32	1.0927	0.0167	312.20	339.04	1.0773
120	0.0242	325.51	354.58	1.1381	0.0203	324.05	352.59	1.1218	0.0175	322.53	350.53	1.1069
130	0.0250	335.58	365.68	1.1660	0.0211	334.25	363.86	1.1501	0.0182	332.87	361.99	1.1357
140	0.0259	345.73	376.83	1.1933	0.0218	344.50	375.15	1.1777	0.0188	343.24	373.44	1.1638
150	0.0267	355.95	388.04	1.2201	0.0226	354.82	386.49	1.2048	0.0195	353.66	384.91	1.1912
160	0.0275	366.27	399.33	1.2465	0.0233	365.22	397.89	1.2315	0.0201	364.15	396.43	1.2181
180	0.0283	376.69	410.70	1.2724	0.0240	375.71	409.36	1.2576	0.0208	374.71	407.99	1.2445
180	0.0291	387.21	422.16	1.2980	0.0247	386.29	420.90	1.2834	0.0214	385.35	419.62	1.2704
190					0.0254	396.96	432.53	1.3088	0.0220	396.08	431.33	1.2960

Table B.3 Saturated Properties for Propane

Refrigerant 290 (Propane) Properties of Saturated Liquid and Saturated Vapor

Temp, K	Pressure, MPa	Vapor Volume, m^3/kg	Liquid Density, kg/m^3	Enthalpy, kJ/kg Liquid	Enthalpy, kJ/kg Vapor	Entropy, kJ/(kg·K) Liquid	Entropy, kJ/(kg·K) Vapor
**85.47	0.30E-09	53716674.	732.90	124.92	690.02	1.8738	8.3548
90	0.15E-08	11180892.	728.37	133.56	693.58	1.9723	8.0953
95	0.75E-08	2362188.	723.37	143.13	697.78	2.0758	7.8413
100	0.32E-07	585463.	718.36	152.74	702.23	2.1743	7.6163
105	0.12E-06	166434.	713.34	162.37	706.88	2.2682	7.4163
110	0.39E-06	53276.	708.32	172.03	711.71	2.3581	7.2377
115	0.11E-05	18913.	703.29	181.73	716.68	2.4443	7.0778
120	0.31E-05	7351.7	698.25	191.46	721.78	2.5271	6.9343
125	0.76E-05	3095.9	693.20	201.23	726.98	2.6069	6.8051
130	0.000018	1399.6	688.14	211.03	732.27	2.6838	6.6885
135	0.000038	674.08	683.07	220.88	737.64	2.7581	6.5833
140	0.000077	343.54	677.99	230.77	743.07	2.8300	6.4881
145	0.000149	184.22	672.90	240.70	748.57	2.8997	6.4018
150	0.000274	103.41	667.79	250.67	754.12	2.9674	6.3237
155	0.000484	60.504	662.66	260.70	759.72	3.0331	6.2529
160	0.000822	36.755	657.51	270.78	765.37	3.0971	6.1886
165	0.001347	23.102	652.34	280.91	771.06	3.1594	6.1304
170	0.002139	14.979	647.15	291.10	776.80	3.2202	6.0775
175	0.003297	9.9919	641.93	301.34	782.58	3.2796	6.0296
180	0.004945	6.8399	636.68	311.66	788.40	3.3377	5.9862
185	0.007238	4.7946	631.41	322.03	794.26	3.3946	5.9469
190	0.010354	3.4347	626.09	332.48	800.15	3.4503	5.9114
195	0.014506	2.5100	620.74	343.01	806.08	3.5049	5.8793
200	0.019934	1.8681	615.35	353.61	812.03	3.5586	5.8502
205	0.026912	1.4138	609.91	364.29	818.01	3.6113	5.8241
210	0.035741	1.0867	604.43	375.07	824.01	3.6631	5.8005
215	0.046753	0.84713	598.89	385.94	830.02	3.7142	5.7793
220	0.060307	0.66902	593.29	396.90	836.04	3.7645	5.7603
225	0.076789	0.53470	587.62	407.97	842.06	3.8141	5.7433
230	0.096607	0.43206	581.89	419.16	848.08	3.8631	5.7280
231.07	0.101325	0.41333	580.65	421.57	849.37	3.8735	5.7249
232	0.10556	0.39788	579.58	423.68	850.49	3.8827	5.7224
234	0.11515	0.36698	577.25	428.24	852.89	3.9022	5.7170
236	0.12540	0.33899	574.91	432.83	855.28	3.9217	5.7118
238	0.13634	0.31358	572.55	437.44	857.68	3.9412	5.7069
240	0.14800	0.29049	570.19	442.07	860.07	3.9605	5.7022
242	0.16041	0.26946	567.80	446.72	862.45	3.9798	5.6977
244	0.17361	0.25028	565.41	451.40	864.83	3.9990	5.6934
246	0.18761	0.23275	562.99	456.10	867.21	4.0182	5.6894
248	0.20246	0.21672	560.57	460.84	869.58	4.0373	5.6855
250	0.21819	0.20202	558.12	465.58	871.94	4.0563	5.6817
252	0.23483	0.18854	555.66	470.36	874.30	4.0753	5.6782
254	0.25242	0.17614	553.18	475.16	876.64	4.0942	5.6748
256	0.27098	0.16474	550.68	479.98	878.98	4.1130	5.6716
258	0.29056	0.15423	548.16	484.82	881.30	4.1318	5.6685
260	0.31118	0.14453	545.62	489.70	883.62	4.1505	5.6656
262	0.33288	0.13557	543.06	494.60	885.93	4.1692	5.6628
264	0.35569	0.12727	540.48	499.52	888.22	4.1878	5.6601
266	0.37966	0.11959	537.88	504.47	890.50	4.2063	5.6576
268	0.40482	0.11247	535.25	509.45	892.77	4.2248	5.6551
270	0.43120	0.10586	532.61	514.45	895.02	4.2433	5.6528
275	0.50276	0.091279	525.87	527.07	900.58	4.2893	5.6475
280	0.58278	0.079054	518.97	539.88	906.03	4.3349	5.6426
285	0.67186	0.068737	511.88	552.87	911.36	4.3804	5.6383
290	0.77063	0.059978	504.58	566.06	916.54	4.4257	5.6343
295	0.87971	0.052499	497.05	579.47	921.57	4.4709	5.6305
300	0.99973	0.046079	489.26	593.11	926.41	4.5160	5.6270
305	1.1314	0.040539	481.17	607.01	931.05	4.5611	5.6235
310	1.2753	0.035735	472.76	621.18	935.45	4.6062	5.6200
315	1.4321	0.031549	463.97	635.66	939.57	4.6516	5.6164
320	1.6027	0.027881	454.74	650.49	943.38	4.6971	5.6124
325	1.7876	0.024653	445.00	665.70	946.81	4.7431	5.6080
330	1.9876	0.021794	434.65	681.37	949.79	4.7896	5.6030
335	2.2036	0.019247	423.56	697.56	952.21	4.8368	5.5969
340	2.4362	0.016960	411.55	714.38	953.92	4.8850	5.5896
345	2.6866	0.014888	398.35	731.96	954.71	4.9346	5.5803
350	2.9556	0.012985	383.54	750.52	954.23	4.9861	5.5681
355	3.2445	0.011206	366.37	770.44	951.90	5.0405	5.5516
360	3.5551	0.0094896	345.34	792.50	946.56	5.0997	5.5277
365	3.8902	0.0077145	316.22	818.95	935.15	5.1699	5.4883
*369.80	4.2420	0.00457	219.	879.2	879.2	5.330	5.330

**Triple point

*Critical point

Temp., K	Viscosity, μPa·s Sat. Liquid	Viscosity, μPa·s Sat. Vapor	Viscosity, μPa·s Gas at 101.325 kPa	Thermal Conductivity, mW/(m·K) Sat. Liquid	Thermal Conductivity, mW/(m·K) Sat. Vapor	Thermal Conductivity, mW/(m·K) Gas at 101.325 kPa	Specific Heat, kJ/(kg·K) Sat. Liquid c_p	Specific Heat, kJ/(kg·K) Sat. Liquid c_v	Specific Heat, kJ/(kg·K) Sat. Vapor c_p	Specific Heat, kJ/(kg·K) Sat. Vapor c_v	Specific Heat, kJ/(kg·K) Gas at 0 Pa c_p	Specific Heat, kJ/(kg·K) Gas at 0 Pa c_v	Velocity of Sound, m/s Sat. Liquid	Velocity of Sound, m/s Sat. Vapor	Velocity of Sound, m/s Gas at 101.325 kPa
150	661	4.25	—	190.9	6.00	—	2.00	1.35	1.10	0.91	1.10	0.91	1649	185	—
160	554	4.50	—	182.9	6.45	—	2.02	1.36	1.14	0.94	1.14	0.94	1575	190	
170	467	4.74	—	174.6	6.99	—	2.04	1.37	1.17	0.98	1.17	0.98	1505	195	—
180	397	4.99	—	166.3	7.60	—	2.07	1.39	1.21	1.01	1.21	1.01	1436	199	—
190	327	5.25	—	158.2	8.29	—	2.10	1.40	1.24	1.05	1.24	1.05	1370	203	—
200	298	5.52	—	150.3	9.05	—	2.13	1.42	1.28	1.09	1.27	1.08	1306	207	—
210	265	5.80	—	142.8	9.86	—	2.16	1.44	1.32	1.13	1.31	1.12	1243	210	—
220	236	6.09	—	135.7	10.72	—	2.20	1.46	1.37	1.16	1.35	1.15	1182	213	—
230	207	6.39	—	128.9	11.62	—	2.25	1.49	1.42	1.21	1.39	1.19	1122	216	—
231.08[a]	205	6.42	6.42	128.2	11.73	11.73	2.25	1.49	1.43	1.22	1.39	1.20	1115	218	218
240	186	6.70	6.66	122.5	12.72	12.52	2.29	1.51	1.48	1.26	1.43	1.24	1062	219	222
250	169	7.02	6.93	116.5	13.84	13.40	2.34	1.53	1.55	1.31	1.47	1.28	1003	220	227
260	153	7.38	7.19	110.8	14.93	14.34	2.41	1.56	1.63	1.36	1.51	1.32	944	220	231
270	140	7.78	7.46	105.5	16.10	15.31	2.48	1.59	1.70	1.41	1.55	1.36	885	219	236
280	129	8.22	7.72	100.4	17.35	16.33	2.56	1.62	1.81	1.47	1.59	1.41	826	218	240
290	119	8.70	7.99	95.5	18.70	17.37	2.65	1.66	1.93	1.53	1.64	1.45	766	216	244
300	110	9.22	8.26	90.8	20.23	18.44	2.76	1.69	2.06	1.60	1.68	1.49	705	214	248
310	93.4	9.78	8.52	86.3	21.89	19.54	2.89	1.73	2.22	1.67	1.73	1.54	642	211	252
320	82.3	10.4	8.79	81.9	23.70	20.66	3.06	1.77	2.43	1.74	1.77	1.58	577	206	256
330	71.9	11.0	9.05	77.5	25.64	21.79	3.28	1.81	2.72	1.82	1.82	1.63	509	198	260
340	61.6	11.7	9.32	73.3	27.71	22.96	3.62	1.85	3.12	1.90	1.86	1.67	437	188	264
350	51.7	12.5	9.58	69.4	29.92	24.13	4.23	1.89	4.30	2.00	1.91	1.72	359	174	268
360	40.1	14.7	9.85	66.4	40.3	25.34	5.98	1.96	7.66	2.18	1.95	1.76	269	155	271
369.96[b]	28.8	28.8	10.11	∞	∞	26.54	∞	∞	∞	∞	2.00	1.81	0	0	275
370	—	—	10.11	—	—	26.55	—	—	—	—	2.00	1.81	—	—	275
380	—	—	10.38	—	—	27.79	—	—	—	—	2.04	1.85	—	—	278
390	—	—	10.64	—	—	28.03	—	—	—	—	2.08	1.90	—	—	282
400	—	—	10.90	—	—	30.30	—	—	—	—	2.13	1.94	—	—	285
420	—	—	11.41	—	—	32.87	—	—	—	—	2.22	2.03	—	—	292
440	—	—	11.92	—	—	35.50	—	—	—	—	2.30	2.12	—	—	299
460	—	—	12.42	—	—	38.18	—	—	—	—	2.39	2.20	—	—	305
480	—	—	12.92	—	—	40.93	—	—	—	—	2.47	2.28	—	—	311
500	—	—	13.41	—	—	43.73	—	—	—	—	2.55	2.36	—	—	317

[a] Normal boiling point.

[b] Critical point.

[c] Very large.

[d] Large.

[e] Small.

Table B.4 Saturated Properties for Butane

Refrigerant 600 (n-Butane) Properties of Saturated Liquid and Saturated Vapor

Temp, K	Pressure, MPa	Vapor Volume, m^3/kg	Liquid Density, kg/m^3	Enthalpy, kJ/kg		Entropy, kJ/(kg · K)	
				Liquid	Vapor	Liquid	Vapor
**134.86	0.67E-06	28631.	735.27	−0.001	494.21	2.3056	5.9702
135	0.69E-06	27909.	735.14	0.270	494.37	2.3076	5.9676
140	0.17E-05	11635.	730.48	9.953	499.96	2.3778	5.8779
145	0.40E-05	5196.0	725.82	19.678	505.64	2.4460	5.7974
150	0.87E-05	2468.0	721.15	29.444	511.39	2.5121	5.7251
155	0.000018	1238.9	716.48	39.252	517.23	2.5764	5.6601
160	0.000035	653.74	711.80	49.102	523.13	2.6389	5.6016
165	0.000065	360.83	707.11	58.997	529.11	2.6998	5.5490
170	0.000117	207.45	702.41	68.938	535.16	2.7592	5.5017
175	0.000202	123.77	697.70	78.928	541.29	2.8172	5.4592
180	0.000337	76.368	692.98	88.969	547.48	2.8738	5.4211
185	0.000544	48.591	688.25	99.065	553.74	2.9292	5.3870
190	0.000853	31.797	683.50	109.22	560.07	2.9835	5.3564
195	0.001304	21.349	678.74	119.43	566.47	3.0366	5.3291
200	0.001944	14.675	673.96	129.71	572.93	3.0887	5.3048
205	0.002835	10.308	669.16	140.05	579.46	3.1398	5.2833
210	0.004048	7.3860	664.34	150.45	586.06	3.1900	5.2643
215	0.005672	5.3900	659.50	160.93	592.71	3.2394	5.2476
220	0.007808	4.0004	654.63	171.49	599.42	3.2879	5.2331
225	0.010575	3.0158	649.74	182.12	606.20	3.3357	5.2205
230	0.014106	2.3065	644.81	192.83	613.02	3.3828	5.2097
235	0.018553	1.7877	639.85	203.62	619.90	3.4292	5.2006
240	0.024083	1.4029	634.85	214.50	626.83	3.4749	5.1929
245	0.030882	1.1135	629.81	225.47	633.80	3.5201	5.1867
250	0.039153	0.89335	624.73	236.52	640.82	3.5647	5.1818
255	0.049112	0.72380	619.61	247.67	647.88	3.6087	5.1781
260	0.060996	0.59183	614.43	258.92	654.97	3.6523	5.1755
262	0.066343	0.54736	612.34	263.45	657.81	3.6696	5.1748
264	0.072055	0.50691	610.25	267.99	660.66	3.6868	5.1742
266	0.078148	0.47005	608.15	272.55	663.52	3.7039	5.1737
268	0.084640	0.43641	606.03	277.13	666.38	3.7210	5.1734
270	0.091547	0.40566	603.91	281.72	669.24	3.7380	5.1732
272.64	0.101325	0.36906	601.09	287.80	673.02	3.7603	5.1732
274	0.10668	0.35175	599.63	290.96	674.98	3.7718	5.1733
276	0.11495	0.32808	597.47	295.60	677.85	3.7886	5.1736
278	0.12371	0.30634	595.31	300.26	680.72	3.8054	5.1739
280	0.13297	0.28634	593.13	304.94	683.60	3.8220	5.1744
282	0.14277	0.26791	590.94	309.64	686.47	3.8387	5.1750
284	0.15311	0.25092	588.74	314.36	689.35	3.8552	5.1756
286	0.16403	0.23522	586.52	319.09	692.23	3.8718	5.1764
288	0.17553	0.22071	584.29	323.85	695.11	3.8882	5.1773
290	0.18765	0.20728	582.05	328.62	697.99	3.9046	5.1783
292	0.20039	0.19484	579.79	333.41	700.87	3.9210	5.1794
294	0.21379	0.18330	577.52	338.22	703.75	3.9373	5.1806
296	0.22786	0.17258	575.24	343.05	706.62	3.9536	5.1819
298	0.24263	0.16261	572.93	347.90	709.49	3.9698	5.1832
300	0.25811	0.15334	570.62	352.77	712.36	3.9860	5.1846
305	0.30010	0.13284	564.75	365.05	719.53	4.0263	5.1885
310	0.34706	0.11556	558.77	377.46	726.67	4.0663	5.1928
315	0.39934	0.10094	552.67	390.01	733.77	4.1062	5.1975
320	0.45731	0.088483	546.44	402.71	740.84	4.1458	5.2025
325	0.52133	0.077825	540.06	415.58	747.85	4.1854	5.2077
330	0.59179	0.068662	533.53	428.61	754.80	4.2248	5.2132
335	0.66906	0.060747	526.82	441.84	761.69	4.2642	5.2189
340	0.75354	0.053881	519.92	455.25	768.49	4.3035	5.2248
345	0.84563	0.047899	512.81	468.88	775.20	4.3428	5.2307
350	0.94573	0.042667	505.46	482.74	781.79	4.3822	5.2367
355	1.0543	0.038071	497.86	496.85	788.27	4.4217	5.2426
360	1.1717	0.034017	489.96	511.22	794.60	4.4613	5.2485
365	1.2984	0.030429	481.73	525.89	800.76	4.5012	5.2542
370	1.4350	0.027238	473.11	540.88	806.72	4.5412	5.2597
375	1.5819	0.024388	464.07	556.21	812.43	4.5817	5.2649
380	1.7396	0.021832	454.51	571.94	817.86	4.6225	5.2696
385	1.9088	0.019528	444.34	588.10	822.93	4.6638	5.2738
390	2.0901	0.017438	433.43	604.76	827.56	4.7058	5.2771
395	2.2844	0.015530	421.61	621.97	831.63	4.7485	5.2793
400	2.4923	0.013773	408.60	639.85	834.95	4.7922	5.2800
405	2.7151	0.012137	394.00	658.55	837.27	4.8373	5.2786
410	2.9538	0.010587	377.09	678.30	838.10	4.8842	5.2740
415	3.2101	0.0090753	356.41	699.62	836.57	4.9342	5.2641
420	3.4863	0.0075018	328.05	723.89	830.34	4.9903	5.2437
*425.16	3.7961	0.00441	227.	783.5	783.5	5.129	5.129

**Triple point

*Critical point

Figure B.1 Pressure-Enthalpy diagram for Propane

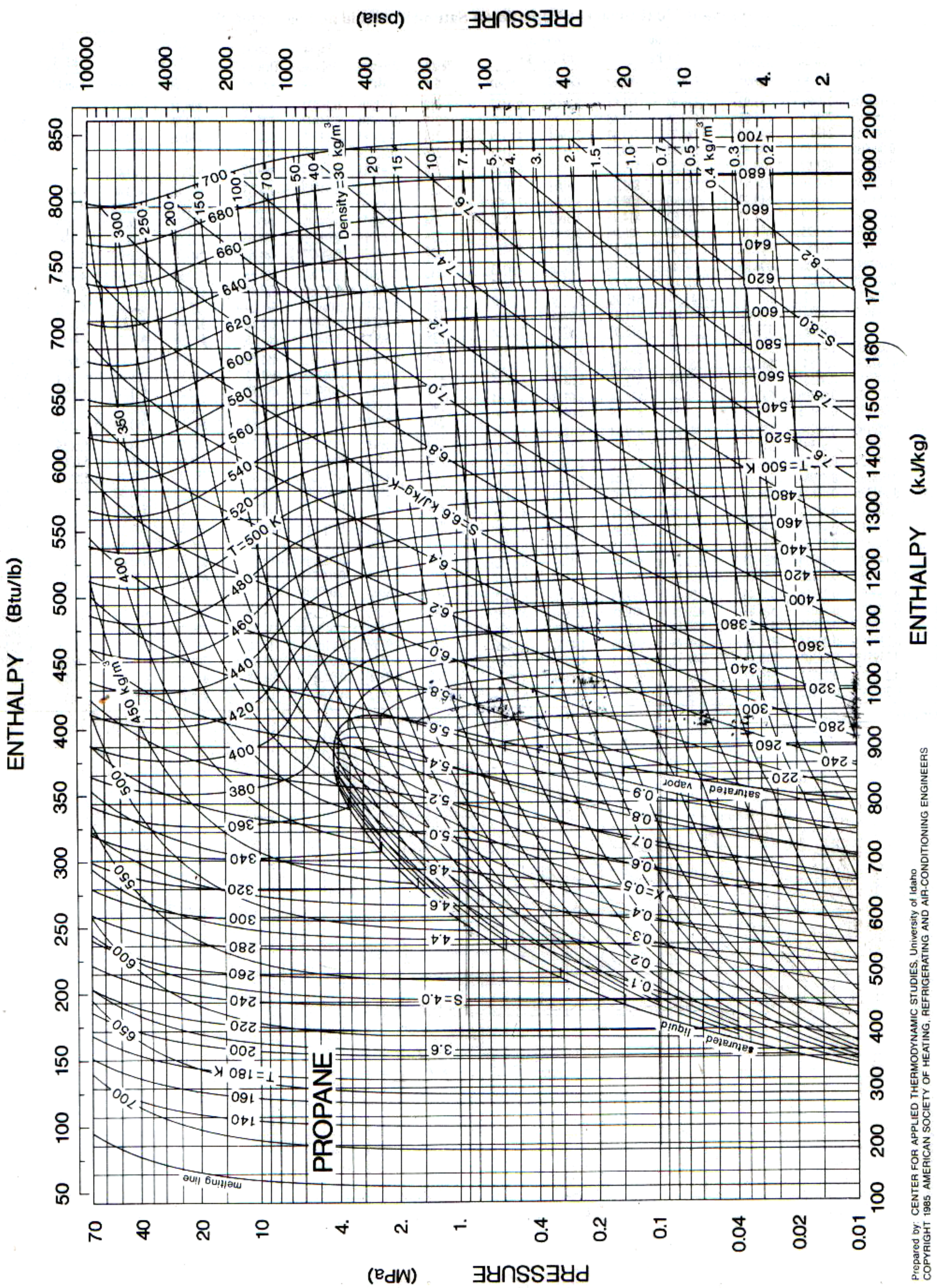


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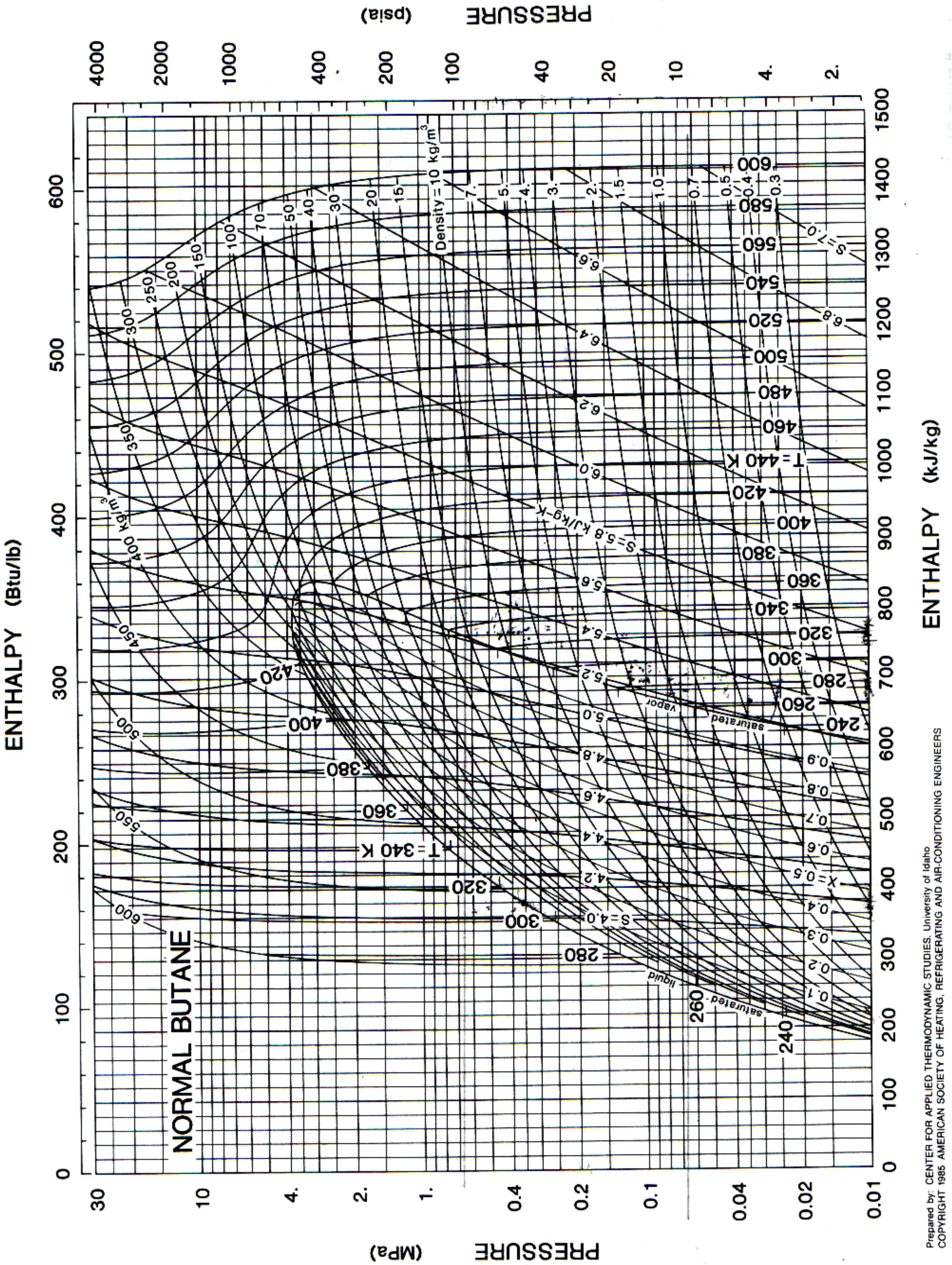
Figure B.2 Pressure-Enthalpy diagram for Butane



دراسة أداء ثلاجة تعمل بالطاقة الشمسية تستعمل مزيجا من غازي البروبان والبيوتان بنسب مختلفة لكل منهما كبديل لغاز التبريد

R-134a

إعداد

مروان يحيى بشير الضيافلة

المشرف

الأستاذ الدكتور محمود حماد

ملخـــــص

يتناول هذا البحث فحص ودراسة أداء خليط من غازي البروبان والبيوتان بنسب مختلفة كغاز للتبريد بدلا من غاز **R-134a** في ثلاجة مستعملة دون تغيير أو تعديل على أجزائها وباستخدام الطاقة الكهربائية العادية والطاقة الكهربائية الناتجة من استغلال الطاقة الشمسية. لكل من غازي البروبان والبيوتان فوائد وأهمها أنهما متوفران محليا وبتكلفة قليلة ويمتلكان نفس الخصائص التي يتمتع بها غاز **R-134a** وأيضا هذان الغازان ليس لهما آثار جانبية عل طبقة الاوزون ولا يساهمان في مشكلة الاحتباس الحراري على العكس من غاز **R-134a** وبالتالي فهما رفيقان بالبيئة.

لتحديد كمية الغاز التي تعطي أفضل أداء, فقد تم وضع ستة كميات مختلفة من الغاز البترولي المسال في الثلاجة وأظهرت النتائج أن أفضل أداء كان عند استخدم 40 غرام من الغاز البترولي المسال وهو ما نسبته 57% من كمية الغاز الاصلي في الثلاجة, وتم اعتماد هذه الكمية لكل التجارب الأخرى.

تم عمل مقارنات على أداء كل خليط وعلى مدى معين من درجات حرارة التبريد والتكثيف, حيث أظهرت النتائج أن هناك توفير في الطاقة بمقدار 7% عند استخدام الغاز البترولي المسال, واستهلاك أكثر للطاقة بمقدار 6% عند استعمال خليط مكون من 50% بروبان و50% بيوتان وكذلك استهلاك أكثر بما نسبته 9% عند استعمال خليط مكون من 70% بروبان و30% بيوتان وكان أكثر استهلاك للطاقة وهو 13% مقارنة بغاز **R-134a** في حالة استخدام البروبان لوحده.

بالمقارنة مع غاز **R-134a** وعلى درجة حراره تكثيف ثابتة فقد أعطى الغاز البترولي المسال كفاءة أكثر بنسبة 6% في حين أن خليط 50% بروبان و50% بيوتان أعطى كفاءة أقل بنسبة 10% وكذلك كفاءة أقل بنسبة 19% عند استعمال خليط 70% بروبان و30% بيوتان وأعطى البروبان كفاءة أقل بما نسبته 32%.

أظهرت النتائج أن الأداء عند استغلال الطاقة الكهربائية الناتجة عن الطاقة الشمسية كان قريبا جدا للأداء عند استخدام الطاقة الكهربائية العادية مع الأخذ بعين الاعتبار استمرارية توفر الطاقة في حالة انقطاع الاشعاع الشمسي.

كذلك أظهرت النتائج أن الغاز البترولي المسال هو البديل الأفضل لغاز **R-134a** وأن النسب الأخرى ممكن استخدامها لتحل مكان غاز **R-134a** ولكن أداءها ليس مشجعا كما في حالة استخدام الغاز البترولي المسال.