INSTALLATION AND INSTRUMENTATION OF A
MICRO-CHP DEMONSTRATION FACILITY

By:

Nicholas Alexander Stone

A Thesis
Submitted to the Faculty of
Mississippi State University
in Partial Fulfillment of the Requirements
for the Degree of Masters of Science
in Mechanical Engineering
in the Department of Mechanical Engineering

Mississippi State, Mississippi

December 2006

UMI Number: 1439534

UMI Microform 1439534

ProQuest Information and Learning Company
300 North Zeeb Road
P.O. Box 1346
Ann Arbor, MI 48106-1346

INSTALLATION AND INSTRUMENTATION OF A MICRO-CHP

DEMONSTRATION FACILITY

By

Nicholas A. Stone

Approved:

Louay M. Chamra Professor of Mechanical Engineering (Major Professor)	W. Glenn Steele Professor and Head of Mechanical Engineering (Committee Member)
Pedro Mago Assistant Professor of Mechanical Engineering (Committee Member)	Steven R. Daniewicz Professor of Mechanical Engineering Graduate Coordinator Department of Mechanical Engineering

Kirk Schulz
Dean of the College of Engineering

Name: Nicholas A. Stone

Date of Degree: December 8, 2006

Institution: Mississippi State University

Major Field: Mechanical Engineering

Major Professor: Dr. Louay Chamra

Title of Study: INSTALLATION AND INSTRUMENTATION OF A MICRO-CHP DEMONSTRATION FACILITY

Pages in Study: 83

Candidate for Degree of Masters of Science

Micro-Cooling, Heating and Power (CHP) is the decentralized generation of electricity in which normally wasted heat is recovered for use in heating and cooling of the space. A micro-CHP demonstration facility is needed to showcase the system and allow for experiments to be performed. This thesis illustrates the steps taken for the installation and instrumentation of a Micro-CHP (Cooling, Heating, and Power) demonstration facility. Equipment sizing was performed by creating an accurate building model and performing a transient building analysis. Temperature, pressure, flow rate, and relative humidity are measured in order to determine accurate energy balances through each piece of equipment in the micro-CHP system. The data is collected using a number of LabView subroutines while a Visual Basic program was developed to display the information.

TABLE OF CONTENTS

CHAPTER Page

LIST OF TABLES

LIST OF FIGURES

FIGURE Page

FIGURE Page

NOMENCLATURE

ΔT	Temperature change found by $T_{out} - T_{in}$, °C or °F
ρ	Density of fluid, $\frac{kg}{m^3}$ or $\frac{lbm}{ft^3}$
CFM	Volumetric Flow Rate, $\frac{ft^3}{\min}$
Cp	Specific Heat in $\frac{kJ}{kg \cdot °C}$ or $\frac{BTU}{lb \cdot °F}$
GPM	Volumetric Flow rate, $\frac{gal}{\min}$
$\dot{m}$	Mass flow rate, $\frac{kg}{s}$ or $\frac{lbm}{s}$
$\dot{Q}$	Heat flow rate, $\frac{BTU}{hr}$
Q	Volumetric Flow, $\frac{m^3}{s}$, $\frac{ft^3}{\min}$ or $\frac{gal}{\min}$
P_V	Velocity Pressure for Flow Sensing Element, inches of H_2O
V	Velocity, $\frac{ft}{\min}$

CHAPTER I

INTRODUCTION

A Micro-Cooling, Heating, and Power (micro-CHP) demonstration facility has been constructed for both research and community outreach. This facility will be used to inform engineers, contractors and end-users about the benefits and upfront requirements of a micro-CHP installation in a residence or small commercial building. While micro-CHP is widely available in the European market, their systems are designed to meet a higher heating load with electrical power as the useful by-product. In the Southeastern United States, micro-CHP systems are designed to either meet the entire electrical and heating/cooling loads of the building, or supplement both the grid and existing heating/cooling devices. Because of these differences, several components required for a micro-CHP installation are not commercially available. While most components can be purchased, mismatches in equipment will exist and optimization will be required. The micro-CHP demonstration facility will allow for these components to be optimized in a real world installation.

What is Micro-CHP?

Micro-CHP is the decentralized generation of electricity in which normally wasted heat is recovered for use in heating and cooling of the space. Micro-CHP denotes the power regime of less than 15 kW of electricity and is applicable to the small commercial and typical residential sectors.

A Micro-CHP system consists of several components in which a building can operate either completely grid independent, or connected to the grid to provide peak load power. The key component of a micro-CHP system is the prime mover, which is used to generate both the electricity and thermal energy. Several prime mover technologies are available which include but are not limited to reciprocating engines, sterling engines, micro-turbines and fuel cells. Commercial availability for the "micro" regime is still limited in the United States but is under active development by several companies.

Commercial Availability of Micro-CHP Components

A Micro Cooling, Heating, and Power (micro-CHP) facility for use in a hot and humid climate are designed to meet the heating and cooling loads of the target building. Since temperatures regularly reach 100°F and humidity levels of 99%, the selected prime mover will normally meet the required electrical load. In some cases in order to meet the thermal load of the building, the prime mover will actually generate more electricity than is required; this electricity can then be sold back to the local electrical provider.

Micro-CHP is still in its infancy in the United States, as the two key components for an installation, the prime mover and absorption chiller, have limited commercial availability or are not available with the required specifications. Europe has commercially available micro-CHP units, but their design specifications were to meet the heating load of a residence with power production as a by-product. European micro-CHP systems are simply a prime mover with heat recovery. Their systems do not cool the living space. The average size of a European home is 940 ft^2 while the average American home is 2330 ft^2, almost 2 ½ times larger. (EuroACE, 2001) (NAHB, 2004) The difference in both climate and house size emphasizes the need for technologies which are designed for use in a hot and humid climate.

The remaining components of the CHP system are widely used in commercial water heating and cooling systems which employ fan-coil units. The system can be designed to use either a two-pipe or four-pipe scheme. Other readily available components include but are not limited to the water tank, pumps, makeup boilers, and other various plumbing components.

Absorption Chiller

The absorption chiller is one of the key components to a micro-CHP installation with limited availability in the United States. This device uses the recovered thermal energy to chill water for use in fan-coil units. In order for an absorption chiller to be used in a micro-CHP system it must be water fired, many small (100 ton or less) absorption chillers are natural gas fired.

Absorption chiller technology is not a "new" technology and has been developed quite extensively for the large commercial market. The main problem with absorption chillers for use in micro-CHP is the availability of smaller units which are water fired. If the absorption chiller is direct fired, by natural gas or LPG, then the heat recovered when cooling is needed cannot be used to provide a cooling effect for the living space and will be wasted. Four of the most well known HVAC manufacturers do not produce water fired chillers in the range that a micro-CHP facility would require. Table 1.1 shows the smallest available water-fired absorption chillers that are available for purchase and installation from these manufacturers. The smallest available unit is 75 tons, which would provide enough cooling for a 38,000 square foot living space in the Southeastern United States, assuming approximately 500 ft^2/ton.

Table 1.1 Smallest Water Fired Absorption Chiller From Large Manufacturers

Manufacturer	Smallest Size (Tons)	Note
Carrier	75	
Lennox	N/A	Does not manufacturer chillers
Trane	N/A	All chillers are steam fired.
York	100	

Through an extensive search of absorption chiller manufacturers' websites, it was found that only two have water fired absorption chillers that would work for a micro-CHP application. Each manufacturer has a 10 ton unit which would be larger than is required for the average American home. Table 1.2 lists the available 10 ton absorption chillers along with the hot water temperature range and required piping system.

Table 1.2 Water Fired Absorption Chiller Ratings

Manufacturer	Size Range (Tons)	Hot Water Temp Range (°F)	Manufactured In
Thermax	10-80	158-230	India
Yazaki Energy	10-30	158-203	Japan

The first manufacturer, Thermax, has a water fired, 10 ton absorption chiller available with a heat medium temperature range of 158 to 230 °F. This unit uses Lithium Bromide as the refrigerant and uses 3 solution pumps for operation and is available only in a single effect configuration.

The second manufacturer of small tonnage water fired absorption chillers is Yazaki Energy. Yazaki's absorption chiller is also a 10 ton unit which provides a cold water temperature of 45°F with a flow rate of 24 GPM. It requires hot water anywhere from 158°F to 203°F with a flow rate of 38 GPM. The cooling tower flows at 80 GPM and rated temperature is 87.5°F. Lithium bromide is used as the refrigerant and is available only in a single effect configuration.

Direct fired absorption chillers have a wider availability in the United States in the smaller tonnages required for micro-CHP applications. These units were developed to replace the conventional vapor compression systems and use natural gas as the energy input. These units are being marketed to home users to help reduce the peak electrical loads during the summer months. Manufacturers of direct fired absorption chillers offer models which can produce chilled water or both chilled and hot water. The units with both heating and cooling effects can replace the entire conventional unit, requiring only a blower and a single coil. The units with only cooling will still require a furnace, but a water coil will replace the refrigerant coil. Of the several manufacturers of direct fired absorption chillers, Robur Corporation and Cooling Technologies, Inc. offer the most robust line of chillers for residential or small commercial applications.

The Robur Corporation, based out of Evansville, Indiana, produces several small tonnage direct fired absorption chillers. Their units are designed to be placed outdoors, with an air cooled condenser. Robur offers units which vary in size from 5 to 20 tons of cooling effect and a water outlet temperature of 37°F. Robur offers several different units with cooling and cooling-heating effects for a wide range of climate conditions.

Their units will require an indoor water coil, water pump and proper plumbing. (Robur, 2006)

Cooling Technologies, Inc., with headquarters in Toledo, Ohio, offers a direct fired absorption chiller with a cooling output of 5 tons. Their units can operate from a variety of heat sources including natural gas, microturbine exhaust and fuel cells. For larger cooling loads they offer a solution to operate their absorption chillers in packs where 2 to 6 unit are connected with single point connections for fuel, chilled water, and electrical connections. The Cooling Technologies absorption chillers come with an optional chilled water pump and will require the installation of indoor plumbing and fan-coil unit. These units only provide chilled water and use of a natural gas or electric furnace will be required for heating. (Cooling Technologies, Inc., 2006)

Prime Mover

The prime mover, which drives the electrical generator, also has limited availability in the United States. Several different types of prime movers are currently under development with market availability coming in the next couple of years. Currently available technologies in the United States include internal combustion engineers, Micro-Turbines, and Stirling engines. Technologies under development, with no commercially available units, include Rankin Cycle engine and the Fuel Cell. A list of manufacturers and information about their available micro-CHP generators can be found in Table 1.3.

Table 1.3 Prime Mover Manufacturers

Manufacturer	Prime Mover Technology	Power Output (kW)	Thermal Output (BTU/hr)	MFG In
Marathon Engine Systems	Internal Combustion	2.0-4.7	48,000	USA
Whisper Tech	Stirling	1.2	27,000	New Zealand
Capstone Energy	Micro-Turbine	30	366,000	USA
Solo Stirling	Stirling	7.5	75,000	Germany

The prime mover can hold two significantly different rolls in a micro-CHP application. Units with relatively small electrical output but large thermal output are better suited for areas with cooler climates in which the recovered thermal energy is of primary interest and the produced electricity is used to reduce the electrical consumption from the grid. Units with large electrical generation can provide for grid independent installations in which no additional power is required. Each installation may require the use of a boiler or other means to meet the thermal requirements of the facility.

The internal combustion engines inclide four-cycle prime movers with one to four cylinders depending on power output; thermal heat is recovered through the water jacket surrounding the motor and through an exhaust heat exchanger. Marathon Engine Systems manufactures a single cylinder engine with a power output of 2.0 to 4.7 kW and a thermal output of up to 48,000 BTU/hr. These units are able to provide the base electrical load requirements of a building. Additional power will be required for peak loads. This energy can be provided from peak load generators, battery array, or from the grid.

The stirling engine is a well developed technology that is making a comeback in power generation. A stirling engine can be powered by any fuel source, including solar energy, and is very quiet during operation. Whisper Tech, based out of New Zealand, manufactures 1.2 kW stirling engines with a thermal output of 27,000 BTU/hr. Another manufacturer of stirling engines is Solo Stirling Engines based out of Germany. Their unit has a power output of 7.5 kW with a maximum thermal output of 75,000 BTU/hr.

Stirling engines are widely accepted in the European market for micro-CHP applications and are currently under development by several US companies. Infinia Corporation, formerly The Sterling Technology Company, is developing a 1 kW unit. The thermal output of the unit has not been specified and the company has no plans of availability of their units in the United States. (ENTAC, 2005) A United States based manufacturer of stirling engines, Stirling Energy Systems, they currently offer solar power stirling engines with future plans for Biogas and Hydrogen systems. Their units will be offered as single units or in “Gensets” where 2 or more units can be connected in parallel to obtain higher electrical and thermal output. (SES, 2006)

Micro-Turbines are an emerging technology for use in the micro-CHP market. The available micro-turbines produce more electricity than is needed for a typical micro-CHP application but could be used for a neighborhood type installation where several homes or businesses are powered from a single installation. Capstone Energy, a California manufacturer of micro-turbines, produces a 30 kW unit which runs off of natural gas and has a thermal output of 366,000 BTU/hr. Capstone microturbines can be “ganged” into packs of 10 to increase both electrical and thermal output.

There are several other manufacturers of microturbines for use in power generation. These units produce electricity from 30 kW to well over 100 kW. The average home in America uses 10,654 kWh of electricity a year, which comes out to an average load of 1.2 kW excluding HVAC equipment loads. (Department of Energy, 2001) Peak loads will vary greatly as an average air conditioning unit will consume 3500 W, computers will consume approximately 65 W, and the various lighting used within the re6sidence will consume 1.1 kW on average. Microturbines have greater potential for use in housing projects, housing units in which several residences are power and cooled from a central location.

Elliot Microturbines of Florida produces 100 kW microturbines for use with CHP applications. Their unit produces 587,000 BTU/hr of heat with an overall thermal efficiency of 85%. (Elliot, 2006) Another manufacturer of microturbines designed for the CHP market is Ingersoll-Rand Industrial Technologies. Their unit produces 70 kW of electrical power and 13,330 BTU/kWh of thermal recovery. (Ingersoll-Rand, 2006)

Rankin cycle engines are currently under development with several companies promising to have commercial units available in the next five years. With a relatively high thermal output and a low electrical output, these units will be used for thermal generation with the electricity being used for load shedding. Cogen Microsystems, based out of Australia, is developing a Rankin cycle generator with a power output of 2.5 kW and a thermal output of 11 kW (3 tons). The expected overall efficiency is 90% based on the higher heating value. Their unit is expected to be commercially available in 2007.

Fuel Cells are an emerging technology which converts the fuel into electricity and heat energy through an electrochemical process without direct combustion of a fuel source. Typically, hydrogen reacts with oxygen electrochemically to create water and a DC current. Fuel cells are of great interest as their only byproducts are pure water when fueled by pure hydrogen. Reforming is used when pure hydrogen is not available and can easily extract the required hydrogen from natural gas. The reforming process is where carbon is released to the atmosphere, but is done without direct combustion.

The electrochemical process creates a DC current and heat. This heat can be recovered and used to help drive the reforming process and for process heat. Fuel cells are very attractive for micro-CHP applications due to their small size, silent operation and reliability. There are several different types of fuel cells, and their main difference is the membrane used for the electrochemical process and the fuel used to drive the reaction. Fuel cells are being developed for power in small commercial and residential markets and as peak shaving units for commercial and industrial uses. The main drawback of fuel cells is the initial cost to purchase and install. Since fuel cells are still relatively new with respect to many other technologies, it is expected that their prices will fall in the years to come.

Ceramic Fuel Cells Limited (CFCL), based out of Australia, is developing a micro-CHP demonstration unit with a 1 kW electrical, 1 kW thermal output and an overall efficiency of 80%. The demonstration unit is designed to work in parallel with the grid and offers peak power shaving and backup power.(CFCL, 2006) CFCL also is currently developing a Distributed Generation (DG) fuel cell which has an estimated 5 to 6 kW average power output with peak loads of up to 10 kW. Heat recovery is an option which can be added to the unit. (CFCL, 2006) Both of CFCL's units have a single phase electrical output of 220V. This fuel cell is suited for off-grid applications in which the fuel cell will be able to meet the entire electrical demand of the facility.

Plug Power of Latham, NY manufactures fuel cells for standby, continuous and emergency use. Plug Power's fuel cells are not applicable to the micro-CHP market as they currently do not manufacturer units with heat recovery options. Their GenCore line was developed for backup power in case of outages and produces either 60 or 120 Vdc power and runs off of pure hydrogen. (Plug Power, 2006) Plug Power is also currently developing a fuel cells for off-grid, prime power applications called GenSys. The technical specifications for this unit are not currently available.

Another source of micro-CHP prime-movers can be found by using existing backup or standby generator sets and installing heat exchangers to recover the normally wasted heat energy. On an internal combustion engine a heat exchanger can be used for the both the water jacket and the exhaust. For microturbines and fuel cells heat exchangers can also be used for the exhaust streams. Depending on the electrical and thermal output of the engine, these units can be designed for load shedding or as an off-grid installation.

CHAPTER II

DESIGN

Demonstration Facility

The target buildings for micro-CHP systems include both residences and small commercial facilities. A demonstration site must be able to showcase the micro-CHP technology for both types of applications, as the thermal loads and electrical loads will vary between the two.

The Mississippi State University micro-CHP demonstration facility includes two separate areas which include a fully working wood shop and an office area. Figure 2.1 shows the overall layout of the demonstration facility. The wood shop area is approximately 2000 sq ft and has 10 foot drop ceilings which resemble typical small commercial buildings. The office area is approximately 1000 square feet with 12 foot solid ceilings which resemble a residence or office area. There is also a small mechanical room located outside the office area which will be used to house the micro-CHP equipment. A large covered area is adjacent to the office area and mechanical room which houses large equipment.

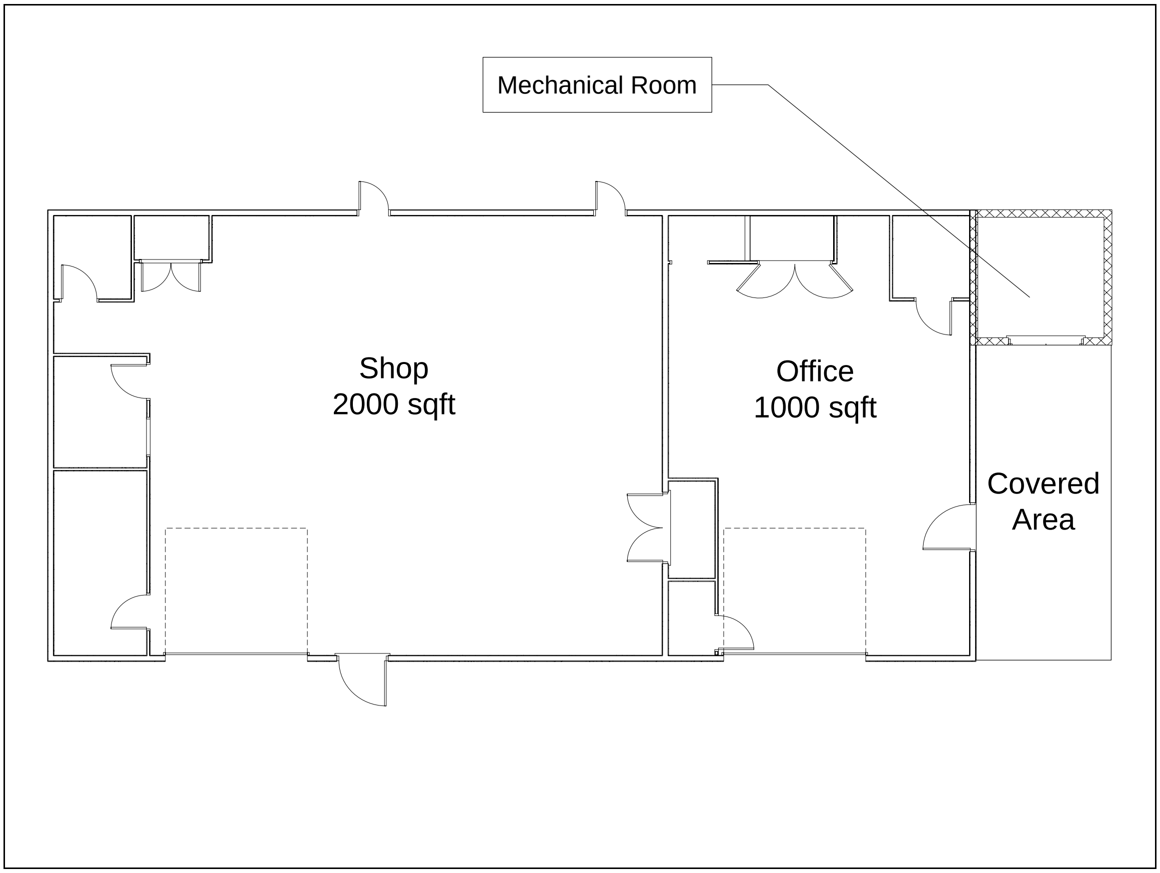


Figure 2.1 Demonstration Facility Layout

To illustrate how equipment will be installed in real world applications, the system was split into two major areas, electrical and thermal generation systems and the HVAC systems. The electrical and thermal generation components are housed in the mechanical room and under the covered area depending on the size of the equipment. The HVAC equipment was placed indoors for office area and the packaged units, placed outdoors, are used for the wood shop area.

Electrical and Thermal Generation Subsystem

Electrical power for the micro-CHP demonstration facility is provided by a generator which was sized to meet the max electrical requirements of the facility. This allows for complete grid independence, and the only fuel source required by the facility is natural gas. An automatic transfer switch is used to select which power source the demonstration facility will use; grid power or generator power. Accommodations have been made in order to allow for easy installation of additional prime mover technologies.

Thermal energy produced by the generator, which is normally vented to the atmosphere, is used to heat water which can then be used to drive thermally activated devices such as absorption chillers, desiccant dehumidifiers and heating coils. The method of heat recovery will vary greatly depending on the type of prime mover used for power generation. A 200 gallon insulated water tank is used for thermal storage in which all hot water circulates from this tank. In cases where the prime mover cannot supply the needed thermal energy for the facility a 200,000 BTU/hr boiler will be installed for makeup energy. Plumbing for the heat recovery loop was designed in such a manner that additional prime movers can be added at a later date.

Cooling is provided through an absorption chiller which was sized to meet the cooling load of the demonstration facility. Fan-coil units are used in the shop and office areas in order to provide the cooling effect. The absorption chiller is water fired as to use the recovered thermal energy from the prime mover. Plumbing was designed in a manner to provide for additional absorption chiller technologies.

The water tank, boiler and absorption chiller along with all required pumps are housed in the mechanical room. The cooling tower required by the absorption chiller has been placed in the rear of the facility. Prime movers and additional absorption chillers will be housed under the covered area as dictated by space. Figure 2.2 shows the overall layout of the mechanical room and covered area.

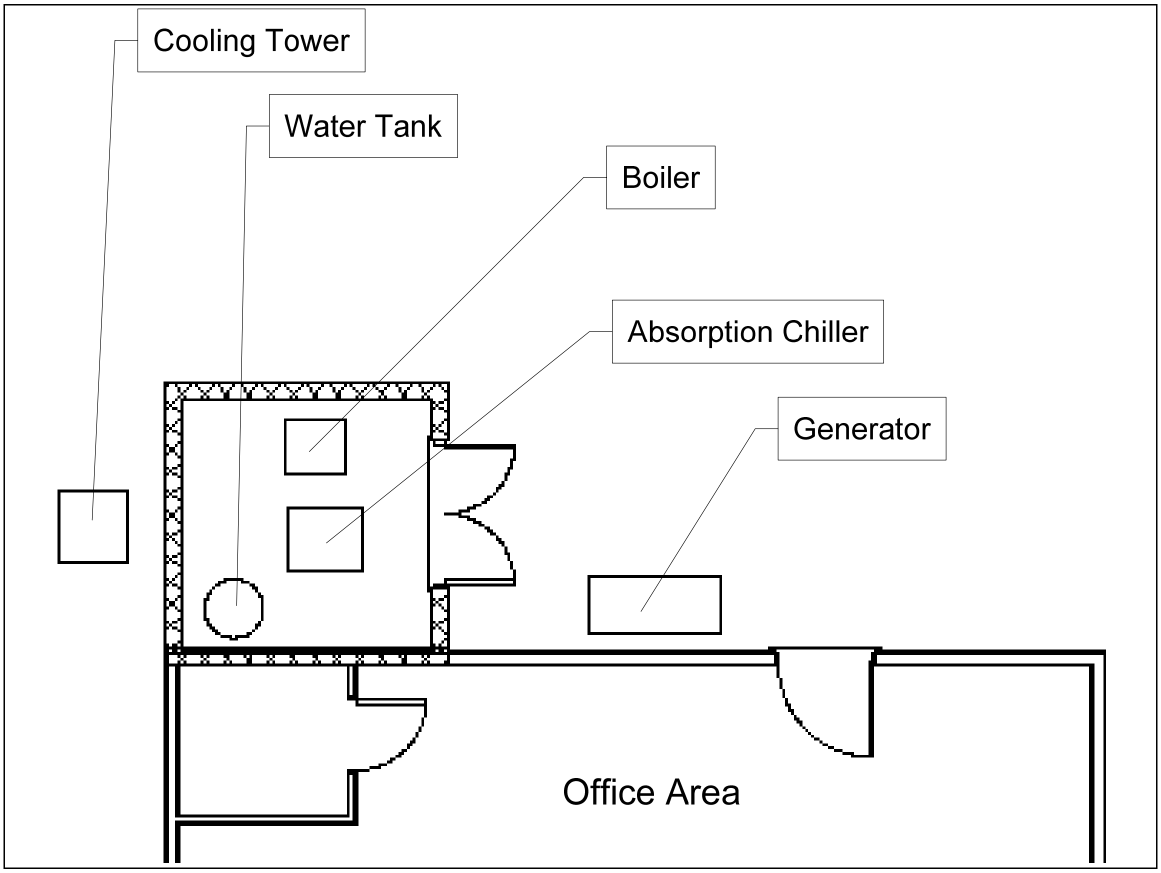


Figure 2.2 Mechanical Room Layout

HVAC Subsystems

The Heating, Ventilation and Air Conditioning systems were split between the shop and office areas to showcase the types of units traditionally found in residential and small commercial installations. Each area is heated and cooled through either a micro-CHP system or a traditional vapor compression system. The installation of two systems allows for comparisons of performance between the two different types of systems to be performed.

The office area has a vertical up flow, four-pipe fan-coil unit which was sized to meet the cooing requirements of the office space. This unit provides heating and cooling to the space through hot or cold water produced from the micro-CHP system. Power for this unit is provided from the generator. The traditional vapor compression system for the office is a split unit with the condensing unit placed outside. This unit has a vertical up flow arrangement with an integrated natural gas furnace to provide heating. Power for the traditional system is provided from the power grid and will not affect the electrical load of the micro-CHP system.

The fan-coil unit and the traditional unit were installed on a common plenum and supply air to a common supply duct. Dampers were installed on the supply side of each unit to isolate the unit which is providing active air conditioning for the space. The common supply and return allows for unbiased comparisons to be performed and each unit will have comparable specifications. Figure 2.3 shows the locations of the office HVAC equipment and location of the ductwork to supply cold air to the space.

The shop area is heated and cooled through outside, packaged units. The micro-CHP fan-coil unit is a four-pipe arrangement and is powered from the generator. The traditional vapor-compression system is an outdoor packaged unit with an integrated furnace to provide heating for the space and is powered from the grid. The micro-CHP system and the vapor compression system share a common supply and return installed on the supply side of each unit. Figure 2.4 shows the layout of the Shop HVAC equipment.

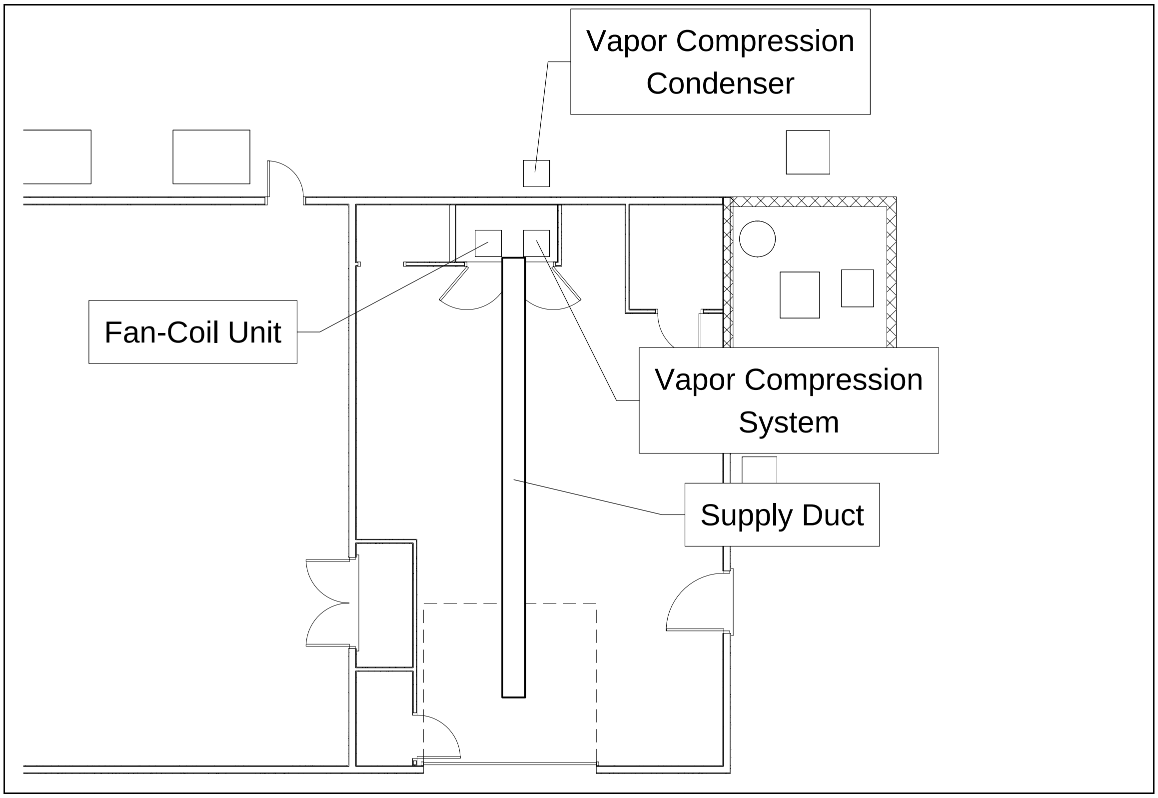


Figure 2.3 Office HVAC Equipment Layout

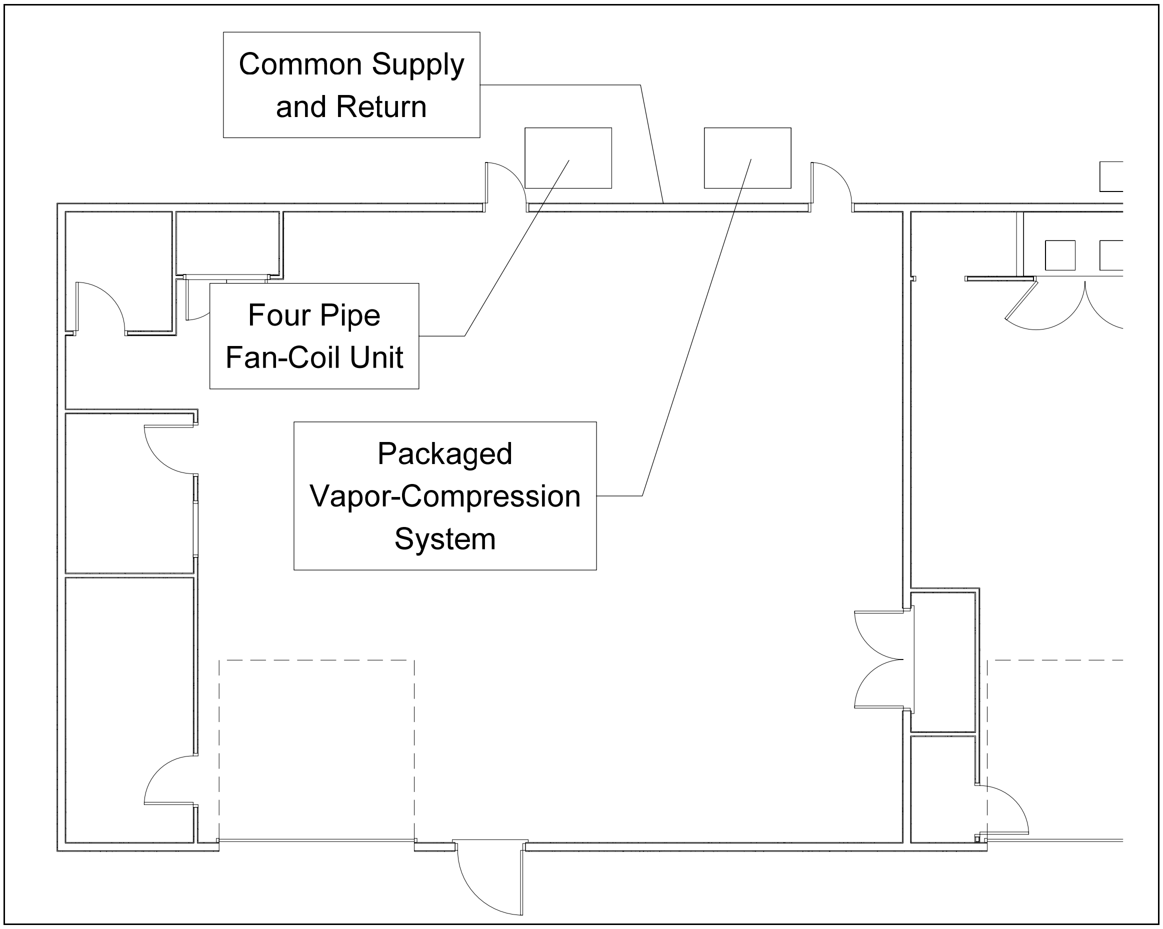


Figure 2.4   Shop HVAC Equipment Layout

CHAPTER III

EQUIPMENT SIZING

Introduction

For the successful installation of a micro-CHP system, components must be properly sized for the area which is to be heated and cooled. Both the electrical and thermal loads of the building must be calculated to insure that the prime mover can provide the required energy. If the motor generator can provide enough thermal energy but not enough electrical, supplemental power from the grid or backup generators will need to be installed. The same applies to the thermal load, where a boiler has been installed to provide supplemental heat.

Equipment sizing was performed through use of the TRNSYS program (www.trnsys.com). TRNSYS is a flexible tool which performs simulations for the transient response of thermal systems. In order to determine the thermal requirements of the building, an energy rate conservation (ERC) simulation was performed. An ERC simulation calculates the thermal energy needed to hold a space at the initial conditions.

The demonstration facility was modeled in TRNSYS using the PREBID component. PREBID allows for accurate modeling of buildings by modeling the radiation absorptivity, heat transfer, and heat capacity of the walls and other masses contained within the building. To build an accurate model of the demonstration facility, an accurate blueprint of the building was constructed by measuring all room dimensions, ceiling heights, and determined wall and door locations. The thermal characteristics of the building were determined by measuring wall thicknesses, insulation, and wall covering types. The building model was split into zones according to each room, with the boundary conditions including the wall type and area. Figure 3.1 shows the demonstration facility and the zone used for the TRNSYS program. The ceilings were modeled taking into consideration the type of ceiling and insulation thickness.

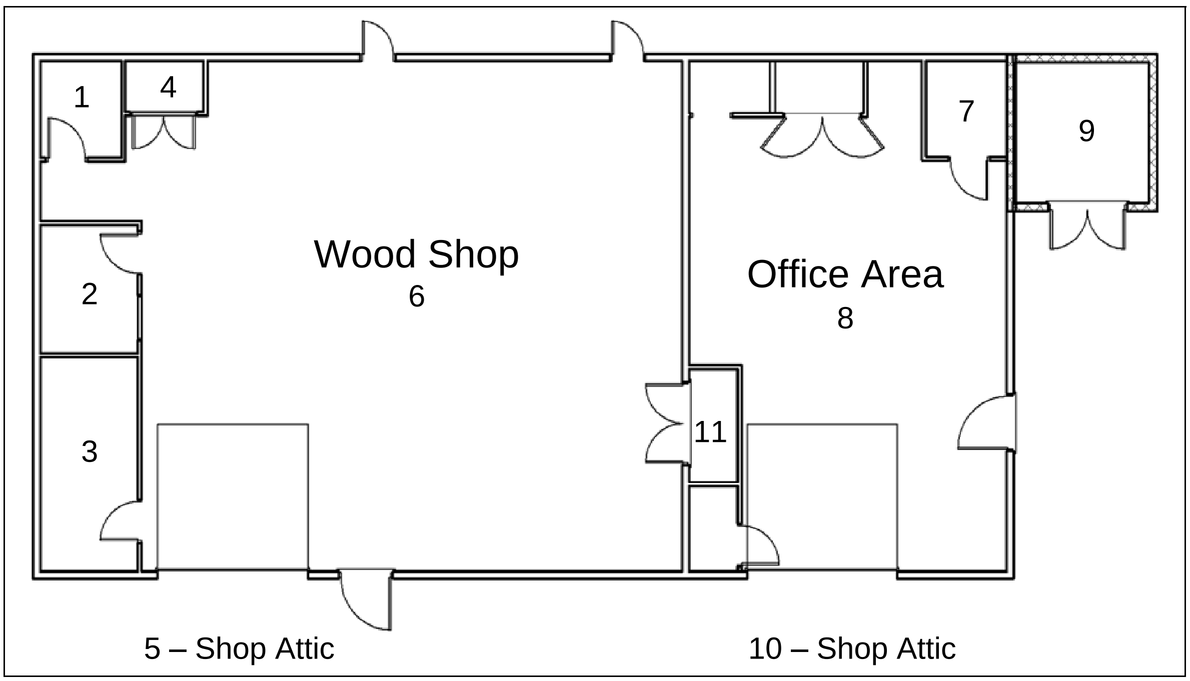


Figure 3.1 Demonstration Facility Zones for PREBID

The concrete slab of the building produces a significant thermal storage and care was taken to properly model this feature. Two different approaches were taken depending on whether the room was interior (all walls are connected to other zones) or exterior (at least one wall was connected to the outside). For exterior rooms the concrete slab was modeled by setting the 3ft strip near the exterior wall at the ambient (outside) temperature. The remaining area was held at the interior room temperature. For interior rooms the concrete slab's temperature was held constant at the room's temperature.

The inputs required for the building model include the ambient air temperature, ambient relative humidity, and a sky temperature model. The radiation is determined through a component which will calculate the radiation on each surface throughout the year. This radiation model uses the latitude and accurate sun paths along with weather information for the location to determine the energy each surface of the building sees.

HVAC Equipment

The micro-CHP demonstration facility was designed to be heated and cooled by two different HVAC systems, one unit for the shop area and another unit for the office area. Figure 3.2 shows which areas are to be served by the office and shop air conditioning units. The required cooling tonnage (1 ton = 12,000 BTU/hr) was determined through an ERC simulation of the demonstration facility. The ERC simulation was run using weather data in a TMY2 format, acquired from the Department of Energy's website, for Meridian, MS. The TMY2 format contains average weather conditions for a given location over the last 10 years and is widely used in building thermal simulations. The simulation was run over the entire year with data taken every hour for each zone which had active air conditioning. Temperatures of the occupied spaces were held constant at 77°F and a relative humidity of 50%.

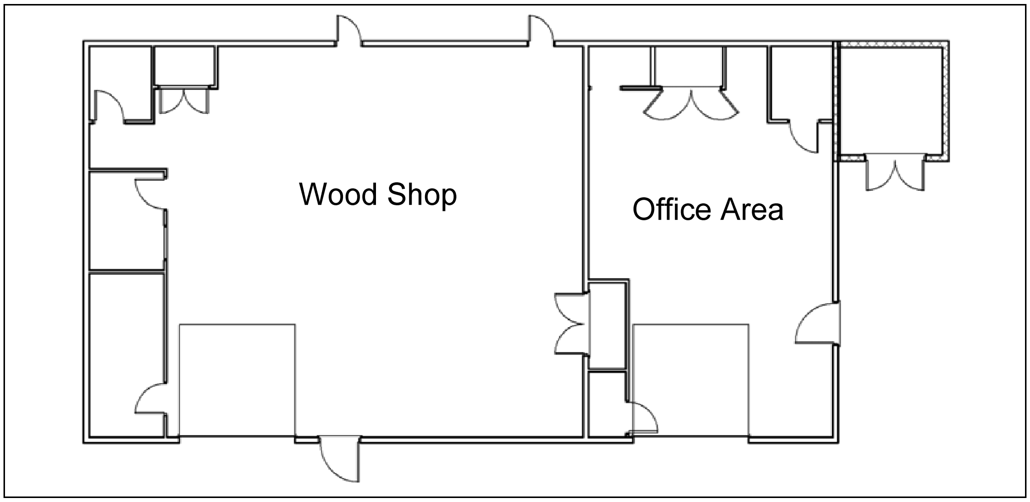


Figure 3.2 HVAC Service Areas

The required cooling loads of the shop and office units were determined by creating histograms depicting the hours operated at half ton intervals for the year, four month cooling season, and worst month and worst day. The worst month was determined by calculating which month used the most total energy for cooling. Table 3.1 shows each month and the total energy used. The worst day was calculated by determining which day used the most total energy for cooling. Table 3.2 shows the worst 10 days for cooling for the office, while Table 3.3 shows the 10 worst days of cooling for the shop.

Table 3.1 Total Cooling Requirements for Shop and Office

Month	Shop			Office		
	Sensible (BTU)	**Latent (BTU)**	**Total (BTU)**	**Sensible (BTU)**	**Latent (BTU)**	**Total (BTU)**
Jan	2.7E+05	5.4E+04	3.3E+05	3.3E+04	3.0E+04	6.3E+04
Feb	3.4E+05	1.4E+05	4.9E+05	4.5E+04	9.1E+04	1.4E+05
Mar	6.0E+05	1.7E+05	7.7E+05	9.7E+04	9.7E+04	1.9E+05
Apr	1.2E+06	4.7E+05	1.7E+06	2.9E+05	2.8E+05	5.7E+05
May	2.2E+06	1.0E+06	3.2E+06	6.2E+05	5.9E+05	1.2E+06
Jun	2.6E+06	2.5E+06	5.1E+06	8.4E+05	1.5E+06	2.4E+06
Jul	3.4E+06	3.4E+06	6.8E+06	1.3E+06	2.1E+06	3.4E+06
Aug	2.8E+06	3.7E+06	6.5E+06	1.0E+06	2.2E+06	3.2E+06
Sep	2.1E+06	2.0E+06	4.1E+06	6.5E+05	1.2E+06	1.9E+06
Oct	1.1E+06	5.8E+05	1.7E+06	2.4E+05	3.4E+05	5.9E+05
Nov	6.2E+05	5.1E+05	1.1E+06	1.2E+05	2.9E+05	4.1E+05
Dec	1.8E+05	2.9E+04	2.1E+05	2.8E+02	1.5E+04	1.5E+04

Table 3.2 Ten Worst Days of Cooling for Shop

Date	Sensible (BTU)	Latent (BTU)	Total (BTU)
07/01	2.2E+05	1.3E+05	3.6E+05
08/12	2.1E+05	1.3E+05	3.4E+05
07/08	2.0E+05	1.4E+05	3.4E+05
07/22	2.0E+05	1.3E+05	3.3E+05
08/19	1.8E+05	1.4E+05	3.2E+05
07/29	2.3E+05	8.4E+04	3.2E+05
07/09	1.7E+05	1.4E+05	3.1E+05
06/24	1.9E+05	1.2E+05	3.1E+05
07/02	1.7E+05	1.2E+05	2.9E+05
08/05	1.7E+05	1.3E+05	2.9E+05

Table 3.3 Ten Worst Days of Cooling for Office

Date	Sensible (BTU)	Latent (BTU)	Total (BTU)
07/01	8.8E+04	8.7E+04	1.8E+05
07/08	7.8E+04	9.1E+04	1.7E+05
08/12	7.9E+04	8.7E+04	1.7E+05
07/22	7.8E+04	8.7E+04	1.6E+05
07/09	7.8E+04	8.4E+04	1.6E+05
08/19	7.0E+04	8.9E+04	1.6E+05
07/02	7.5E+04	7.5E+04	1.5E+05
08/05	6.2E+04	8.3E+04	1.5E+05
06/24	6.7E+04	7.8E+04	1.4E+05
07/29	8.8E+04	5.6E+04	1.4E+05

With the worst month and worst day determined for both the shop and office, histograms were created showing the hours operated at the given level. The histogram bin sizes were split into half ton increments, depicting the normal air conditioner coil sizes. A line was added to the histograms showing the percentage of total time each bin operates at the given tonnage.

Figure 3.3 through Figure 3.6 show the histograms for the shop space for the year, cooling season (May through September), and worst month and worst day which were used to size the HVAC equipment. Figure 3.7 through Figure 3.10 show the histograms for the office space for the year, cooling season, and worst month and worst day.

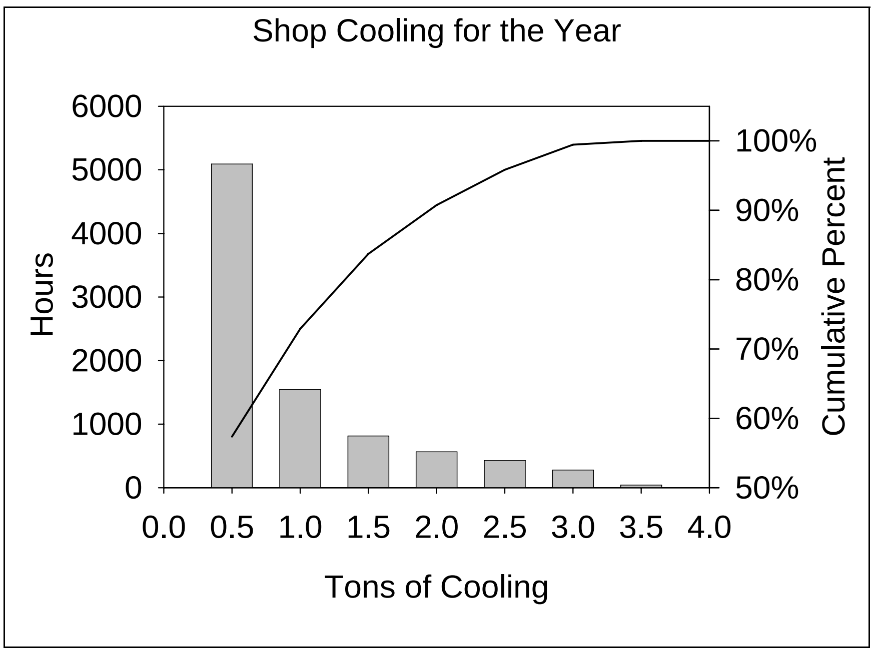


Figure 3.3 Shop Cooling for the Year

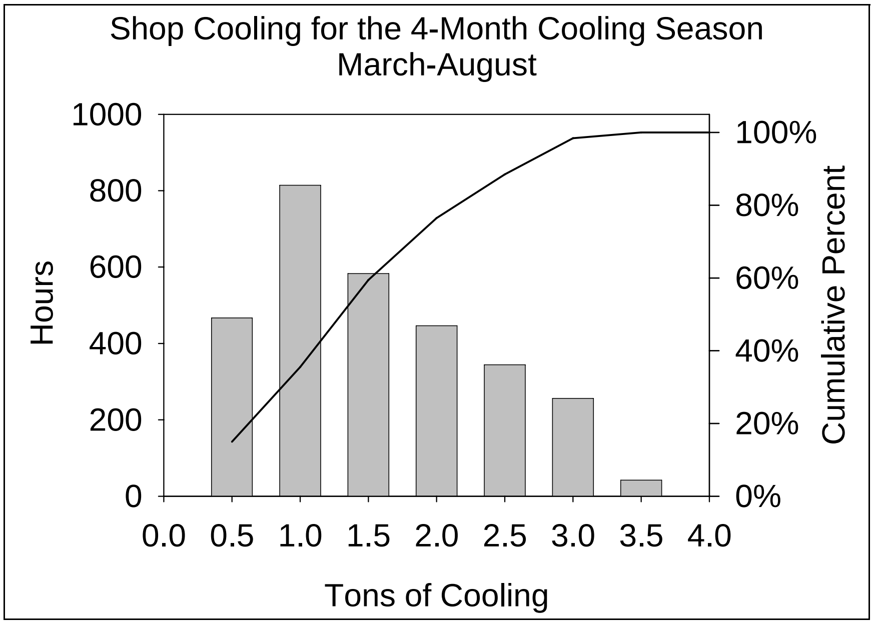


Figure 3.4 Shop Cooling for the Cooling Season

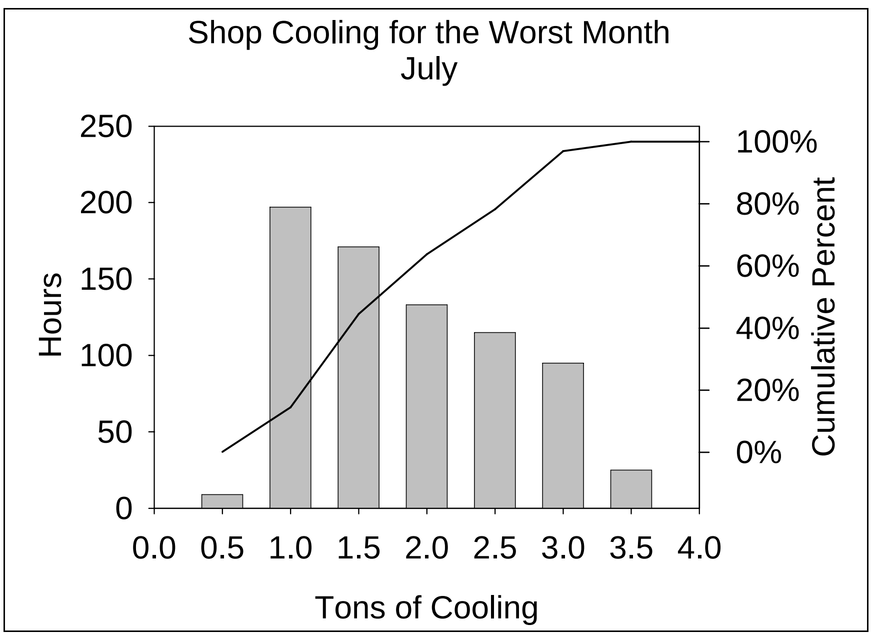


Figure 3.5 Shop Cooling for the Worst Month

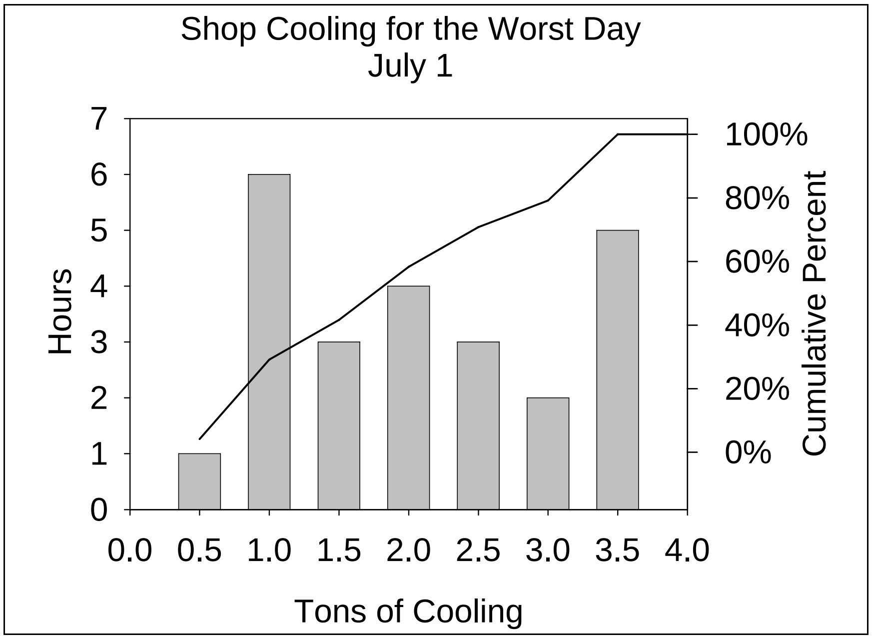


Figure 3.6 Shop Cooling for the Worst Day

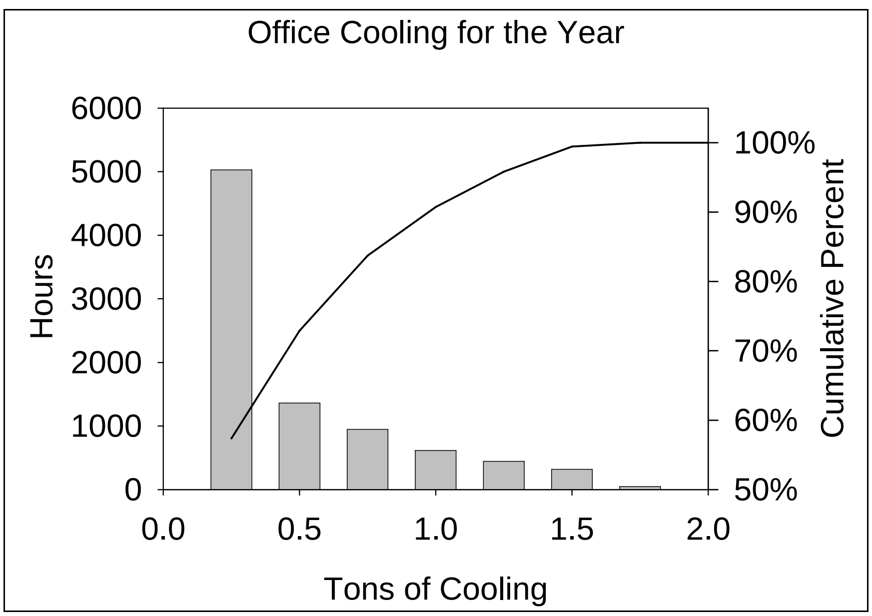


Figure 3.7 Office Cooling for the Year

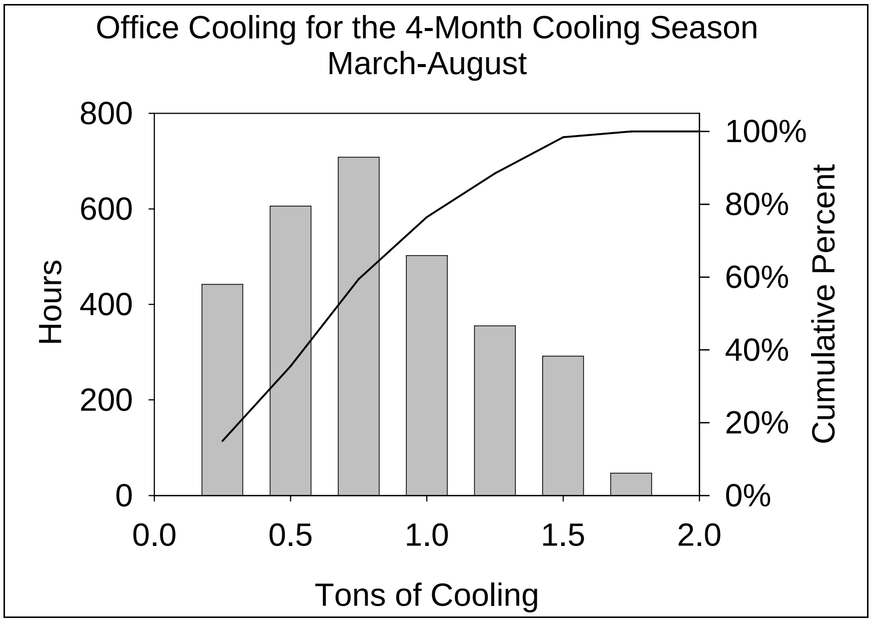


Figure 3.8 Office Cooling for the Cooling Season

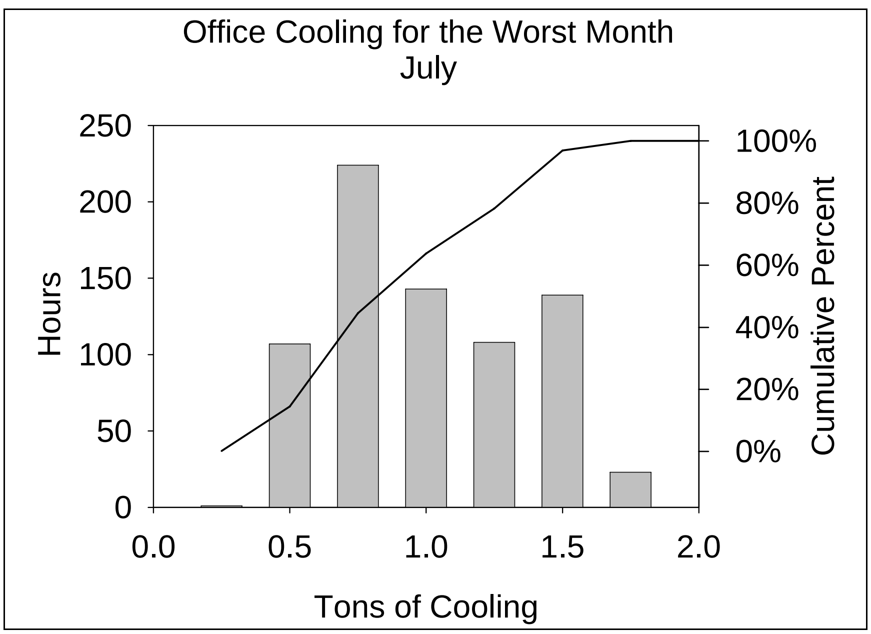


Figure 3.9 Office Cooling for the Worst Month

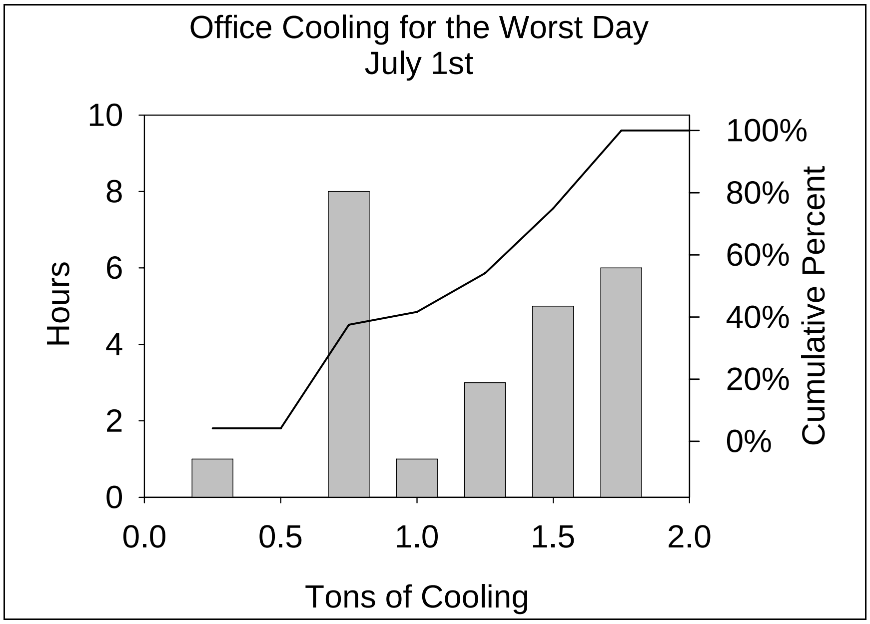


Figure 3.10 Office Cooling for the Worst Day

Using the histograms the office and shop air conditioning units were sized to meet the cooling requirements of the space. For the office a coil size of 2 tons was selected. As can be seen in Figure 3.10, two tons will be able to cool the space 100% of the time. Since air conditioners are sold in half ton sizes, a unit of 1.5 tons would only be able to meet the cooling requirements of the space on the worst day 80% of the time. For the worst month a 1.5 ton unit would meet the cooling requirements 96% of the time.

A Trane XV90 air handler with integrated natural gas condensing furnace was selected as the conventional system for the office area. Cooling is provided by a 14 Seer condenser with 2 ton comfort coil installed above the air handler. This unit will be installed in parallel with a 2 ton fan-coil unit. The fan-coil unit is a Trane vertical up-flow unit with 800 CFM air flow and contains four coils, 2 each for cooling and heating.

The vapor compression system and the fan-coil units were installed with a common supply and return to insure accurate comparisons.

For the shop area, a coil size of 5 tons was selected. This coil is oversized per the histograms shown, and is due to the use of the area. The shop area is a fully working wood shop with several pieces of machinery which are run on variable schedules and their thermal output could not be modeled. There are also extended periods of times in which the area's rollup door is open to allow access for large pieces of wood. The open door will greatly increase the infiltration rate of the space.

The office systems have been installed with a common return and supply in which only one system will be operated at a time. Back flow is prevented through dampers installed on the supply side of each unit which are activated by powering the unit. The common supply and return alleviates discrepancies when comparing the performance of the two systems.

An outdoor packaged unit, with a max cooling rate of 5 tons, manufactured by Trane was selected as the conventional air conditioning unit for the shop space. This unit contains a two stage compressor which can operate at either 3 or 5 tons of cooling. This will allow for greater efficiency and lower cooling bills as it will only operate at the 5 ton level when the interior temperature continues to rise with 3 tons of cooling. This unit contains a natural gas condensing furnace for winter heating. The unit has a Seer rating of 12.

The conventional unit has been installed in parallel with a 5 ton, 4 pipe, fan-coil unit. This unit will provide heating and cooling to the space using the water heated and cooled by the micro-CHP system and its fan is powered by the generator. The fan-coil and conventional system for the shop area have separate returns, due to installation requirements, and a common supply. The common supply helps alleviate discrepancies when comparing the performance of the two systems.

With a combined cooling load of 7 tons for both the office and shop areas a 10 ton absorption chiller was selected for creating the chilled water for use with the micro-CHP system. The absorption chiller selected was a Yazaki Energy Systems WFC-SC10. This unit produces 10 tons of cooling with an outlet temperature of 45°F at 24.2 GPM. Heat is supplied to the unit with 190°F water at 38 GPM with a total heat input of 191.7 GPM. Cooling water is required at 87.5°F and 80 GPM with a heat output of 291,000 BTU/hr. While this unit exceeds the maximum cooling by 3 tons, it was the smallest commercially available water fired absorption chiller. The pressure drops through the chilled water, heat medium, and cooling water loops are 8.1 psi, 13.1 psi and 12.3 psi respectively. The absorption chiller requires a maximum of 210 W of three phase power to operate.

Plumbing

Once the HVAC equipment was sized to meet the requirements of the demonstration facility, the water tank, pumps, and plumbing were properly sized. Figure 3.11 displays the overall plumbing schematic, pipe diameters and flow rates used for the demonstration facility.

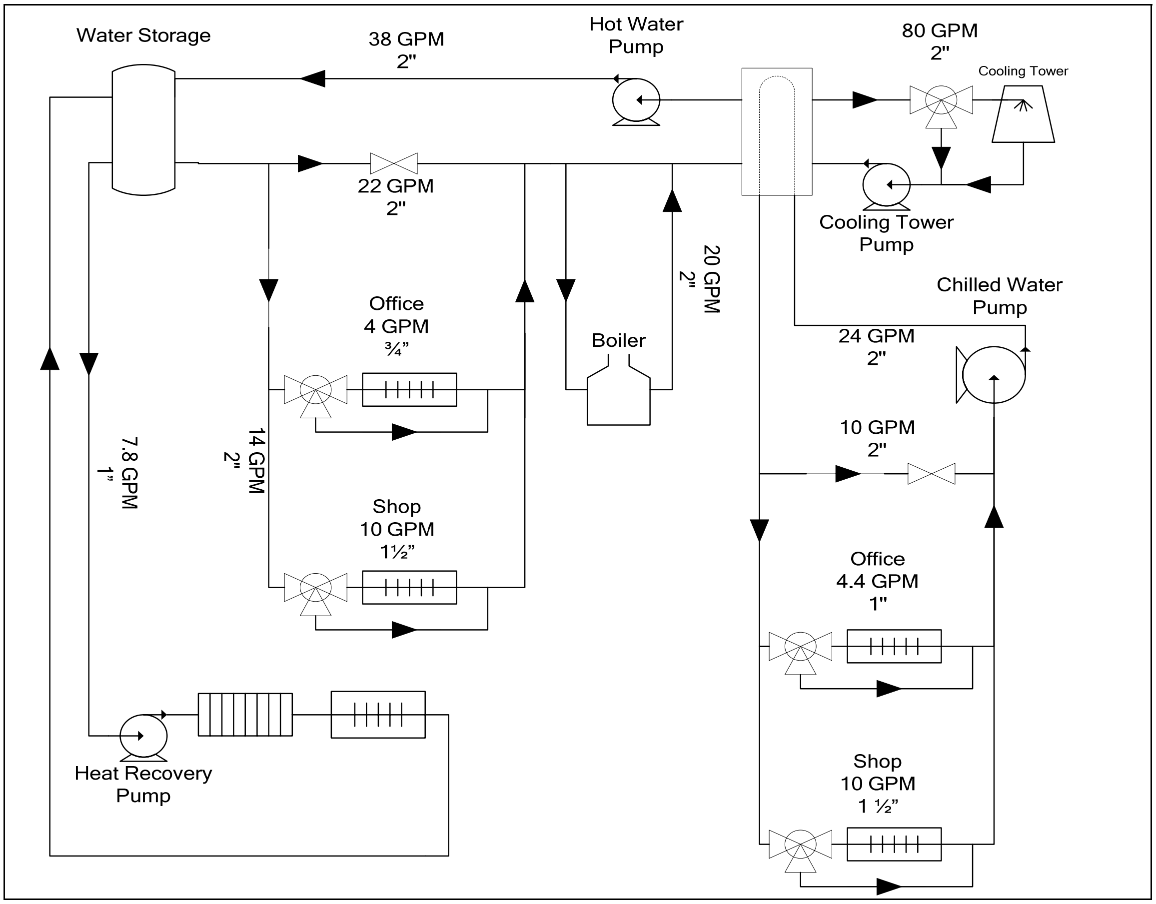


Figure 3.11 Plumbing Schematic

Electrical and Thermal Generation

The generator was sized to be able to handle the entire electrical load of the demonstration facility minus the equipment included in the wood working shop. This equipment was omitted since it was powered from 3 phase electricity, which small commercial and typical residences normally do not require. The peak electrical load was calculated by inspecting all equipment to be included in the building and calculating the electrical usage. The lighting, computers, TVs, refrigerators, and other various components were included in the calculations to insure the generator would not be overloaded.

The shop area contains 4 rooms which house equipment or serve as restrooms. The lighting in these areas is by fluorescent light bulbs with 2 bulbs contained in each fixture at 20 watts per bulb. It was found that the shop area contained a total of 30 light fixtures for a total power draw of 1.2 kW. The office area contains twenty 30 watt compact fluorescent light bulbs for a total power draw of 600 W. The 4 exterior 100 watt incandescent light bulbs were also included in the power calculations.

The HVAC equipment power draws will include the blowers used in the fan-coil units, pumps used to circulate water and the power required by the absorption chiller. The office fan-coil unit uses a maximum of 200 W while the shop unit will use a maximum of 1 kW. Table 3.4 shows the required motor sizes and fully loaded amps required to drive the required pumps. The cooling tower fan is powered by a 1 ½ HP motor with a current draw of 6.6 Amps. The absorption chiller draws a maximum of 210 W when the solution pump is active. The total electrical power draw by the HVAC equipment was calculated to be 9.6 kW when all pumps are fully loaded.

Table 3.4 Pump Motor Horsepower and Current Draw

Pump	Power (HP)	Amps (Fully Loaded)
Hot Water	2	8.3
Chilled Water	1	6.4
Cooling Tower	1 ½	8
Heat Recovery	1	6.8

The total electrical power required for operation of the micro-CHP demonstration facility is 12.4 kW. Table 3.5 displays the electrical draw of each component considered for the facility.

Table 3.5 Power Requirements of Equipment

Component	Electrical Draw
Hot Water Pump	1.9 kW
Chilled Water Pump	1.5 kW
Cooling Tower Pump	1.8 kW
Heat Recovery Pump	1.5 kW
Absorption Chiller	210 W
Cooling Tower Fan	1.5 kW
Office Fan-coil Unit	200 W
Shop Fan-coil Unit	1 kW
Shop Lights	1.2 kW
Office Lights	600 W
Additional Equipment	1 kW
Total	**12.4 kW**

In order to meet the electrical demand of the demonstration facility a 15 kW Generac Standby Generator model number 004742 was selected. This generator was not specifically designed for micro-CHP applications and does not have heat recovery, thus two heat exchangers were added to the unit. From the specifications of the generator, the engine thermostat is set at 190°F and a plate heat exchanger was installed before the radiator. A second fin-tube heat exchanger was installed in the exhaust line. The exhaust leaves at 1200°F, and there can be a maximum pressure drop of 2.1 inches of water in the exhaust lines. The heat recovery loop is constantly circulating in order to control the temperature and insure there is no boiling in the lines. An exhaust diverting valve is used before the fin-tube heat exchanger. The motor used to control the diverting valve is spring loaded in the normally open position such that in the case of a power or controls failure, the exhaust will default to diverting the heat exchanger.

CHAPTER IV

INSTRUMENTATION

Introduction

One of the core functions of the micro-CHP demonstration facility is to determine the performance of the overall system and of each component. This data is used to show the economical and environmental benefits of a micro-CHP system. In order to determine the performance of each component and the overall system, the energy flow rates must be determined. The energy flow rate includes thermal and electrical power used or generated.

The energy flow rates for water streams are determined through Equation (4-1).

$$\dot{Q} = \dot{m} \cdot Cp \cdot \Delta T \tag{4-1}$$

Cp was determined through creating a polynomial function based on temperature for water which is shown in Equation (4-2) with an uncertainty of .028 kJ/kg °K.

$$\begin{aligned} C_p &= 4.217 + -3.484 \cdot 10^{-3} \cdot T + 1.286 \cdot 10^{-4} \cdot T^2 - 2.731 \cdot 10^{-6} \cdot T^4 \ldots \\ &\quad -3.587 \cdot 10^{-10} T^5 + 1.934 \cdot 10^{-12} \cdot T^6 - 4.544 \cdot 10^{-15} \cdot T^7 \end{aligned} \tag{4-2}$$

The temperature used for the Cp function will be evaluated at the average temperature. The mass flow rate ($\dot{m}$) will be determined through Equation (4-3).

$$\dot{m} = \frac{Q}{\rho} \tag{4-3}$$

The density ρ will be determined through creating a polynomial function based on the temperature for water and will be evaluated at the average temperature. The polynomial found for the density is shown in Equation (4-4) and has an uncertainty of 2.66 kg/m^3.

$$\rho = 999.833 + 0.075 \cdot T - 8.896 \cdot 10^{3} \cdot T^{2} + 7.364 \cdot 10^{-5} \cdot T^{3} \ldots \\ - 4.746 \cdot 10^{-7} \cdot T^{4} + 1.349 \cdot 10^{-9} \cdot T^{5} \tag{4-4}$$

For a water stream, Q and ΔT are the two variables which need to be measured. ΔT will be measured by placing temperature transducers on the inlet and outlet of the device of interest.

The energy flow rate of an air stream will be determined through a psychrometric code. This code is based on the Gibbs free energy equation and uses dry bulb temperature and relative humidity as its inputs. The code has density and enthalpy of the wet air as its outputs. Equation (4-5) will be used to calculate the heat flow rate into or out of the air stream.

$$\dot{Q} = \dot{m} \cdot (h_{out} - h_{in}) \tag{4-5}$$

The mass flow rate for the air stream will be determined by Equation (4-2) using the density determined from the psychrometric code. For the wet air stream the dry bulb temperature, relative humidity, and flow rate will be needed to calculate the heat flow rate.

Heat input into the generator, boiler and gas furnaces will be found through measuring the natural gas flow rate and by determining the heating value of the gas. Power generated or used by equipment will be determined by either directly measuring the power or through measuring the voltage and current and determining the power through Equation (4-6).

$$P = V \cdot I \tag{4-6}$$

Transducers

Power

The Generac 15 kW standby generator produces 240VAC at a maximum of 70 amps of power. The power generated will be measured through an Ohio Semitronics PTB412E1 multifunction power meter. The multifunction power meter measures the voltage and amperage on both lines of the 240VAC system and measures the total power passing through the meter. This device has a maximum input of 150V and 100A for each line. The current will be measured by passing the line through a coil which steps the amperage down by 20:1. The device has an accuracy of $\pm 0.5\%$ full scale for voltage, amperage and power.

Power used by all other equipment will be determined through Ohio Semitronics ACT current transducers. This transducer has an accuracy of $\pm 0.25\%$ full scale for current measurements up to 20 Amps. For current measurements exceeding 20 Amps, the accuracy increases to $\pm 0.5\%$ full scale. Devices powered by 120VAC will use one current meter to measure the power, while devices requiring 240VAC will use two meters to measure the current used on each line. The absorption chiller required three phase power which was created through a transformer which used 240VAC single phase power. Table 4.1 shows the devices where power will be determined and the amperage range needed. The power will be determined through Equation (4-6) where the voltages will be determined from the multifunction power meter connected to the generator.

Table 4.1 Current Transducer Range

Component	Voltage (VAC)	Amperage Range
Hot Water Pump	240	20
Chilled Water Pump	240	20
Cooling Tower Pump	240	20
Heat Recovery Pump	240	20
Cooling Tower Fan	240	20
Absorption Chiller	240	20
Office Fan-coil Unit	120	20
Shop Fan-coil Unit	240	20
Office Indoor Traditional Unit	120	20
Office Outdoor Condenser	240	25
Shop Packaged Traditional Unit	240	50

The current and power transducers came with factory calibrations which were checked by producing a current through a variable resistance. Power meters which did not meet the specified accuracy were returned to the manufacturer and replaced.

Temperature

Temperatures will be measured at the inlet and outlet of each device to determine the temperature change through the device in order to calculate the heat losses throughout the system. Temperatures of water streams will be measured by a National Instruments Ready-Made RTD. The National Instruments Ready-Made RTDs are Platinum resistance temperature devices with a resistance of 100Ω at 0°C with a slope of 0.00385 $°C/\Omega$. The RTD has an accuracy of $\pm(0.3+0.005|t|)°C$ where t is the absolute value of the temperature being measured in °C.

The RTDs calibration was checked through a water bath which was initially at 0°C and was raised to 100°C. An accurate mercury thermometer was used as the standard for the calibration. The temperature read by the RTD was checked at 5°C intervals and recorded to an excel spreadsheet. RTDs which did not meet the specified accuracy were discarded.

The dry bulb temperature of the air streams will be measured by a Greystone Energy Systems TE200DC Continuous Averaging Duct Sensor. The TE200DC has a 20' copper tube which contains evenly spaced 100 Ω platinum RTDs throughout. The sensor electronics are mounted to the outside of the duct and the copper coil is installed in such a manner that the coil crosses the entire profile of the duct. The TW200DC has a default range of 0 to 70°C, an accuracy of $\pm$0.1% full scale, is powered by 24 VDC and has a 4-20 mA output.

Relative Humidity

The relative humidity of the air stream is measured by an Omega Engineering HX94C relative humidity/temperature transducer. This probe measures the relative humidity at a single location in the air stream and is placed near the center of the flow. The HX94C has an accuracy of $\pm$2% RH with a range of 3% to 95% RH, is powered by 24 VDC and has a 4-20 mA output. A picture of the relative humidity probe can be seen in Figure 4.1.

Figure 4.1 HX94C Relative Humidity Sensor
(www.omega.com)

Pressure

Pressure measurements are taken on the inlet and outlet of each component in order to calculate the head losses of the component and of the pipe. The transducer range was determined by examining the inlet and outlet conditions of the hot water pump. Water is supplied to the suction side of the hot water pumps at 30 psi in which the pump produces 30 feet of head for a maximum pressure of 43 psi. Cole-Parmer EW-68073-10 High-Accuracy Industrial Pressure Transmitters with a range of 0 to 50 psi gauge were selected to measure the pressure of each water line. The transmitter has an accuracy of $\pm$0.13% full scale with a compensated temperature range of -4°F to 176°F, is powered by 24 VDC and has a 4-20 mA output. Figure 4.2 shows a picture of the pressure transmitter used.

The calibration of the pressure transducers was checked through the use of a dead weight testing device. The pressure indicated by the transducer was recorded at 5 PSI intervals throughout the range of the transducer. Pressure transducers which did not meet the specified accuracy were discarded.

Figure 4.2 EW-68073-10 Gauge Pressure Transducer (www.cole-parmer.com)

Flow Rate

Water flow rate is determined through a Dynasonics Ultrasonic Transit Time flow meter. The transit time flow meters use two transducers which operate as both a transmitter and receiver. Ultrasonic sound is first transmitted in the direction of flow and then against the flow. Since the moving fluid will carry the sound wave faster the difference in the transit time is directly proportional the fluid velocity. Figure 4.3 shows the operation of an ultrasonic transit time flow meter.

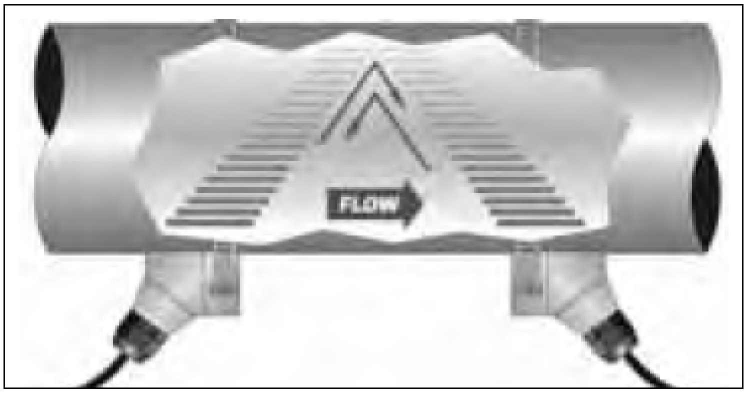


Figure 4.3 Transit Time Flow Meter Operation
(www.dynasonics.com)

The Dynasonics flow meters are used to measure the water flow rate through the hot, chilled and cooling water loops through the absorption chiller, and the hot and chilled water passing through each water coil. The heat recovery loop and boiler loops are measured using the Dynasonics flow meters as well. The Dynasonics flow meters required 24VDC for power and have an accuracy of $\pm 1\%$ of reading with a 4-20 mA output.

The absorption chiller controls a bypass valve which is placed on the hot water inlet side of the chiller. To obtain accurate energy balances this flow rate is measured on the outlet side of the chiller such that only the flow through the chiller is measured. The chilled water is also measured on the outlet of the absorption chiller. The cooling tower flow rate is measured on the inlet side of the chiller in a position where the pipe will not run dry when the cooling tower pump is turned off. The water flow rate for the fan-coil units is measured before the bypass valves because of the complex plumbing which exist after the valves. In order to obtain accurate energy calculations, the temperatures are also measured before the bypass valves. Other water flow rates which are measured are the boiler loop and the heat recovery loop. Table 4.2 lists the flow meters which are installed and the range specified for each transducer.

Table 4.2 Ultrasonic Flow Meter Locations and Ranges

Location	Flow Range (GPM)
Absorption Chiller – Hot Water	0-50 GPM
Absorption Chiller – Chilled Water	0-50 GPM
Cooling Tower	0-90 GPM
Boiler	0-30 GPM
Heat Recovery Loop	0-15 GPM
Office – Hot Water	0-10 GPM
Office – Chilled Water	0-10 GPM
Shop – Hot Water	0-30 GPM
Shop – Chilled Water	0-30 GPM

The ultrasonic flow meters are accurate in measuring the flow rate of several types of liquids and are calibrated at the factory for the specified conditions. Field checks of the calibration are performed by measuring the pressure drop through the circuit setters which exist in the system to regulate the flow. In order to obtain accurate flow readings from these devices, the circuit setter is opened fully to alleviate errors in reading the position of the valve. The circuit setter contains a venturi type flow meter with high and low pressure ports. The flow rate through the circuit setter is found by reading the differential pressure and reading the supplied charts.

Natural gas flow rates are measured by creating a pressure drop across a Laminar Flow Element and measuring the differential pressure across this element. The FloCat LA10 precision gas flow meters were selected to measure the flow rate of natural gas for the boiler, generator and the furnaces. These meters are installed in the gas line and have a flow rate display incorporated. The meters have an accuracy of $\pm 1\%$ full scale, are powered by 24 VDC, and have a 4-20 mA output. The boiler and generator have a range of 0 to 250 L/min while the natural gas furnace flow meters have a range of 0 to 100 L/min. NIST calibration certifications exist for these devices and calibration is field checked through timing the residential gas meter indicators.

The air flow rate measured in the duct is measured through a duct velocity averaging element which traverses the entire duct sensing the velocity through the entire profile. The element operates by creating a differential pressure through a positive pressure port positioned into the flow and a static pressure port which is placed on the same plane separated by twice the critical angle. A drawing of the operation of the sensing element can be seen in Figure 4.4. The sensing ports are placed throughout the length of the sensing element. For rectangular ducts the sensing elements are placed throughout the duct as seen in Figure 4.5. In circular ducts, the sensing element is placed in a cross pattern as seen in Figure 4.6.

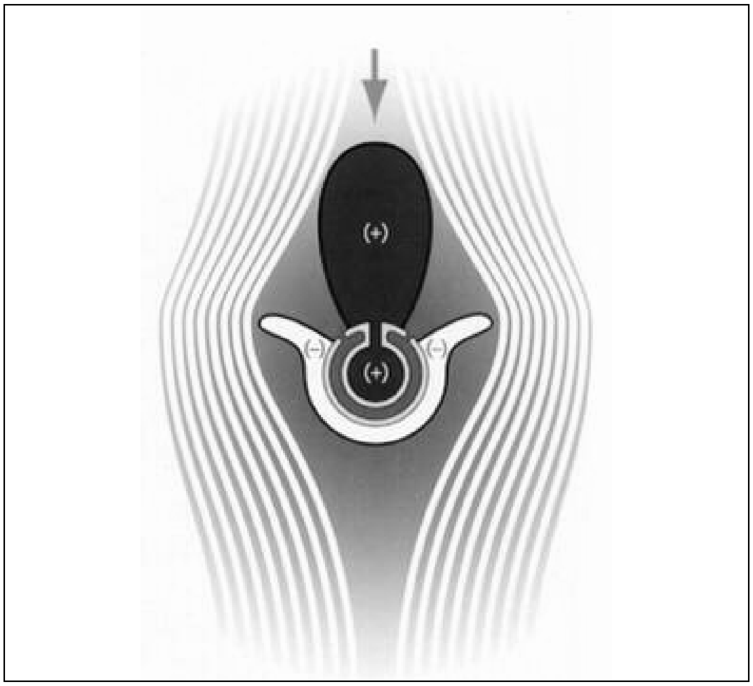


Figure 4.4 Paragon Controls Primary Sensing Element (www.paragoncontrols.com)

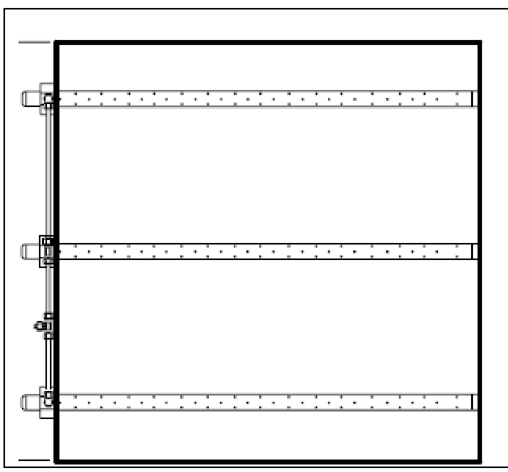


Figure 4.5 Rectangular Duct Configuration (www.paragoncontrols.com)

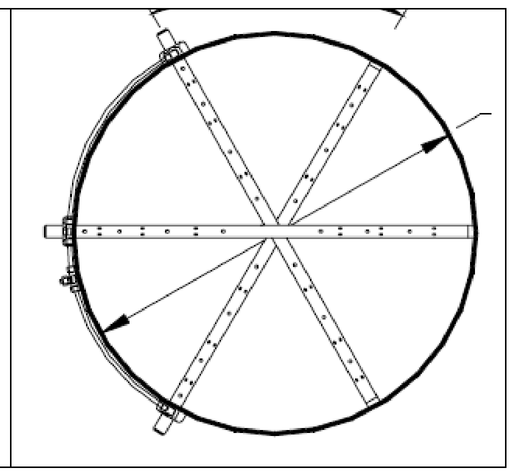


Figure 4.6 Circular Duct Configuration (www.paragoncontrols.com)

The office duct has an external diameter of 16 inches with one inch of insulation and has two sensing elements installed in a cross pattern. The Shop supply duct is rectangular with a 14 inch by 48 inch dimensions and has two sensing elements evenly spaced in the flow. The flow sensing elements have an accuracy of $\pm 2\%$ of the calculated velocity for velocities of 100 FPM and higher. The differential pressure is measured by an Omega Engineering PX655-0.5DI differential pressure transmitter with a range of 0 to 0.5 inches of water. These meters are powered by 24 VDC, have a 4-20 mA output and an accuracy of $\pm 0.25\%$ full scale. The flow velocity is determined from the following equation.

$$V = \sqrt{\frac{P_V}{\rho}} \cdot C \tag{4-7}$$

Where P_V is the measured differential pressure, V is the velocity of the flow stream, ρ is the fluid density and C is a coefficient which is equal to 1096.7. The calculated velocity is then multiplied by the area of the duct to obtain the volumetric flow rate. The air flow rate is converted to CFM for display and calculations.

Data Acquisition

A distributed modular data acquisition system was used for the micro-CHP demonstration facility to allow for shorter wire runs, instrumentation of additional equipment and replacement of faulty equipment. Data acquisition systems will be installed in the office and shop areas, in locations close to the HVAC equipment, and in the mechanical room. Having the data acquisition system close to the transducers will allow for shorter wire runs which will reduce noise and increase accuracy. The modular system will allow for additional equipment to be instrument by adding modules to the existing data acquisition controller or by adding a new controller and modules. The modular system will also allow for “hot” swapping of the individual modules in the event of failure. Figure 4.7 shows the location of the data acquisition systems.

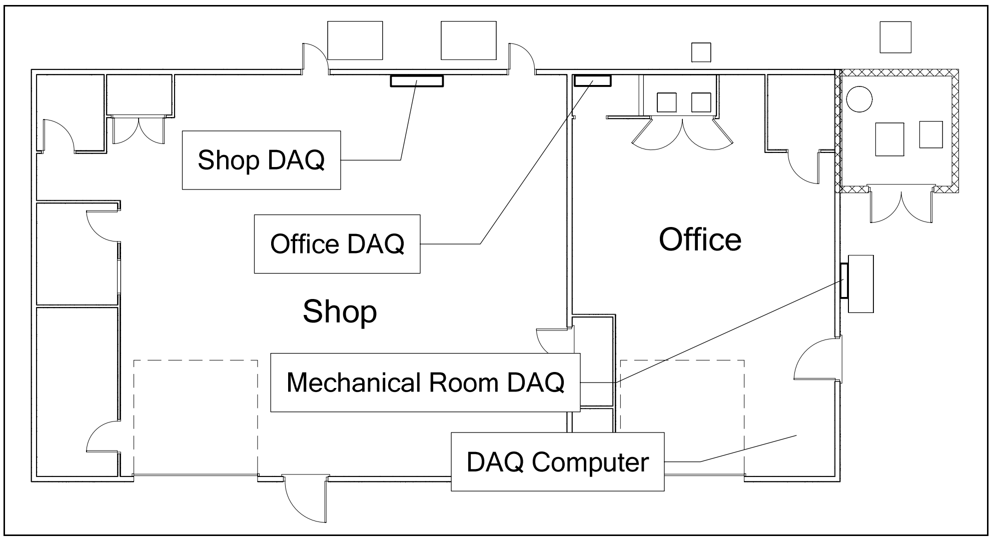


Figure 4.7 Data Acquisition System Locations

National Instruments (NI) FieldPoint DAQ products were selected for the data acquisition system. The FieldPoint DAQ system allows for communication with a computer through serial communication or over a TCP/IP network. The FieldPoint DAQ system contains a single controller module which will acquire data from up to nine DAQ modules. The FieldPoint DAQ modules allow for measuring analog and digital signals and outputting digital and analog signals depending on the module installed.

The NI FP-RTD-122 allows for measurement of up to eight 3-wire RTDs. The module uses a stable current source for excitation and contains a microcontroller which will return the temperature in °C, °F or °K. The RTD module has 16 bit resolution, 50/60

Hz noise rejection and an accuracy of $\pm 0.25°C$. The RTD module is powered by the controller.

The NI FP-AI-110 module is used to measure the 4-20 mA output signals of the transducers. This module allows for the measurement of 8 or 16 voltage measurements with a range of ± 125 V and up to 8 current measurements with a range of ± 25 mA. The module has built in noise rejection for 50, 60 and 500 Hz and has an offset error of $\pm 1\,\mu A$ with a gain error of $\pm 0.04\%$ for current measurements. This module allows for connection of common power source which is distributed to each channel in order to provide power to the transducers. Table 4.3 shows the pin-out of the FP-AI-110 module.

Table 4.3 FP-AI-110 Pin-Out

Chanel	Terminal Numbers			
	V_{IN}	I_{IN}	V_{SUP}	COM
0	1	2	17	18
1	3	4	19	20
2	5	6	21	22
3	7	8	23	24
4	9	10	25	26
5	11	12	27	28
6	13	14	29	30
7	15	16	31	32

The required number and type of modules were determined through creating drawings of each location with the sensors in the required locations. The number of sensors was then counted for each location and the required channels required were calculated. Figure 4.8 shows a diagram of the mechanical room plumbing with the locations of the transducers. Figure 4.9 and Figure 4.10 show detailed views of the transducer locations for the generator and absorption chiller respectively.

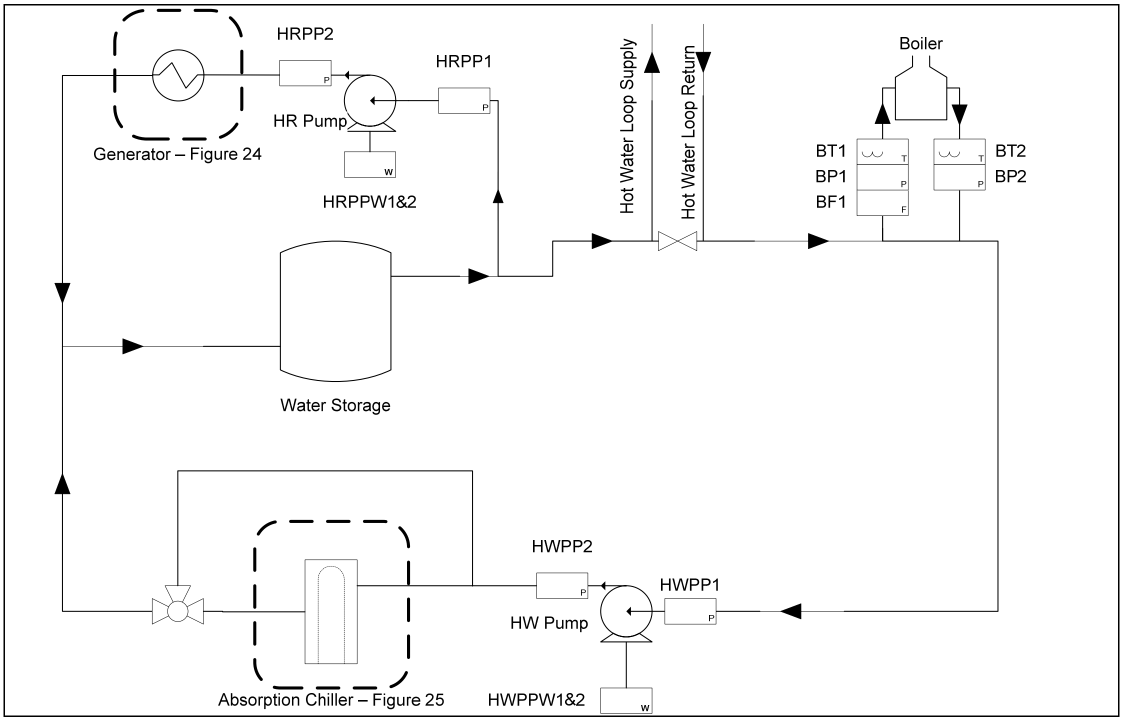


Figure 4.8 Mechanical Room Transducer Locations

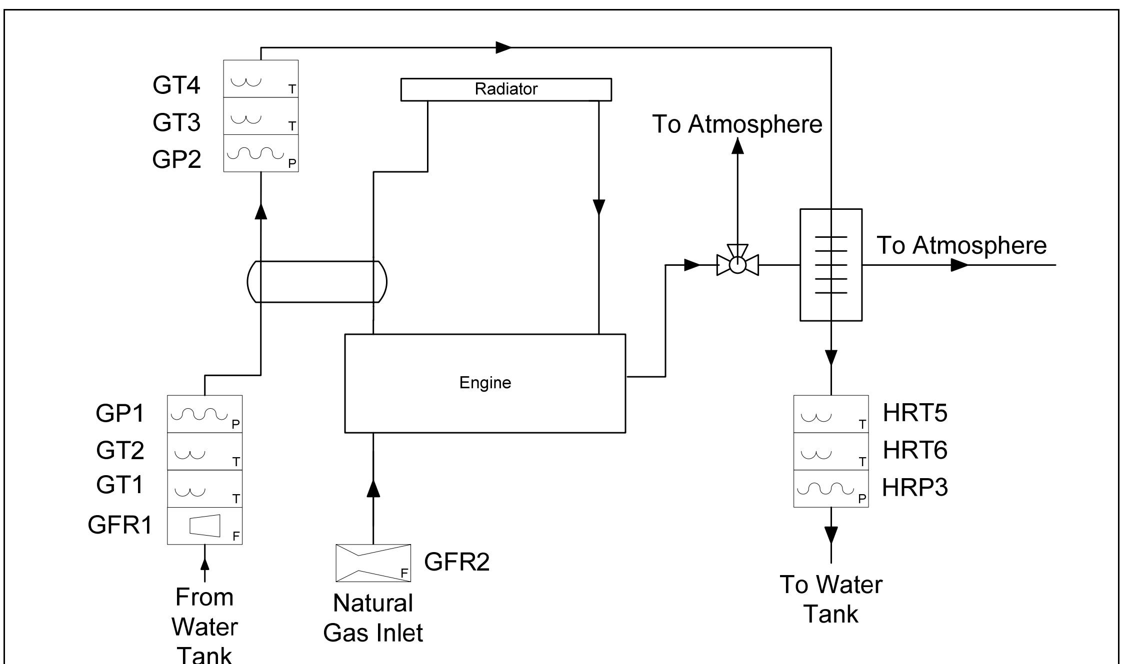


Figure 4.9 Generator Transducer Locations

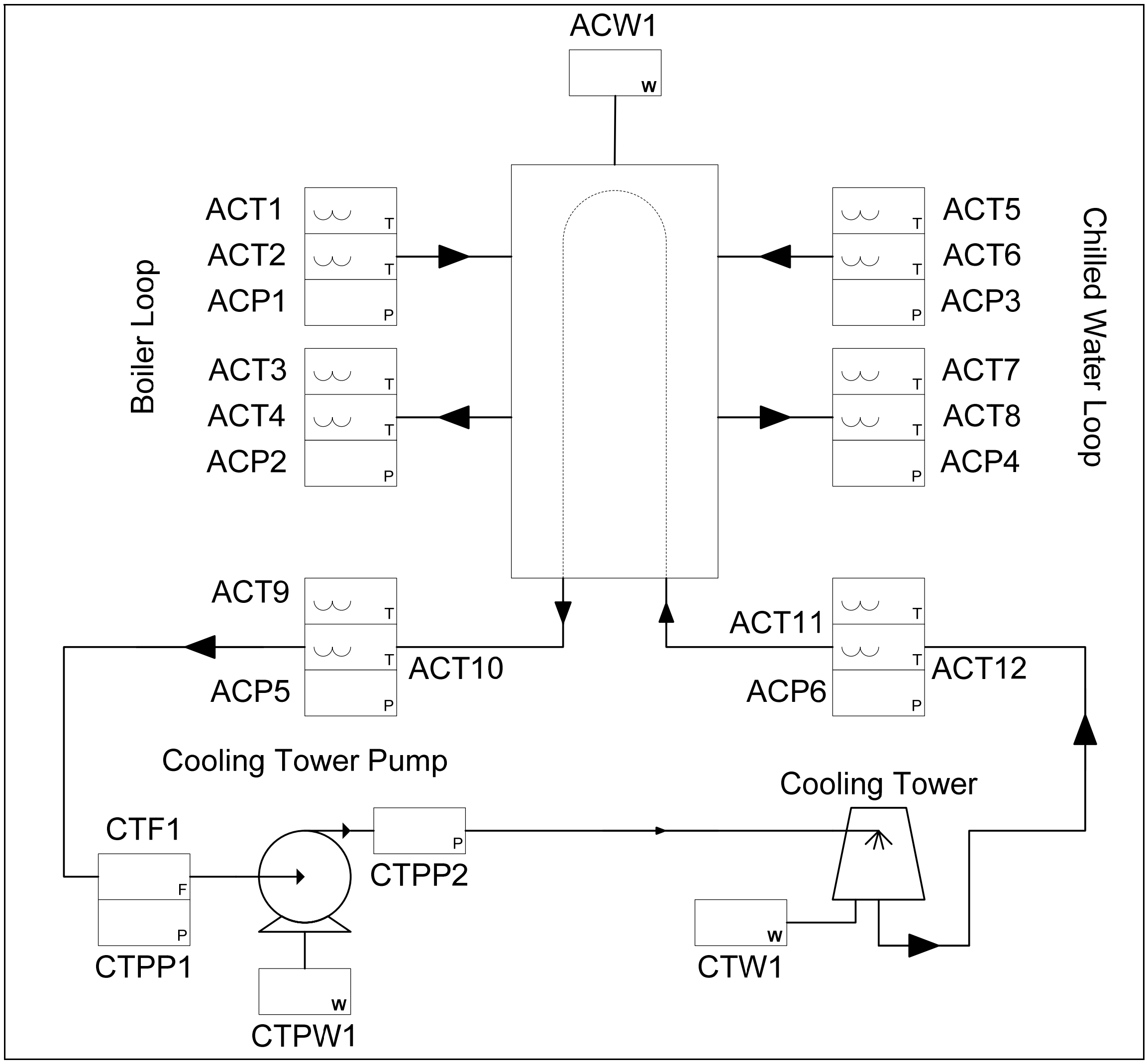


Figure 4.10 Absorption Chiller Transducer Locations

Figure 4.11 shows the transducer layout for both the shop and office HVAC systems. The shop HVAC system will have an additional duct averaging temperature transducer and an additional relative humidity transducer due to the separate returns.

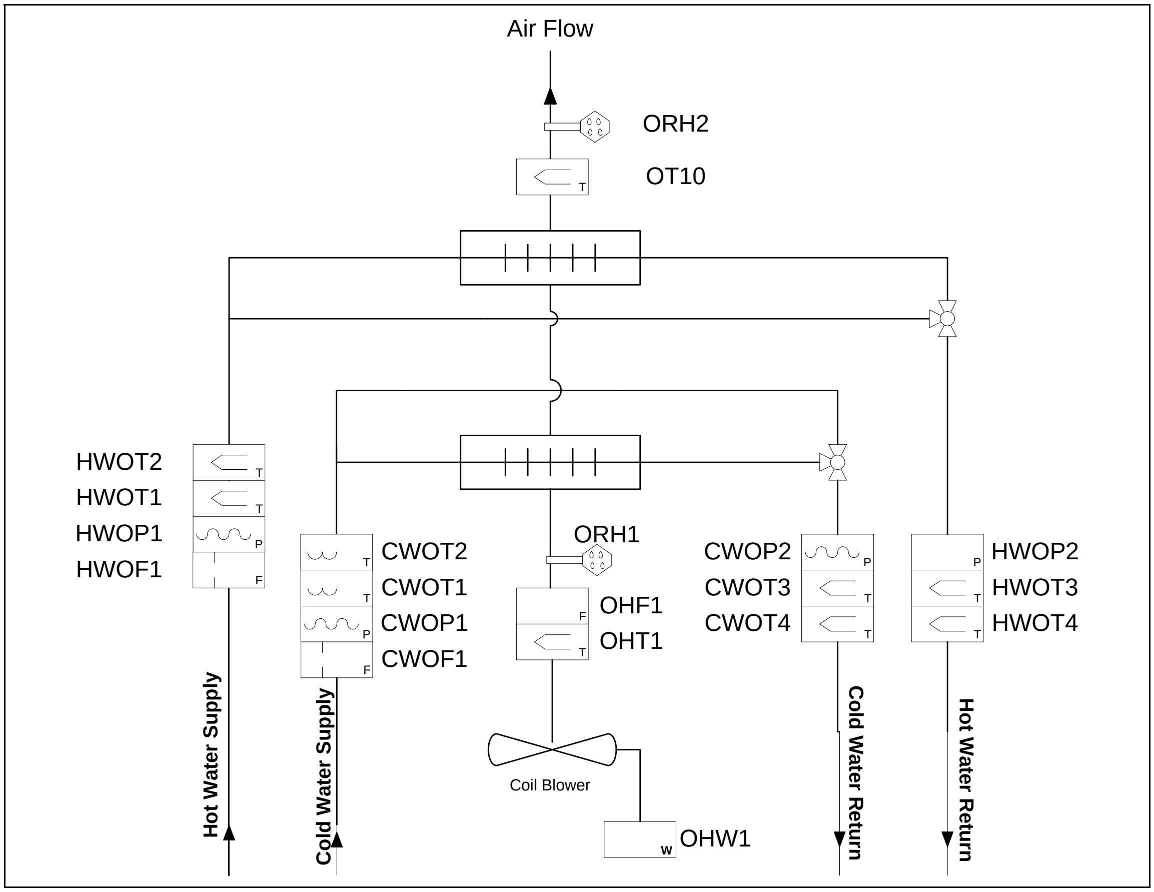


Figure 4.11 Shop and Office HVAC Transducer Locations

The traditional vapor compression system for the office area will have two current meters using three channels since the indoor fan unit uses 120VAC and the outdoor unit used 240VAC. The traditional vapor compression unit for the shop area will have a single current meter using three channels since the unit requires three phase power. Table 4.4 lists each location, the type of transducer and the number of total channels required for each type of measurement.

Table 4.4 Transducer Quantities and Locations

	Transducer Type	Channels
Mechanical Room		
	RTD	20
	Water Flow Rate	4
	NG Flow Rate	2
	Power Meter (Per line)	12
	Pressure	20
	Total Channels	**58**
Shop		
	RTD	8
	Water Flow Rate	2
	Natural Gas Flow Rate	1
	Air Flow Rate	1
	Relative Humidity	3
	Duct Average Temp	3
	Power Meter (Per line)	5
	Pressure	4
	Total Channels	**27**
Office		
	RTD	8
	Water Flow Rate	2
	Natural Gas Flow Rate	1
	Air Flow Rate	1
	Relative Humidity	2
	Duct Average Temp	2
	Current Meter (Per Line)	6
	Voltage Meter (Per Line)	2
	Power Meter (Total)	1
	Pressure	4
	Total Channels	**29**
TOTAL CHANNELS		**119**

The FieldPoint Modules were selected in order to meet the required channels listed in Table 4.4. Additional channels were added in order to provide data acquisition for equipment which may be installed at a later date. Figure 4.12 shows the FieldPoint layout for the mechanical room DAQ panel. The panel contains 24VDC power supplies which will provide power to both the FieldPoint Controller modules and the transducers.

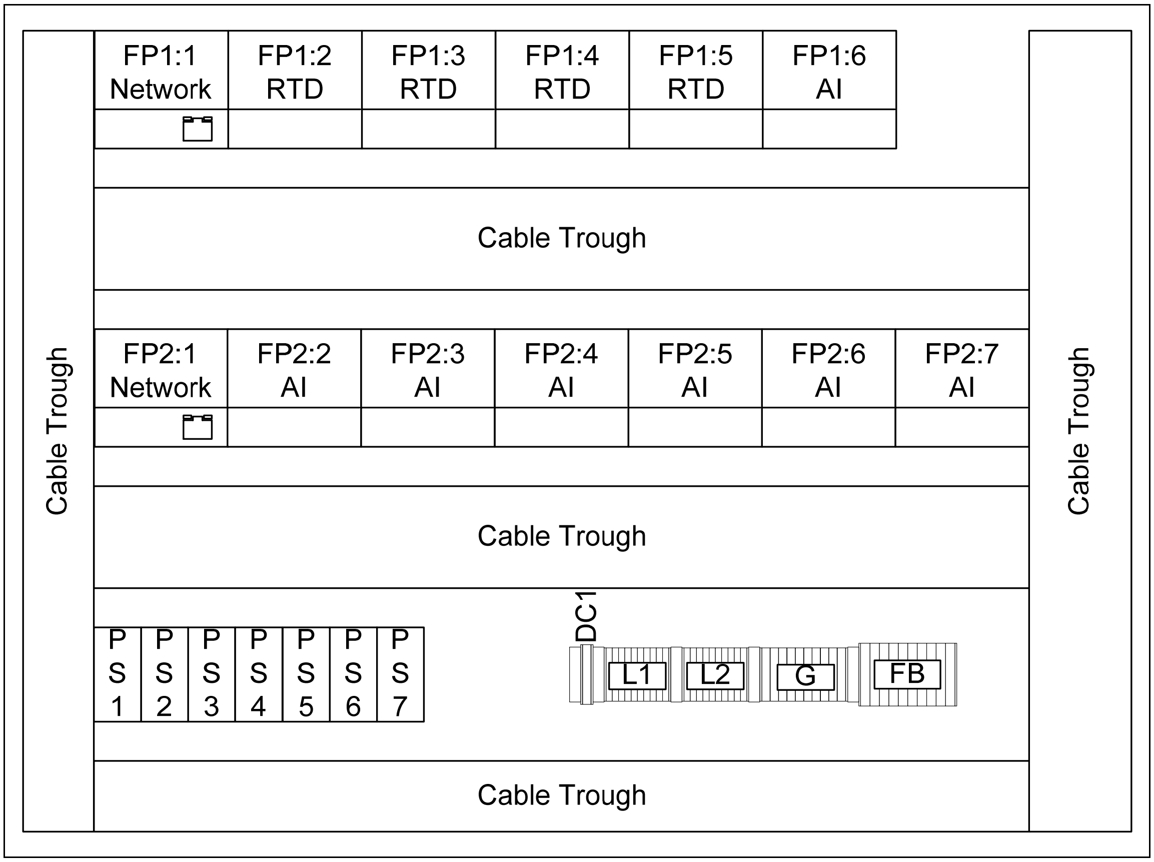


Figure 4.12 Mechanical Room Data Aquisition Panel Layout

The mechanical room panel contains 4 RTD modules which will allow up to 32 temperature measurements to be made. The panel contains 7 analog input modules for a total of 56 4-20 mA inputs to be measured. There is room for one additional module to be installed which will allow for additional measurements or control of equipment.

The office and shop panel have similar layouts and can be seen in Figure 4.13. The panels contain 24VDC power supplies to provide power to the FieldPoint controllers and transducers. Power to the panel can be turned off by DC1, a disconnect switch, and each power supply's output is fused. The displays for the Dynasonics Ultrasonic flow meters are also mounted inside the panel enclosure for security. The shop and office

DAQ systems use one RTD module for temperature measurement and three analog input modules for a total of 24 4-20 mA inputs.

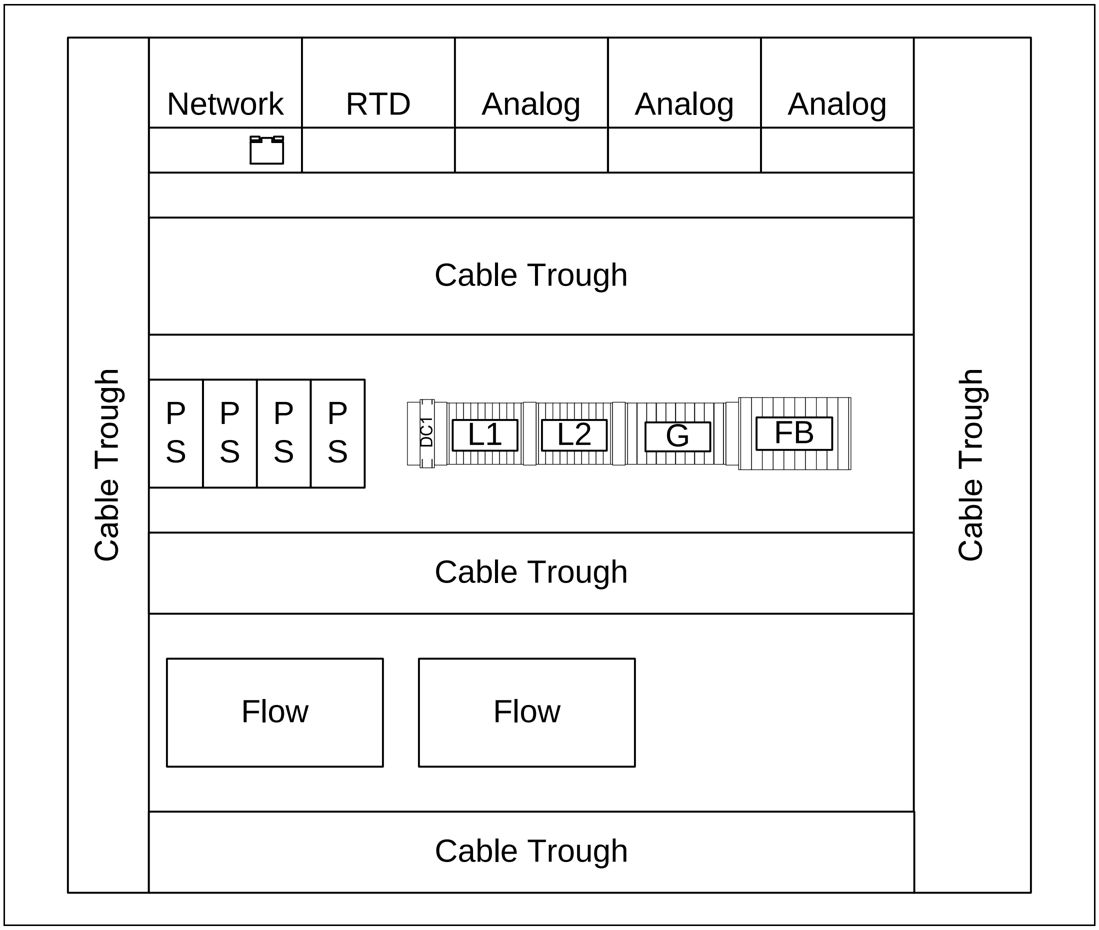


Figure 4.13 Shop and Office DAQ Panel Layout

Data Storage and Display

Displaying the performance of the micro-CHP system and each component is needed for showcasing the equipment and providing information to the visitors of the demonstration facility. A Microsoft Visual Basic program was developed which displays an overall view of the facility and allows the user to select components for a more detailed display. A window will open and display the selected component of the system and the current state of the component. The current state includes the pressure, temperature and flow rate of water and air streams, power input into electrical devices and the energy flow in and out of the component. Figure 4.14 shows the overall view of the system.

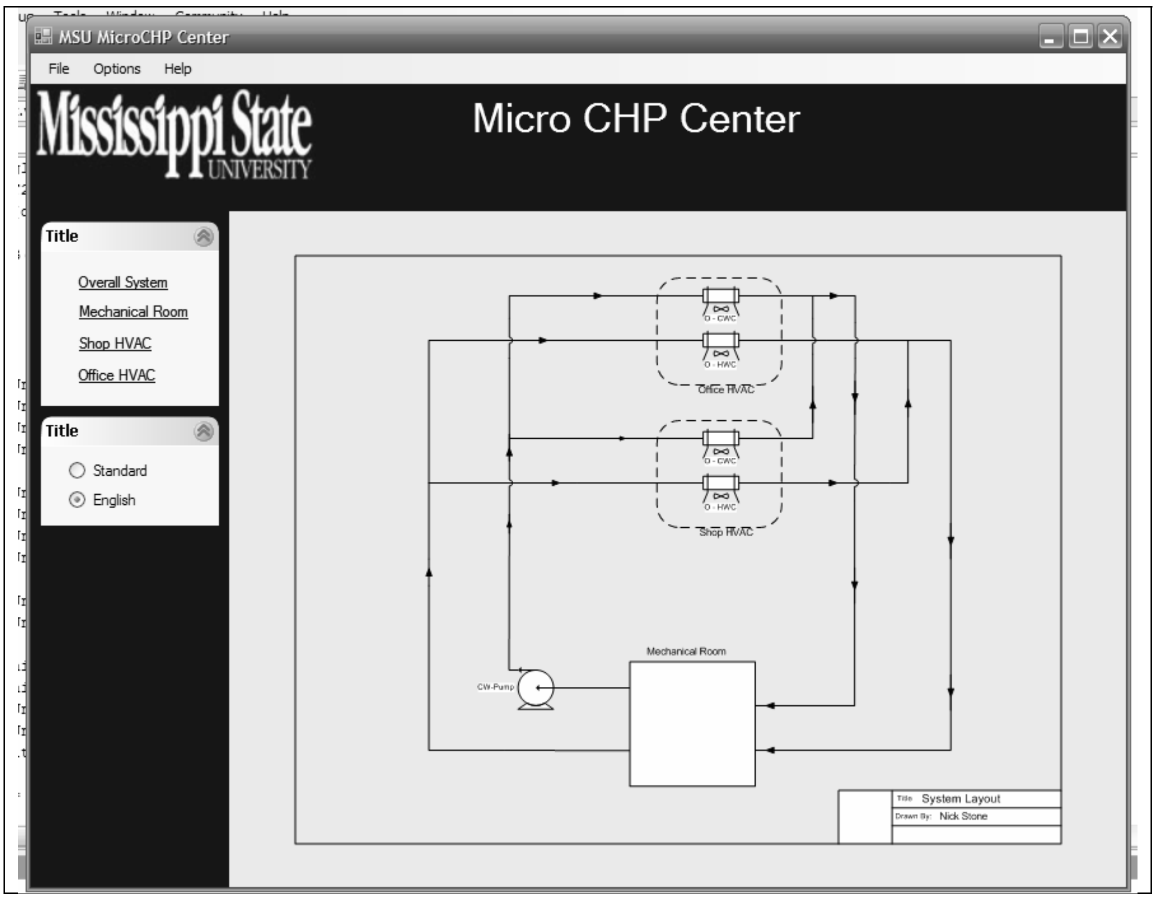


Figure 4.14 Micro-CHP Front-End Main Display

The front-end allows for users to select which system they would like to see in the upper left hand panel. Selecting a system will load the appropriate drawing in the main panel which will allow selection of individual components. The second panel on the left hand side allows the user to select the units they wish displayed. The first option is Standard which will display the temperature in °C, flow rates in m^3/min and energy rates in kJ/hr. The second option is English which will display temperatures in °F, flow rates in GPM for water and CFM for air, and energy rates in BTU/hr.

The component windows display a schematic for the component of interest, the flow rates of air and water, inlet and outlet temperatures and pressures and all energy flow rates in to, and out of the system. For the generator an, electrical, thermal, and overall efficiency is displayed. Depending on the type of component, efficiencies are displayed for thermal and electrical performance. Figure 4.15 shows the Absorption Chiller detail popup. (The numbers for this component are not correct as the data was acquired while the system was not fully running)

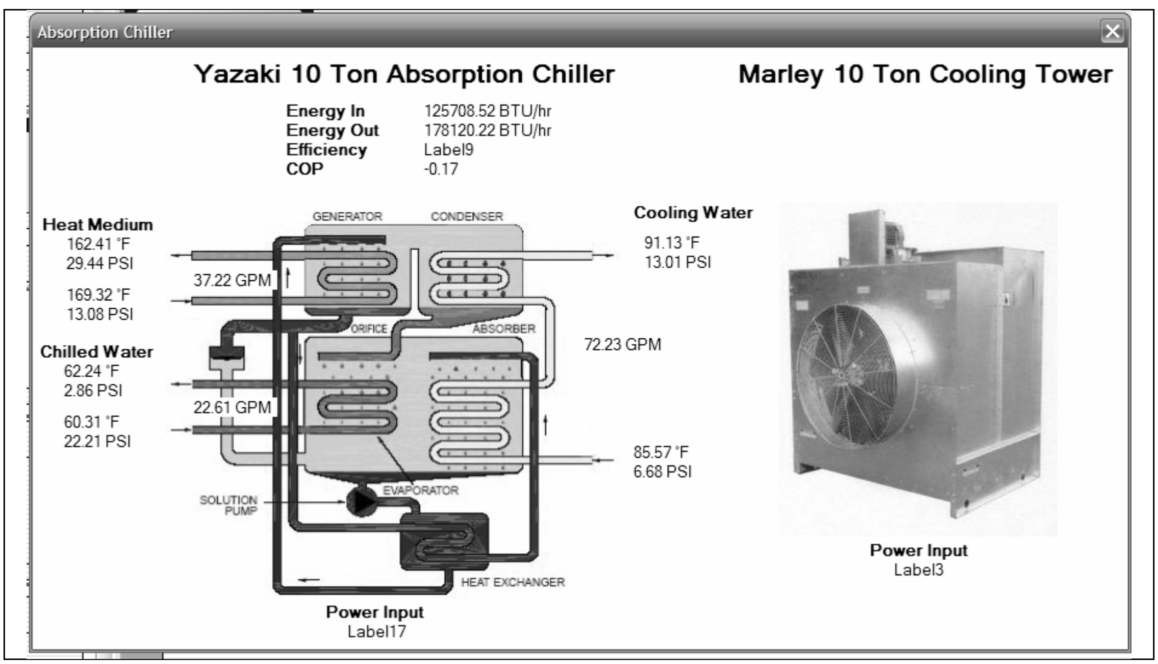


Figure 4.15 Absorption Chiller Detail Screen

The data will be retrieved from the FieldPoint controllers with a National Instruments LabView program. Several modules (sub-VIs) were developed in order to scale the 4-20 mA input to the proper number. For the flow meters, power transducers, duct average temperature, and current transducers, a common subVI was developed in which the min and max values which signify the range of the device are set and the sub-VI outputs the actual value the device is reading in the proper units. The relative humidity and duct flow rate measurements were converted from the 4-20 mA signal to the actual value through the equations given with the literature. The main LabView VI for data acquisition and the sub VIs are included in Appendix B.

The acquired data is then stored in a MySQL database. The MySQL database allows for a larger amount of data to be stored than would be possible in text based files. The database also allows for easy querying of the needed data in which the user can select the date span and which columns of data they would like to obtain. A MySQL database was used over the Microsoft Access database for increased speed and robustness. Microsoft access did not have the response time that a MySQL database server has which could possibly cause data loss.

A two database table scheme was used for data storage. The first table, display, is updated every 2 seconds in which all data is first deleted then the new data is added. This table is used for the Visual Basic front-end and to allow any other program to access live data. The second table, measurements, is updated at a user selected interval, which has a default of 5 minutes, and no data is ever deleted. This table is used for comparisons or to evaluate performance over a length of time. The LabView program automatically creates the needed tables in the event that they do not exist. This was done in order to allow for less experienced users of the MySQL Database Administrator to add additional instrumentation to the database.

CHAPTER V

CONCLUSION AND FUTURE WORK

The micro-CHP demonstration facility was designed to work as both a system in which experiments on the performance for micro-CHP technologies can be performed and as a center for information on micro-CHP. The facility selected for the micro-CHP system closely resembles both a small commercial building and a typical residence.

Through the use of existing commercially available equipment, the micro-CHP system was sized to meet both the electrical and thermal requirements of the facility. A 15 kW standby generator with a heat recovery system was installed to supply both electricity and thermal energy for the building, while a 10-ton water-fired absorption chiller was used to meet the cooling requirements of the facility. Four-pipe fan-coil units were used to heat and cool the space while running on the CHP system. High efficiency traditional vapor compression units were installed in parallel with the four-pipe units in order to perform comparisons of traditional systems with micro-CHP performance.

The whole micro-CHP system was instrumented in order to obtain energy balances for all thermal devices. Temperature, pressure and flow rates of water and temperature, relative humidity, and flow rates of the air streams are measured in order to determine the energy transfer rate. The flow rate of natural gas is measured for each device which uses natural gas as the fuel.

A National Instruments FieldPoint distributed instrumentation system is used to collect the measurements of all transducers. Three wire RTDs are used to measure the temperature of the water streams which require a NI FieldPoint module designed specifically for three wire RTDs. All other transducers have a 4-20 mA output and are measured through an analog input module which can measure transducers with either voltage or amperage output. The data collected is processed through a National Instruments LabView system to convert the 4-20mA input signal to the proper measurement. Once processing is completed, all data is stored in a MySQL database to allow for large amounts of data to be saved.

Future work to be performed on the facility includes testing the full system for a period of time to insure all equipment is working optimally. Extended running of the system may exposes potential problems and allow for easy fixes. Problems with the instrumentation can also be found and corrected before experiments on the performance are performed.

In addition to an extended test run of the system, current transducers need to be installed to obtain the pump power usage. This will allow for pump curves and efficiency to be determined. Field checks of the flow meters and pressure transducers need to be performed on a regular basis to insure the accuracy of these measurements.

REFERENCES

http://www.nahb.org/fileUpload_details.aspx?contentID=59145, "Single Family Detached Homes", National Association of Home Builders, 2004.

http://www.ukace.org/pubs/consult/EACEECbd.pdf#search=%22average%20european%20home%20size%22, "EuroACE Response to the Draft Directive on Energy Performance of Buildings", The European Alliance of Companies for Energy Efficient Buildings, October 2001.

http://www.thermaxindia.com/v2/ProdGrpPage.asp?levelno=1&objectid=9&pageno=1&divid=2, "Hot Water Driven Chillers", Thermax, 2006.

http://www.yazakienergy.com/docs/YazakiWaterFiredChillHeatBroch.pdf, "Water Fired Chiller/Chiller-Heater", Yazaki Energy, 2006.

http://www.robur.com/gestione/immagini/allegati_prodotti/D%20LBR%20222_04%20MCM%20SPV%20011_dati%20tecnici_GA_S60_ENG.pdf, "Gas Fired High Efficiency Absorption Chillers and Chillers-Heaters", Robur Corporation, 2006.

http://www.coolingtechnologies.com/pdf/Cooltec5%20DS.pdf, "Cooltec5™ Gas Fired Cooling", Cooling Technologies, Inc, 2006.

http://www.coolingtechnologies.com/pdf/CoolpakDS2.pdf, "Coolpak™, Gas Fired Cooling", Cooling Technologies, Inc, 2006.

http://www.marathonengine.com/downloads/ecopower_faq.pdf, "Frequently Asked Questions relating to ecopower micro CHP unit: 1-1-06", Marathon Engine Systems, 2006.

http://www.whispergen.com/content/library/AC_specBase.pdf, "Whisper GEN, AC Specifications", Whisper Tech, 2006.

http://www.stirling-engine.de/engl/SOLO_STIRLING_g.pdf, Solo Stirling 161, Solo Stirling Engine, 2006.

http://www.enatec.com/indexUK.htm, "ENATEC signs international cooperation agreement for development, production and distribution of microCHP systems", ENTAC, Press Release in Rotterdam, June 20, 2005.

http://www.stirlingenergy.com/default.asp, "Stirling Energy Systems", SES, 2006.

http://www.microturbine.com/_docs/PDS_C30NatGasPerfSpecs1R.pdf, "C30 Natural Gas Microturbine Performance Characteristics", Capstone Energy, 2006.

http://www.eia.doe.gov/emeu/reps/enduse/er01_us.html, "U.S. Household Electricity Report", United States Department of Energy, 2005.

http://www.elliottmicroturbines.com/files/EESI_51-1.pdf, "100 kW CHP Microturbine", Elliot Microturbines, 2006.

http://www.irenergysystems.com/IS/product.asp-en-18219, "MT70 Series Microturbine", Ingersoll-Rand, 2006.

http://www.cogenmicro.com/index.htm, "Micro Cogeneration System for Residential and Small Commercial Applications", Cogen Microsystems, Inc, 2006.

http://www.cfcl.com.au/Links/CFCL_MicroCHP_0305.pdf, "Combined Heat and Power (micro-CHP) Domestic Demonstration Unit", Ceramic Fuel Cells Limited (CFCL), 2006.

http://www.cfcl.com.au/Links/CFCL_DG_Leaflet0404.pdf, "Distributed Generation (DG) Concept for Domestic and Small Commercial Applications", Ceramic Fuel Cells Limited (CFCL), 2006.

http://www.plugpower.com/products/pdf/GENCORE_UPS.pdf, "Fuel Cells for Uninterruptible Power", Plug Power Inc., 2006.

http://www.omega.com/pptst/HX94.html, "Relative Humidity/Temperature Transmitter, Duct Style, Models Stainless Steel Housing, Models HX94C and HX94V", Omega Engineering Inc., 2006.

http://www.coleparmer.com/catalog/product_view.asp?sku=6807310&pfx=EW, "Cole-Parmer® High-Accuracy Gauge Pressure Transmitters", Cole-Parmer®, 2006.

http://www.dynasonics.com/resources/products/pdfs/TFXL.pdf, "Ultrasonic Clamp-on Flow Meter", Dynasonics, 2006.

http://www.paragoncontrols.com/Paragon%20Controls,%20Inc/Sensing%20Elements/Flow%20Elements/FE-1000%20Tech%20Data%20Sheet.pdf, "FE-1000 Insertion Type Airflow Sensing Element", Paragon Controls Inc., 2006.

APPENDIX A

LABVIEW PROGRAM

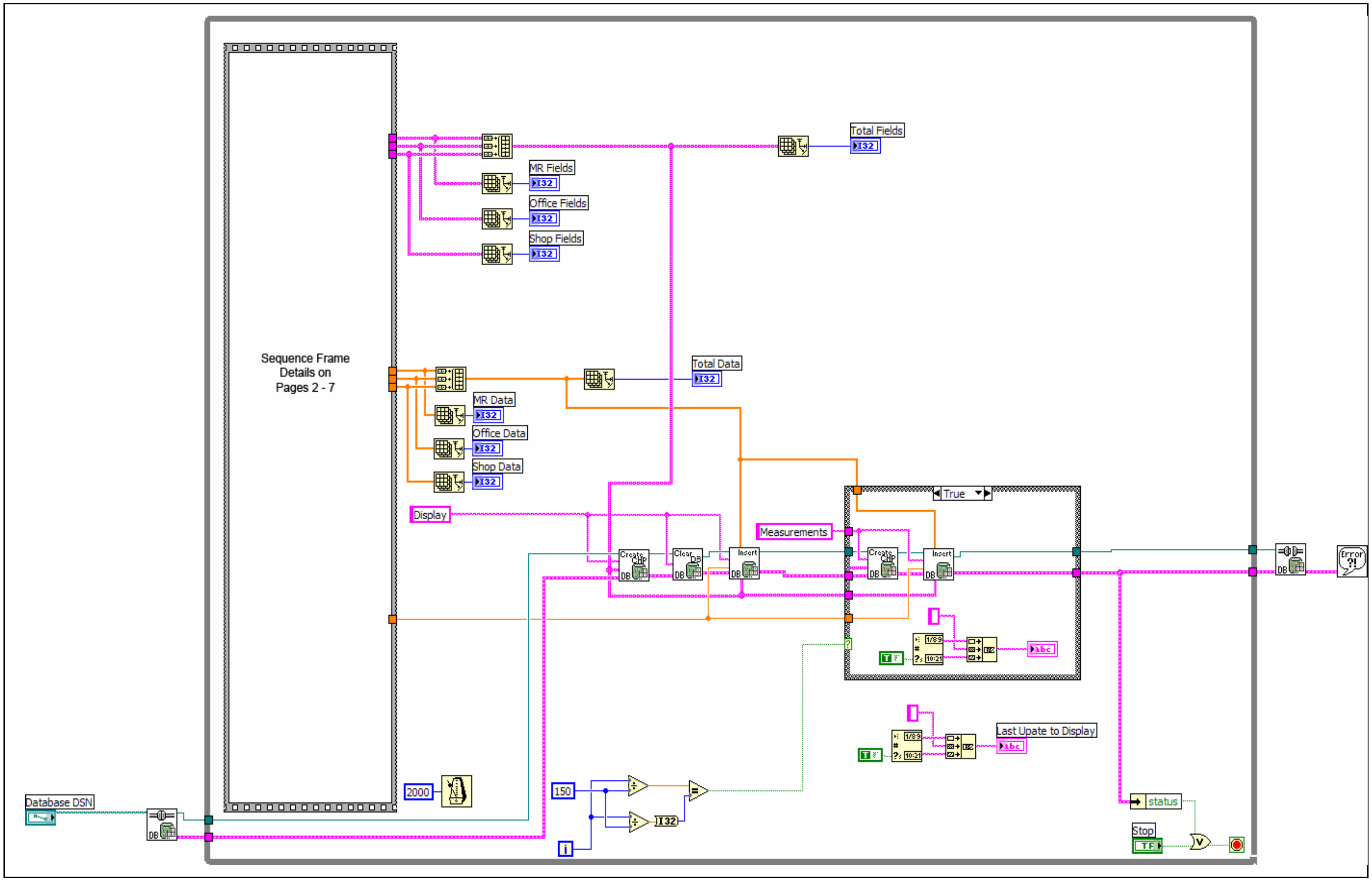


Figure A.1 Database Backend Main VI

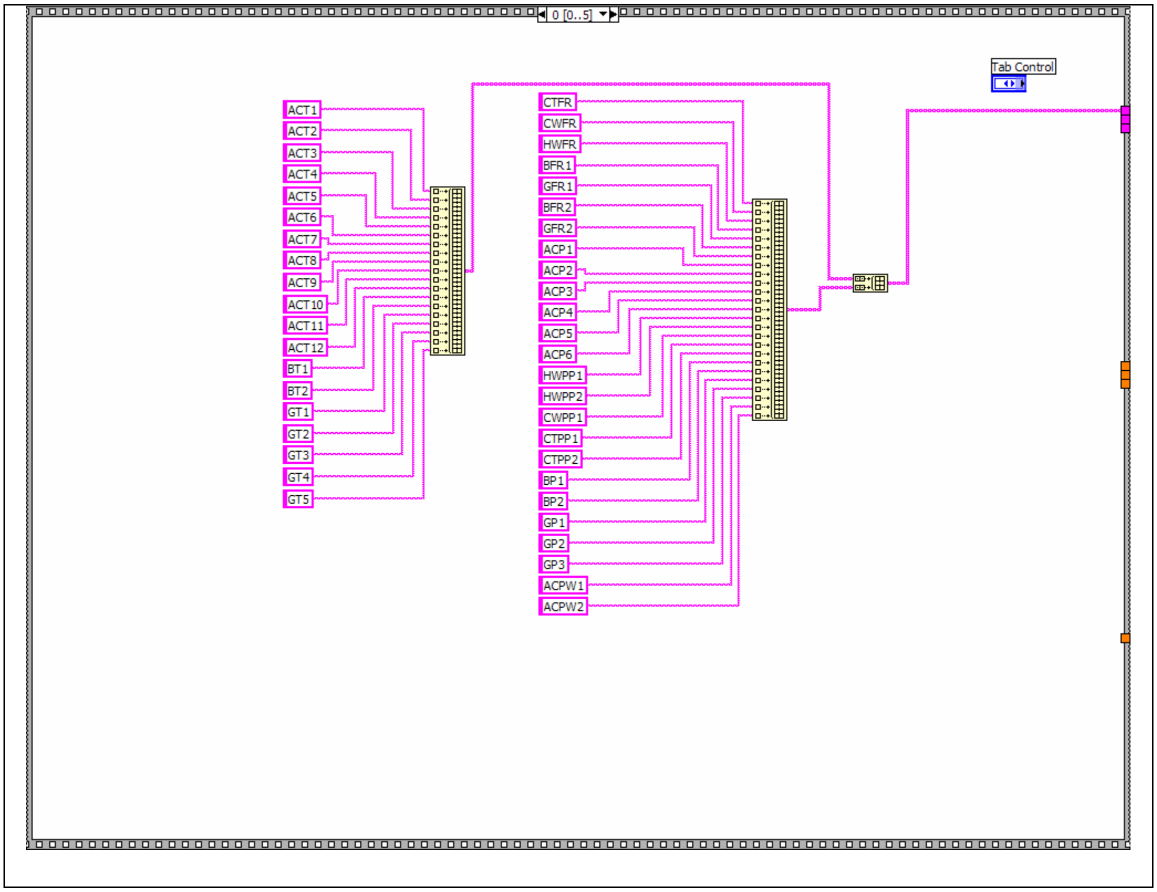


Figure A.2 Mechanical Room Database Fields Array

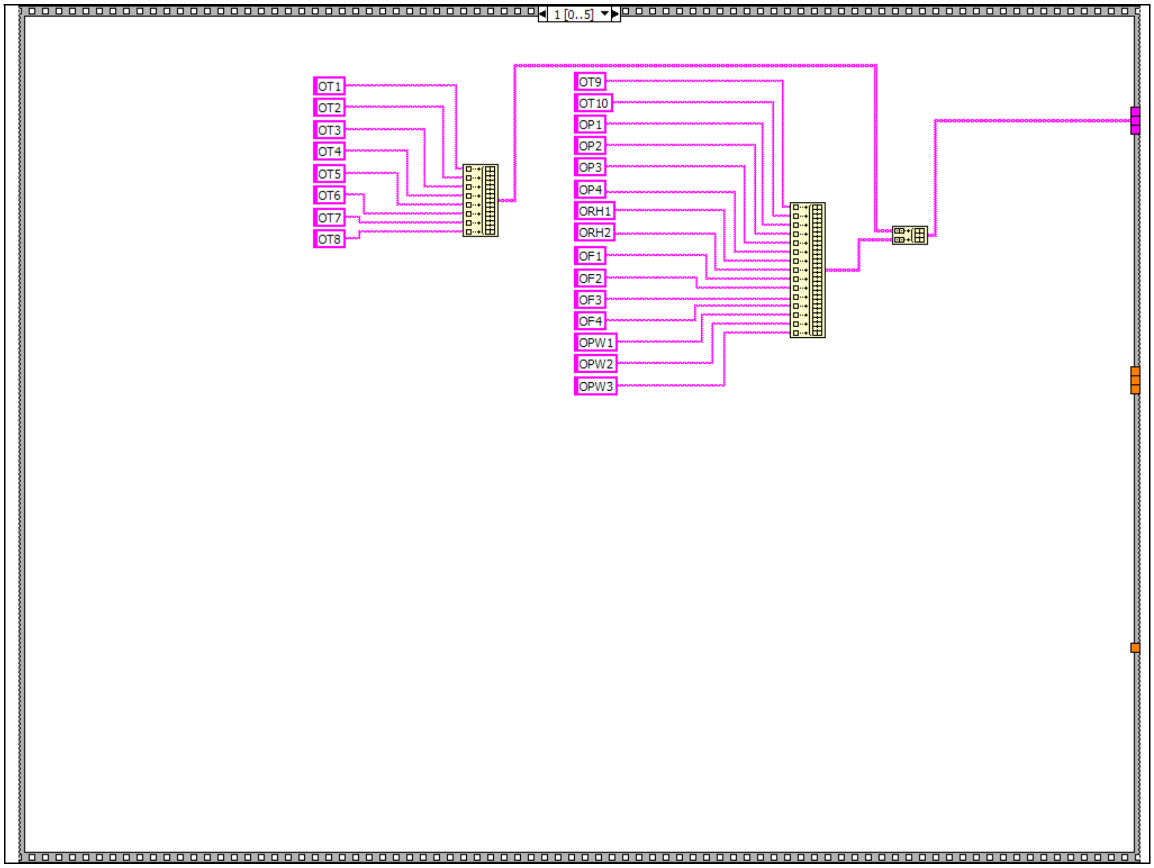


Figure A.3   Office Database Fields Array

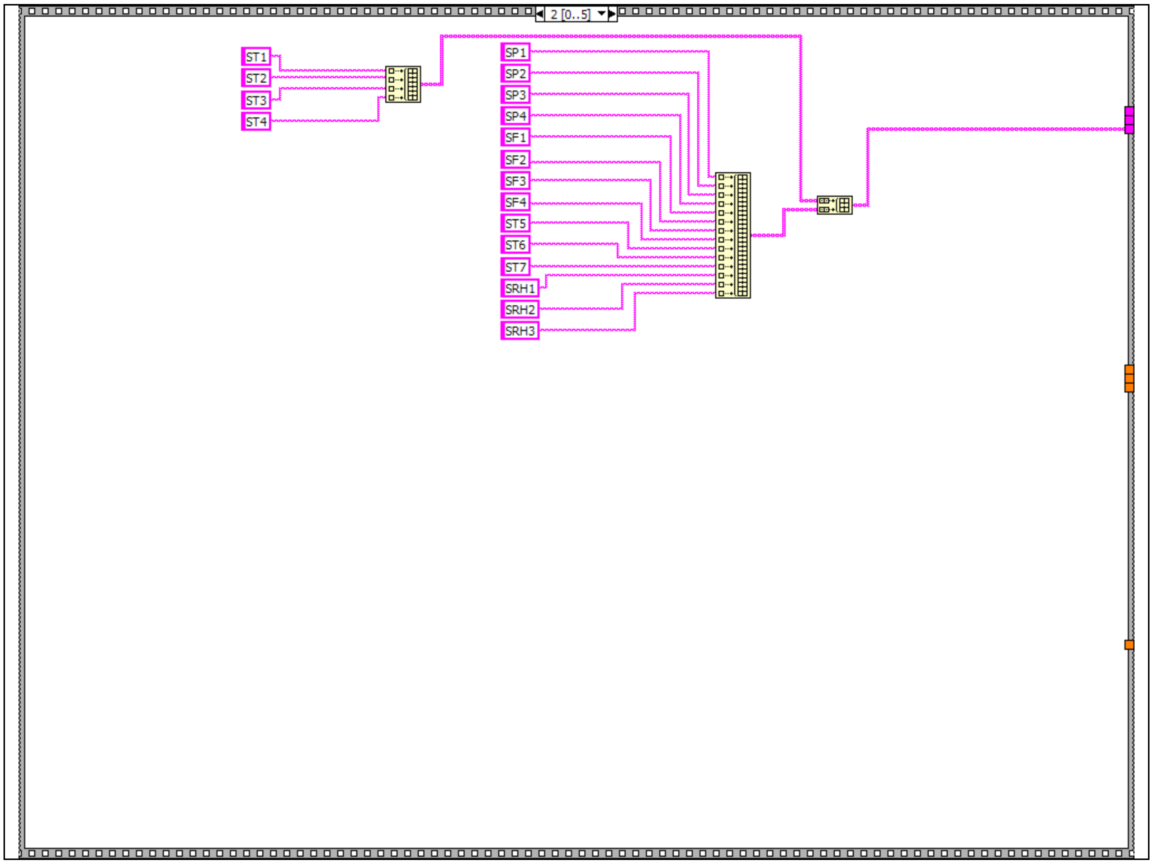


Figure A.4 Shop Database Fields Array

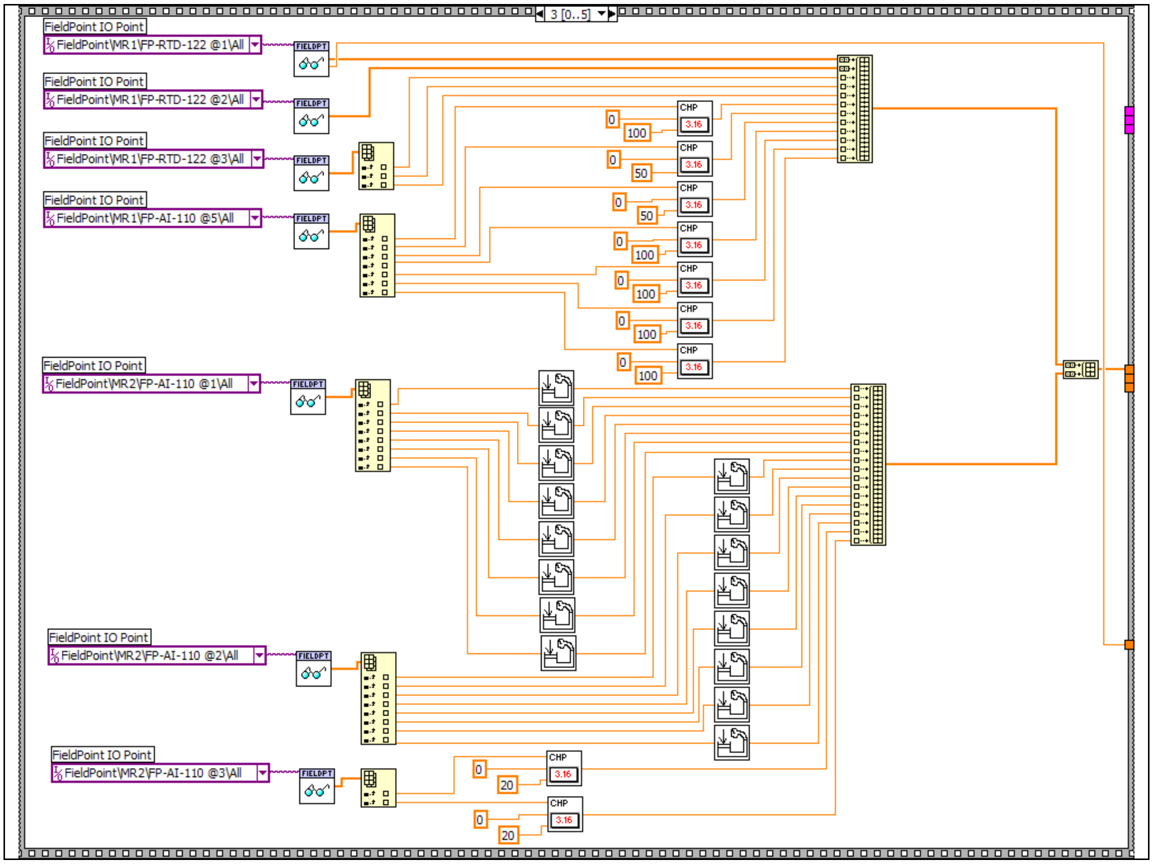


Figure A.5 Mechanical Room Data Acquisition

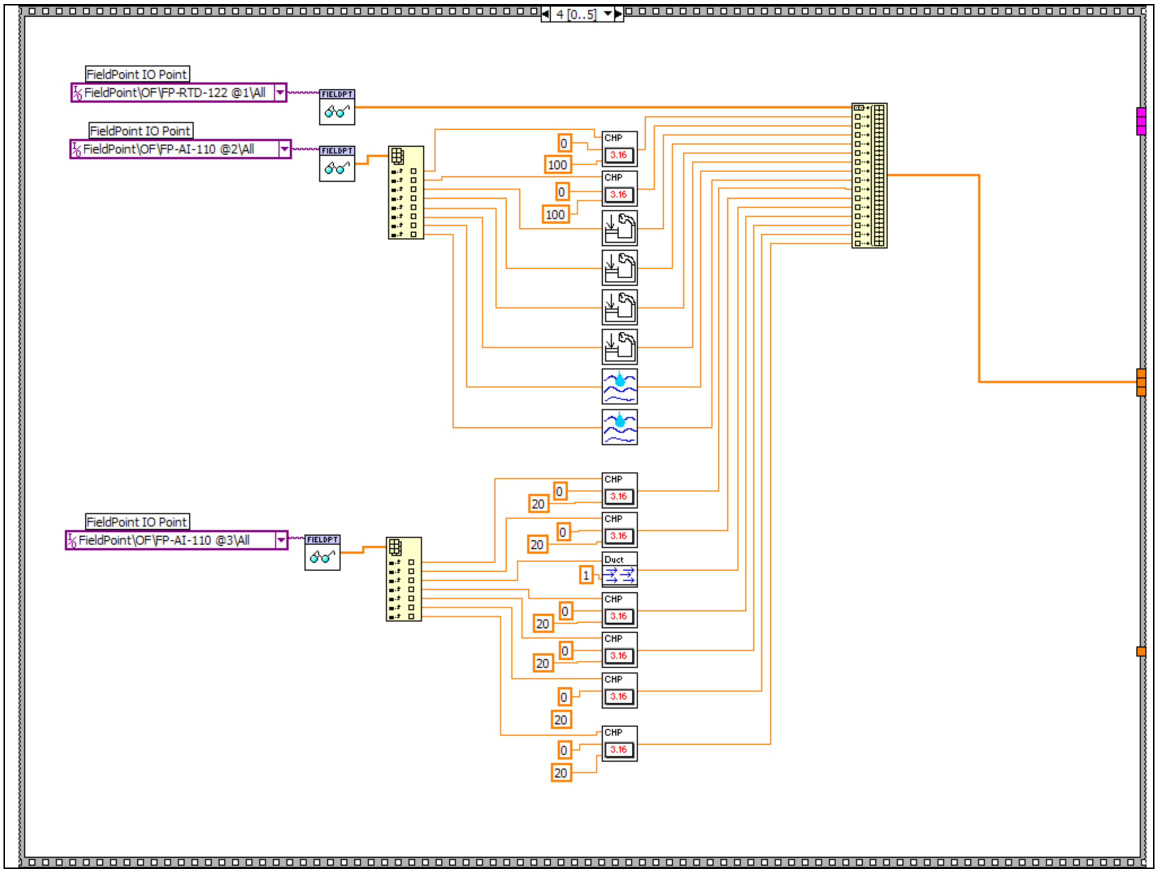


Figure A.6 Office Data Acquisition

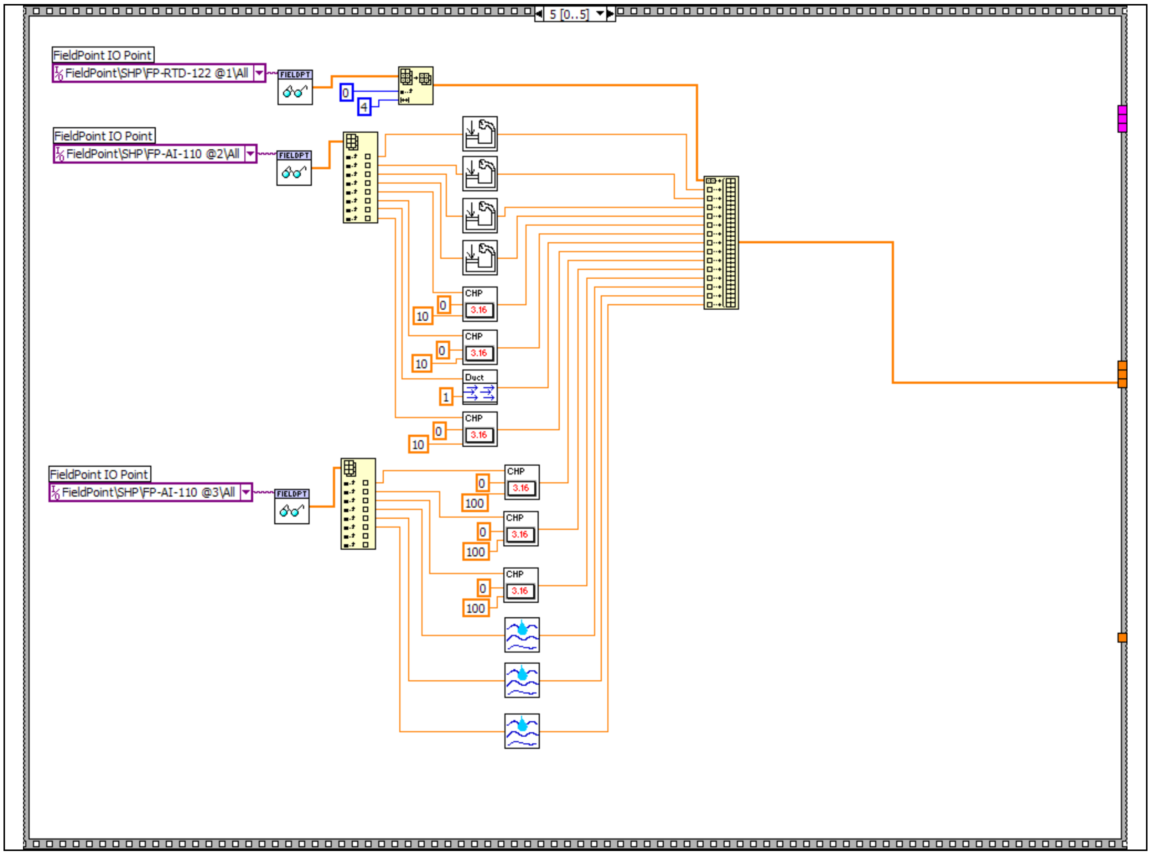


Figure A.7 Shop Data Acquisition

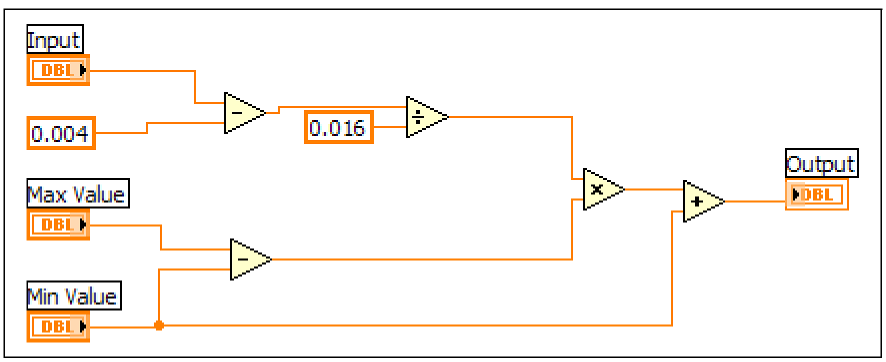


Figure A.8 4-20mA Sub VI

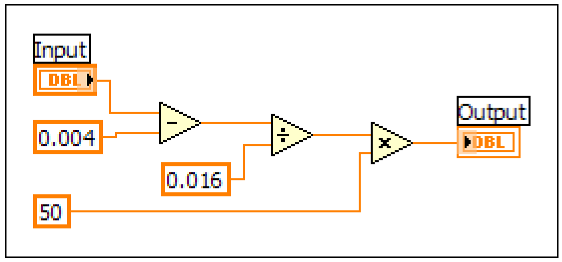


Figure A.9 Pressure Transducer Sub VI

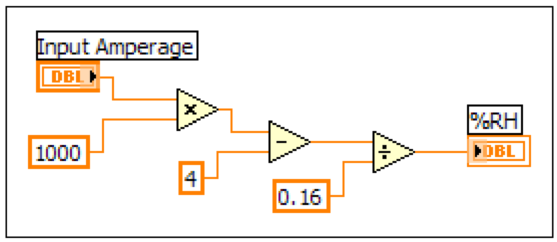


Figure A.10 Relative Humidity Sub VI

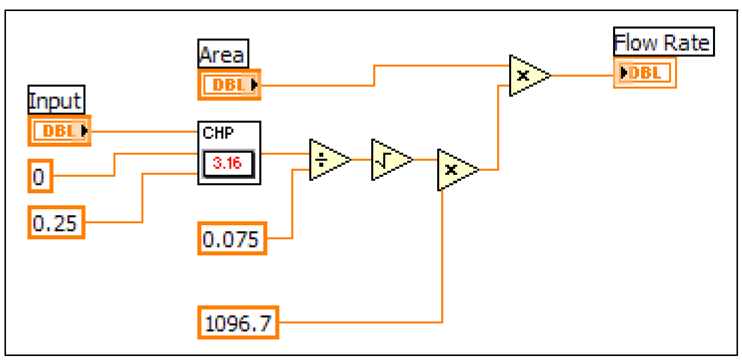


Figure A.11 Duct Flow Rate Sub VI

APPENDIX B

TRANSDUCER SPECIFICATIONS

SINGLE PHASE AC CURRENT TRANSDUCER *MODEL* ACT-

0.25% ACCURACY

FEATURES

- Accurate, reliable current measurement over a wide frequency range.
- Low Cost
- Designed to withstand motor start-up transients.

5 YEAR WARRANTY

APPLICATIONS

- Designed for use in applications where UL listed measurement devices are required.

INPUT AC AMPS	SENSOR SIZE	STANDARD OUTPUTS MODEL ACT- UL, CUL & CE 0 - 1mAdc*	4 - 20mA**	0 - 10Vdc*	0 - 5Vdc*	UL & CUL 4 - 20mA
0 - 1	int.	001A	001E2	001C	001CX5	001E
0 - 5	int.	005A	005E2	005C	005CX5	005E
0 - 10	int.	010A	010E2	010C	010CX5	010E
0 - 20	int.	020A	020E2	020C	020CX5	020E
0 - 25†	W	025A	025E2	025C	025CX5	025E
0 - 50	W	050A	050E2	050C	050CX5	050E
0 - 100	W	100A	100E2	100C	100CX5	100E
0 - 200	W	200A	200E2	200C	200CX5	200E
0 - 300	W	300A	300E2	300C	300CX5	300E
0 - 400	X	400A	400E2	400C	400CX5	400E
0 - 500	X	500A	500E2	500C	500CX5	500E
0 - 600	X	600A	600E2	600C	600CX5	600E
0 - 800	X	800A	800E2	800C	800CX5	800E
0 - 1000	Y	1000A	1000E2	1000C	1000CX5	1000E
0 - 1500	Y	1500A	1500E2	1500C	1500CX5	1500E

c UL us LISTED

Measuring Equipment 7N93

* Models are self-powered from measured line.
**4 - 20 mA loop-powered unit, (15 - 24Vdc).
† Indicates two turns through transformer window.
Standard 4 - 20mA models require 115Vac instrument power.
Optional 230Vac instrument power - add suffix **"- 22"**.

Transducer output is derived from the average absolute value of the input and calibrated in terms of the RMS value of the sine wave input.

ORDERING INFORMATION

Example: 20 Amps AC Input with
4 - 20mA Output.
ACT - 020E

SPECIFICATIONS

INPUT

Frequency Range .... 50/60 Hz
Burden .... 1.0VA F.S.
Current Overload
- 2 X F.S. rating (continuous) .... except 20A model
- 20A model .... 1.25 X F.S.rating
- 50 X F.S. .... (1 sec. transient)

Dielectric Test .... (Input/Output/Case) 2200Vac
Instrument Power .... (Std. 4 - 20mA Units)
115Vac, 50/60Hz, ±15%, 10VA max.
"-22" Option....230Vac, 50/60Hz, ±15%, 10VA max.

OUTPUT

ACCURACY
- **Internal sensor .... ± 0.25% F.S. @ 60Hz**
- **External sensor .... ± 0.5% F.S. @ 60Hz**

Includes Effects of Linearity and Set Point
Output Ripple .... < 1.0% F.S.
Response .... 400 milliseconds
Output Loading (Ohms)
- 1mA .... (A) .... 0 - 10K
- 4 - 20mA ...... (E) .... 0 - 1K
- 4 - 20mA ...... (E2) .... 0-600 Ohms at 24V
- 5V & 10V ...... (CX5, X5) .... >10M

Field Adjustable Cal. .... ± 5%
Temperature Effect .... ± 1.0% Rdg.
Temperature Range .... -20°C to +60°C

OHIO SEMITRONICS, INC. 4242 REYNOLDS DRIVE * HILLIARD, OHIO * 43026-1264
PHONE: (614) 777-1005 * FAX: (614) 777-4511
WWW.OHIOSEMITRONICS.COM * 1-800-537-6732

Figure B.1 Ohio Semitronics ACT Current Transducer

MULTIFUNCTION POWER TEST PANEL *MODEL* PTB-

VOLTS, AMPS, WATTS, WATTHOURS, POWER FACTOR & VOLT/AMPS

DESCRIPTION

The PTB board level system monitor is designed to measure and provide analog output signals for all parameters of voltage, current and total power in an electrical system. Optional outputs are available for power factor, apparent power and watthours as plug-in "daughter" boards.

The PTB comes standard with seven 0 - 10Vdc analog outputs for voltage, current and power. As options, 0 - 1mA and 4 - 20mA outputs are also available.

The 10.75" x 8.9" x 2.5" circuit board is provided with mounting holes to fit a 10" x 12" NEMA case or the circuit board can be mounted in the user's cabinet with the stand-offs provided. Input and output terminals are located directly on the circuit board.

The electronic circuitry uses solid-state multipliers, RMS converters and amplifiers. The unit requires 115Vac instrument power.

FEATURES

- Small Package
- Less Wiring
- High Accuracy
- Up to 9 Analog Outputs
- Circuit Board Design
- Direct Input to 600Vac
- Low Cost
- Calibrated with CT's

Shown in NEMA Case

ORDERING INFORMATION

Example: 3PH-3W, 2 Elem, 0-150Vac, 0-100Aac, 10Vdc & Watthour Outputs, 115Vac Inst. Power.
PTB - 212D1W

	SYSTEM		VOLTS		AMPS		OUTPUTS		INST. PWR.	OPTION P	OPTION W	OPTION C
1	1 PH-2 W	1	0 - 150 Vac	1	0 - 5 Aac	D	0 - 10Vdc	1	115Vac	Apparent	Watthours	NEMA Case
2	3 PH-3 W	2	0 - 300 Vac	2	0 - 100 Aac	B	0 - 1mAdc			Power &		
3	*3 PH-4 W	3	0 - 600 Vac	3	0 - 200 Aac	E	4 - 20mAdc	2	230Vac	Power		
4	*1 PH-3 W			4	0 - 400 Aac					Factor		

* Specify L-N Voltage

SPECIFICATIONS

INPUT

VOLTAGE
- F.S. Linear Range .... See Table
- Overvoltage .... 150Vac .... (175Vac)
  - 300Vac .... (350Vac)
  - 600Vac .... (610Vac)
- Burden 0.25VA/Phase

CURRENT
All models are linear through full-scale current range.
- Continuous overcurrent
  - 5A models 10Aac
  - All other ranges .... 125% of F.S.
- Burden .... < 0.25VA/Phase

Frequency Range .... (Linear) .... 48 Hz - 70Hz
Power Factor .... Any
Dielectric Test .... (Input To Outputs) 1500Vac

OUTPUT SCALING

Voltage (RMS) (3) .... 0 - 10Vdc = 0 - F.S. Voltage
Current (RMS) (3) .... 0 - 10Vdc = 0 - F.S. Current
Watts (True Power) .... 0 - 10Vdc = 0 - F.S. Watts
*Based on F.S. Volts x F.S. Amps x No. of Elements x 0.8
Output Burden .... 10V .... > than 2K
- 1mA .... 0 - 10K
- 20mA .... 0 - 500

Ripple .... < ±1% F.S.

OPTIONS

Apparent Power (VA) .... * Same as watts
Power Factor .... 0 - 10Vdc ...... 0 - 1 Lead or Lag.
Watthours
- 5A Models .... 1 WH/C
- 100A Models .... 20 WH/C
- 200A Models .... 40 WH/C
- 400A Models .... 80 WH/C

Relay Rating 120V, 0.5A
Relay Closure Duration .... 200 milliseconds

ACCURACY

(Includes linearity, setpoint and power factor at 25°C)
- 5A Models .... Voltage .... ±0.3% F.S.
  - Current .... ±0.3% F.S.
  - Power .... ±0.3% F.S.
- 100A - 400A Models ..... Voltage .... ±0.5% F.S.
  - Current .... ±0.5% F.S.
  - Power .... ±0.5% F.S.

Watthours .... (Option) .... ±0.5% F.S.
Power Factor..(10-100% Input) ..(Option) .... ±0.01 PF
Response Time .... 250 milliseconds
Temperature Effects .... (10° to 35°C) .... ±0.5%
Instrument Power .... 115Vac, ±10%, 50-400Hz, 8.5VA
- (Option) .... 230Vac, 50/60Hz, ±10%

OHIO SEMITRONICS, INC.
4242 REYNOLDS DRIVE * HILLIARD, OHIO * 43026-1264
PHONE: (614) 777-1005 * FAX: (614) 777-4511
WWW.OHIOSEMITRONICS.COM * 1-800-537-6732

Figure B.2 Ohio Semitronics PTB Multifunction Power Transducer

Ordering Information

Field-Cuttable Thermocouples

J-type
- Grounded 745685-J01
- Ungrounded 745685-J02

K-type
- Grounded 745685-K01
- Ungrounded 745685-K02

T-type
- Grounded 745685-T01
- Ungrounded 745685-T02

E-type
- Grounded 745685-E01
- Ungrounded 745685-E02

Ready-Made Thermocouples

J-type
- 1 m 745690-J001
- 2 m 745690-J002

K-type
- 1 m 745690-K001
- 2 m 745690-K002

T-type
- 1 m 745690-T001
- 2 m 745690-T002

E-type
- 1 m 745690-E001
- 2 m 745690-E002

Thermocouple Wire

J-type
- 30 m 745687-J030
- 300 m 745687-J300

K-type
- 30 m 745687-K030
- 300 m 745687-K300

T-type
- 30 m 745687-T030
- 300 m 745687-T300

E-type
- 30 m 745687-E030
- 300 m 745687-E300

Thermocouple Extension Wire

Jx-type
- 30 m 745689-J030
- 300 m 745689-J300

Kx-type
- 30 m 745689-K030
- 300 m 745689-K300

Tx-type
- 30 m 745689-T030
- 300 m 745689-T300

Ex-type
- 30 m 745689-E030
- 300 m 745689-E300

Accessories

Thermocouple Miniconnector Plugs (Quantity 10)
- J type 745688-J10
- K type 745688-K10
- T type 745688-T10
- E type 745688-E10

Uncompensated 745688-U10

Spring-loaded fitting 745688-32

Tubing cutter 745688-37

RTDs

Field-Cuttable RTD
- 100 Ω, Pt, 3-wire 745686-01

Ready-Made RTDs
- 1 m 745691-01
- 2 m 745691-02

Specifications

Thermocouple Characteristics

Extension Wire

Temperature range .... -20 to 221 °F (-6.7 to 105 °C)

RTD Characteristics

Type .... Platinum
Resistance .... 100 Ω at 0 °C
Probe range .... -58 to 900 °F (-50 to 482 °C)
Ready-made range .... -58 to 400 °F (-50 to 204 °C)
Calibration .... DIN 43760-1980 (European) Standard Curve (a = 0.00385)
Accuracy .... ±(0.3+0.005 |t|) °C (where t is the absolute valueof the temperature being measured in °C)
Configuration 3-wire

Calibration	Conductor		Temp. Range	Limits of Error[1] (whichever is greater)
	Positive	Negative		
J-type	Iron (White)	Constantan (Red)	32 to 900 °F (0 to 482 °C)	±2.2 °C (4.0 °F) or ±0.75%
K-type	Chromel (Yellow)	Alumael (Red)	32 to 900 °F (0 to 482 °C)	±2.2 °C (4.0 °F) or ±0.75%
T-type (probe only)	Copper (Blue)	Constantan (Red)	-328 to 32 °F (-200 to 0 °C) 32 to 500 °F (0 to 260 °C)	±2.2 °C (4.0 °F) or ±0.75% ±1.0 °C (2.0 °F) or ±0.75%
T-type (ready-made only)	Copper (Blue)	Constantan (Red)	32 to 500 °F (0 to 260 °C)	±1.0 °C (2.0 °F) or ±0.75%
E-type	Chromel (Purple)	Constantan (Red)	32 to 900 °F (0 to 482 °C)	±1.7 °C (2.0 °F) or ±0.75%

Probe and Ready-Made Thermocouple Calibrations
[1]Where error is given in percent, the percentage applies to the temperature being measured, not the range.

Figure B.3 NI Ready-Made RTD

Temperature **Catalogue Information**

Continuous Averaging

Product Ordering Information

Enclosures

ABS


W - Weatherproof

M - Metal

Description

The TE Series continuous averaging temperature sensor averages stratified air in ducts with the use of a continuous element which closely matches the temperature profile of a platinum RTD.

A transmitter option is also available to be used with the 1000 ohm platinum sensor which provides either 4 -20mA, 0 – 5 VDC or 0 – 10 VDC output proportional to a selected temperature span. A 100 ohm sensor is optional.

The transmitters provide high accuracy, long-term stability, low hysteresis, fast response and a wide operating temperature range.

Maximum Temperature range of probe –40°C to 100°C (-40°F – 212°F).

Every transmitter offers accuracy of 0.1% of span or better and are highly stable due to excellent RFI rejection and are also virtually immune to power supply noise and input voltage fluctuations.

Transmitter General Specifications:

Supply Voltage:	24 VDC/VAC
Output:	4 – 20mA, 0–5 VDC or 0-10 VDC
Accuracy:	±0.1% of span
Operating temp:	0°C – 70°C (32°F – 158°F)

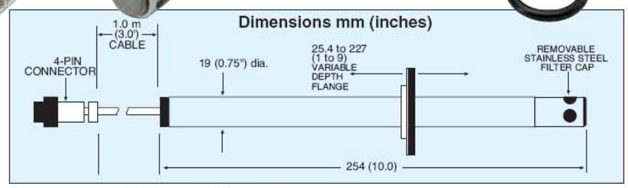
Figure B.4 Greystone Energy Continuous Averaging Temperature Sensor

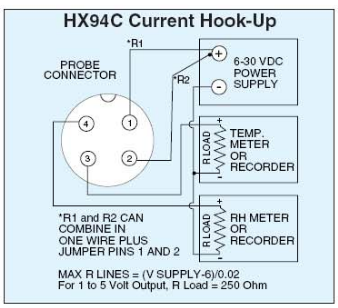
Relative Humidity Temperature Transmitters

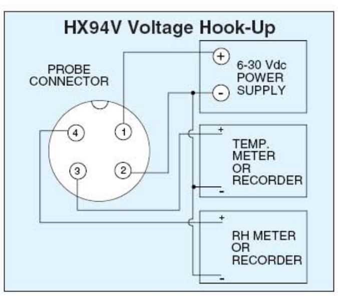
- Stainless Steel NEMA-4 Housing
- 3 Different Output Connection Styles Available for Mounting Versatility
- 4 to 20 mA/0 to 1 Vdc Outputs
- Removable Stainless Steel Sensor Filter for Cleaning Ease

HX94 Series Starts at $235

The HX94 relative humidity/ temperature transmitter provides a reliable and low cost method for duct mount monitoring applications. Solid state sensors provide excellent sensitivity, fast response, and stability. Simple hookup and linearized output permit interfacing with most display and control devices.







Specifications

RELATIVE HUMIDITY
Thin-Film Polymer Capacitor
Input Voltage Range:
6 to 30 Vdc, (polarity protected)
Range/Accuracy/Repeatability:
3 to 95% RH/±2% RH/±1% RH
Temperature Compensation:
-20 to 85°C (4 to 185°F)
Current Output:
HX94C: 4 to 20 mA (0 to 100% RH)
Voltage Output:
HX94V: 0 to 1.0 Volt (0 to 100% RH)
Time Constant: (for 90% response at 25°C; in moving air, 1m/sec.)
Less than 20 seconds, 10 to 90% RH
Less than 30 seconds, 90 to 10% RH

TEMPERATURE
Thin-Film 100 ohm Platinum RTD (DIN 43760)
Input Voltage Range:
6 to 30 Vdc, (Polarity Protected)
Range: 0 to 100°C (32 to 212°F)
Accuracy: ±0.6°C (±1°F)
Repeatability: ±0.3°C (±0.5°F)
Current Output:
HX94C: 4 to 20 mA for 0 to 100°C
Voltage Output:
HX94V: 0 to 1.0 Volt for 0 to 100°C
Time Constant: (for 60% response)
Less than 2 seconds in moving air (1m/sec) Less than 10 seconds in still air

MECHANICAL
Housing: Stainless steel NEMA-4 enclosure
Probe: 254 x 19 mm (10 x 0.75") dia., 305 mm (12") cable
Duct Flange: Removable, variable 25.4 to 227 mm (1 to 9") depth. 70 mm (2.75") dia., duct hole 21 mm (0.812") dia. 4 mtg holes. 4 mm (0.156") dia. (for #6 sheet metal screws) on 51 mm (2.00") dia. circle. Wall mounting bracket included.
Connections: HX94C/94V: 4 pin mating connector accepts 26 to 18 AWG wires. HX94CW/94VW: 1 m (3') braided and shielded cable, PVC sheathing. HX94CNPT/94VNPT: ½" male NPT conductor with 1 m (3') braided/shielded cable
Weight: 198 g (7 oz) with duct flange

ALL MODELS AVAILABLE FOR FAST DELIVERY!

To Order *(Specify Model Number)*

Model No.	Price	Description
HX94C	$265	RH/temp transmitter with 4 to 20 mA outputs with 4 pin connector
HX94V	265	RH/temp transmitter with 0 to 1 Vdc outputs with 4 pin connector
HX94CW	235	RH/temp transmitter with 4 to 20 mA outputs with 1 m (3') lead wires
HX94VW	235	RH/temp transmitter with 0 to 1 Vdc outputs with 1 m (3') lead wires
HX94CNPT	245	RH/temp transmitter with 4 to 20 mA outputs with ½" male NPT fitting and 1 m (3') leads
HX94VNPT	245	RH/temp transmitter with 0 to 1 Vdc outputs with ½" male NPT fitting and 1 m (3') leads
HX94-MC	10	Spare 4 pin mating connector
PSR-24S	60	Regulated power supply, US plug, 90 to 264 Vac input, 24 Vdc output, 400 mA, screw terminals, UL
PSR-24L	60	Regulated power supply, US plug, 90 to 264 Vac input, 24 Vdc output, 400 mA, stripped leads, UL
PSR-24L-230	60	Regulated power supply, European plug, 230 Vac input, 24 Vdc output, 400 mA, stripped leads, CE
PSU-93	40	Unregulated power supply, 16 to 23 Vdc, 300 mA max, screw terminal
TX4-100	28.50	4 conductor shielded transmitter cable, 30 m (100')
CAL-3-HU	125	NIST-traceable calibration

Comes with mating connector, removable protective sensor filter, removable duct flange, wall mounting bracket, and operator's manual.
Ordering Example: HX94C,** duct mount RH/temperature transmitter with 4 to 20 mA output, **$265.

Hu-32

Figure B.5 Omega Engineering HX94 Relative Humidity Transmitter

Cole-Parmer High-Accuracy Industrial Pressure Transducers

Withstands high shock and vibration applications

- Welded stainless steel (SS) housing rated to NEMA 4 (IP65) standards

Transducers feature SS capacitive sensor for your more demanding systems—even ElectroMagnetic Interference (EMI)/Radio Frequency Interference (RFI) resistance ensures accurate and consistent performance in any environment.

Transducers feature adjustable zero and span potentiometers. Transducers with 4 to 20 mA output have red (positive power) and black (output) wires. Transducers with 0.1 to 5.1 V output have red (positive power), green (output), and white/black (common) wires.

68073-14

Specifications & Ordering Information

ISO 9001:2000 CERTIFIED SUPPLIER

Accuracy: ±0.13% full-scale

Temperature range (compensated): –4 to 176°F (–20 to 80°C)

Operating temperature: –40 to 260°F (–40 to 126°C)

Process connection: 1/4" NPT(M)

Power: 12 to 28 VDC (unregulated)

Electrical connection: 2-ft L cable

Media compatibility: gases or liquids compatible with 17-4PH stainless steel

Dimensions: 5"L x 2" diameter

Range	4 to 20 mA output		0.1 to 5.1 V output	
	Catalog number	Price	Catalog number	Price
Compound transducers				
–14.7 to 15 psi	K-68073-00		K-68074-00	
–14.7 to 30 psi	K-68073-02		K-68074-02	
–14.7 to 60 psi	K-68073-04		K-68074-04	
–14.7 to 100 psi	K-68073-06		K-68074-06	
Gauge pressure transducers				
0 to 25 psig	K-68073-08		K-68074-08	
0 to 50 psig	K-68073-10		K-68074-10	
0 to 100 psig	K-68073-12		K-68074-12	
0 to 500 psig	K-68073-14		K-68074-14	
0 to 1000 psig	K-68073-16		K-68074-16	
0 to 3000 psig	K-68073-18		K-68074-18	
0 to 5000 psig	K-68073-20		K-68074-20	
0 to 10,000 psig	K-68073-22		K-68074-22	

Figure B.6 Cole Parmer 0-50 PSI Pressure Transmitter

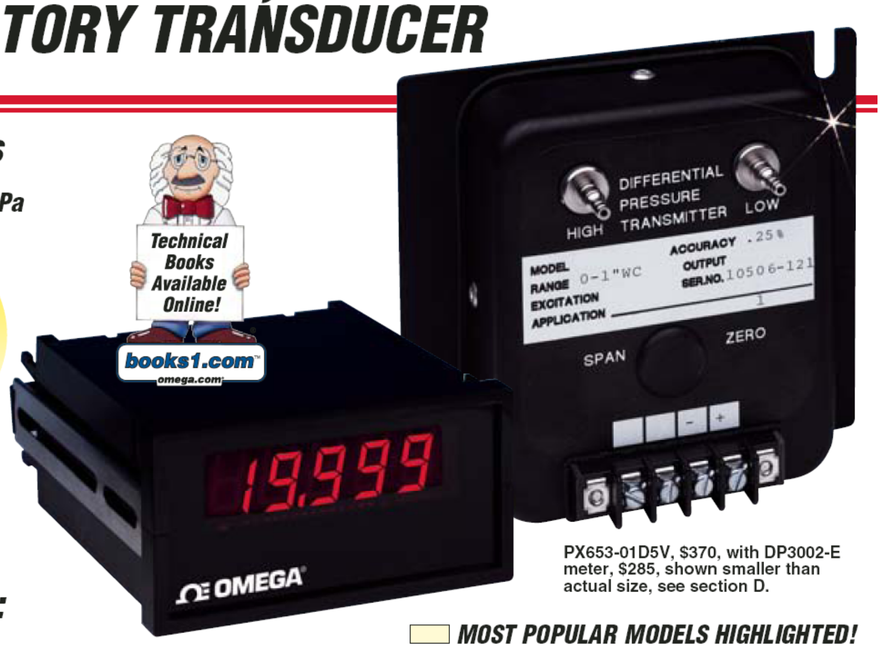
HIGHLY ACCURATE, LOW-PRESSURE LABORATORY TRANSDUCER

PX653 Series

0-0.1 to 0-50 inH_2O
0-25 Pa to 0-12.5 kPa

Starts at $370

1 YEAR WARRANTY · MADE IN USA · NIST



PX653-01D5V, $370, with DP3002-E meter, $285, shown smaller than actual size, see section D.

Ideal Applications:

- Clean Rooms
- HVAC
- Laboratory Fume Hoods

SPECIFICATIONS

Excitation: 12 to 36 Vdc
Output: 1 to 5 Vdc (3 wire)
Linearity: 0.3% FS (BFSL)
Hysteresis: 0.02% FS
Repeatability: 0.05% FS
Operating Temperature: -29 to 72°C (-20 to 160°F)
Compensated Temperature: 2 to 57°C (35 to 135°F)
Thermal Effects:
  Zero: 0.015% FS/°F
  Span: 0.015% rdg/°F
Proof Pressure: 15 psi
Burst Pressure: 20 psi
Static Pressure: 25 psi
Gage Type: Capacitance
Supply Current: <5 mA
Calibration Report: NIST cal at 25, 50, 75 and 100% FS; upscale and downscale provided
Response Time: 250 ms
Wetted Parts: Dry, clean, non-corrosive gases only
Enclosure: NEMA 2 (IP62), 107 H x 117 W x 53 mm D (4.2 x 4.6 x 2.1")
Pressure Port: ¼ barbed fittings (tubing TY-316-100)
Electrical Connections.: Screw terminal
Weight: 368 g (13 oz)

MOST POPULAR MODELS HIGHLIGHTED!

To Order *(Specify Model Number)*

RANGE inH_2O	Pa/kPa	MODEL NO.	PRICE	COMPATIBLE METERS*
0 to 0.1	0 to 25	**PX653-0.1D5V**	**$470**	DP25B-E, DP41-E, DP460-E
0 to 0.25	0 to 62	**PX653-0.25D5V**	**430**	DP25B-E, DP41-E, DP460-E
0 to 0.50	0 to 125	**PX653-0.5D5V**	**400**	DP25B-E, DP41-E, DP460-E
0 to 0.75	0 to 187	**PX653-0.75D5V**	**370**	DP25B-E, DP41-E, DP460-E
0 to 1	0 to 249	**PX653-01D5V**	**370**	DP25B-E, DP41-E, DP3002-E
0 to 2	0 to 498	**PX653-02D5V**	**370**	DP25B-E, DP41-E, DP460-E
0 to 3	0 to 748	**PX653-03D5V**	**370**	DP25B-E, DP41-E, DP460-E
0 to 5	0 to 1.25	**PX653-05D5V**	**370**	DP25B-E, DP41-E, DP460-E
0 to 10	0 to 2.49	**PX653-10D5V**	**370**	DP25B-E, DP41-E, DP3002-E
0 to 25	0 to 6.23	**PX653-25D5V**	**370**	DP25B-E, DP41-E, DP460-E
0 to 50	0 to 12.5	**PX653-50D5V**	**370**	DP25B-E, DP41-E, DP460-E
BIDIRECTIONAL RANGES				
±0.1	25	**PX653-0.1BD5V**	**$430**	DP25B-E, DP41-E, DP460-E
±0.25	62	**PX653-0.25BD5V**	**400**	DP25B-E, DP41-E, DP460-E
±0.50	125	**PX653-0.5BD5V**	**370**	DP25B-E, DP41-E, DP460-E
±1	249	**PX653-01BD5V**	**370**	DP25B-E, DP41-E, DP460-E
±2.5	623	**PX653-2.5BD5V**	**370**	DP25B-E, DP41-E, DP460-E
±5	1.25	**PX653-05BD5V**	**370**	DP25B-E, DP41-E, DP460-E
±10	2.49	**PX653-10BD5V**	**370**	DP25B-E, DP41-E, DP460-E
±25	6.23	**PX653-25BD5V**	**370**	DP25B-E, DP41-E, DP460-E
±50	12.5	**PX653-50BD5V**	**370**	DP25B-E, DP41-E, DP460-E

Comes with complete operator's manual. ** See section D for compatible meters.*

Ordering Example: PX653-01D5V, *high-accuracy, low-pressure transducer with a 0 to 1 inH_2O range,* ***$370.***

ACCESSORY

MODEL NO.	PRICE	DESCRIPTION
OP-17	**$15**	Reference Book: Measure for Measure

Figure B.7 Omega Engineering Differential Pressure Transducer

SPECIFICATION

Series TFXL

DESCRIPTION	SPECIFICATION
Liquid Types	Most clean liquids or liquids containing moderate amounts of suspended solids or aeration.
Power Requirements	11-30 VDC @ 0.25A
Velocity	0.1 to 40 FPS (0.03 to 12.4 MPS)
Inputs/Outputs	**4-20mA Output (standard output)** Resolution: 12-bit for all outputs Power: Source Insertion loss: 5V maximum Loop impedance: 900 Ohms maximum Isolation: Can share ground common with power supply — isolated from piping system **Turbine Frequency Output/TTL -Pulse Output** Switch selectable Type: Non-ground referenced AC / Ground referenced square wave Amplitude: 500mVpp minimum / 5VDC Frequency range: 0-1,000Hz Duty cycle: 50% ±10%
Display	Type: 2 line x 8 character LCD; Top row: 0.7" (18 mm) tall, 7-segment; Bottom row: 0.35" (9 mm) tall, 14-segment Rate: 8 maximum rate digits, lead zero blanking Total: 8 maximum totalizer digits, exponential multipliers from –1 to +6
Units	Engineering Units: Feet, gallons, ft^3, million-gal, barrels (liquor & oil), acre-feet, lbs, meters, m^3, liters, million-liters, kg Rate Units: Second, minute, hour, day
Ambient Temperature	General Purpose: 0 to +185 °F (-20 to +85 °C); Hazardous Locations: 0 to +105 °F (-20 to +40 °C)
Liquid Temperature	0 to +185 °F (-20 to +85 °C), Integral Mount and DTTS -40 to +300 °F (-40 to +121 °C), DTTN
Enclosure	NEMA 3 (Type 3) ABS or polycarbonate, PVC, Ultem®, brass or SS hardware, 3W x 6L x 2.5H inches (75W x 150L x 63L mm), pipe mount
Transducer Type	Clamp-on, uses time of flight ultrasonic
Pipe Sizes	1/2-inch (12 mm) and higher
Pipe Materials	Carbon steel, stainless steel, copper, and plastic
Accuracy	±1% of reading at rates above 1 FPS (0.3 MPS); ±0.01 FPS (.003 MPS) of reading at rates lower than 1 FPS (0.3 MPS)
Response Time	0.3 to 30 seconds, adjustable
Protection	Reverse-polarity, surge suppression
Approvals	**Integral System and DTTS Transducer** General Requirements: ANSI/ISA 82.02.01; Class 1 Div 2 Groups C & D Hazardous Locations: CSA C22.2 No 213, E79-15-95, Class 1 Div 2, Groups C & D (DTFXL3 & DTFXL4 models only) **DTTN Transducer** General Requirements: Ordinary Area Class I Div 2, Groups C & D C22.2 No. 142; UL 916 Hazardous Locations: Intrinsically Safe Option Class I Div 1, Groups C & D CSA C22.2 No. 157; UL 913: 2002
UltraLink™ Utility	Windows® based software utility, requires serial communication cable Windows® 95, 98, 2000, and XP compatible

Figure B.8 Dynasonics TFXL Ultrasonic Clamp-On Flow Meter

The Flocat LA10-A Series of volumetric gas flow meters uses two of the best-studied physical properties of gases to measure flow: Pressure and Viscosity. Differential pressure measurement across a laminar flow element results in a flow meter that is inherently linear. Flocat LA10-A flow meters measure within the laminar region to achieve turndowns of 100:1 typically. A very wide range of measurement, 0.5 milliliter per minute full-scale to 1000 liters per minute full-scale, is standard. Unique laminar flow elements, along with modern electronics, ensure that each differential pressure flow meter from the Flocat LA10-A Series is both affordable and accurate.

Differential pressure flow meters from the Flocat LA10-A Series are simple, rugged devices. The membrane switch user interface and dynamically labeled graphic display combine to provide exceedingly flexible and user-friendly operation. The Flocat LA10-A Series can have several screen "modes" depending on how the device is ordered.

The Flocat LA10-A volumetric flow meters are intended for use in low pressure applications. This is because an accurate measurement of the volumetric flow rate by means of differential pressure requires the flow at the differential pressure sensor to be in a laminar state.

Operating Limits

- Pressure: 125 PSIG Max
- Temperature: 0 to 50°C (operating)

Specifications

- Accuracy: ±1% FS
- Repeatability: ±0.5% FS
- Turndown Ratio: 100:1
- Response Time: 10 ms
- Pressure Drop FS: 0.4 PSI
- Operating Temperature: 0 to +50°C
- Zero Shift*: 0.02% FS/°C/atm
- Span Shift*: 0.02% FS/°C/atm
- Excess Flow Rate: 2.4% FS
- Pressure: 125 PSIG Max
- Supply Voltage: 7-30 VDC
- Supply Current: 30mA
- Output: 0-5 VDC, 0-10 VDC, 4-20 mA
- Wetted Surfaces: 303 & 302 SS, Viton, silicone RTV, glass reinforced nylon
- Connections: NPT (F)
- Media: Air, Argon, Nitrogen, Oxygen, Hydrogen, Helium, Carbon Dioxide, Methane, Propane, Carbon Monoxide, Ethane, Nitrous Oxide, Neon**, Nitric Oxide

Figure B.9 FloCat Volumetric Gas Flow Meter

PCI PARAGON CONTROLS INCORPORATED

FE-1000 Technical Specifications

1. **Accuracy**
   Within 2% of actual flow (even in moderately turbulent flows) with approach angle variation of ±20°, when installed in accordance with published recommendations

2. **Operating Velocity Range**
   100 to 10,000 fpm

3. **Material**
   6063-T5 anodized aluminum (standard)
   Type 316L stainless steel (optional)
   Hastelloy C22 (optional)
   Type 1 PVC (optional)
   Note
   Other corrosive resistant materials are available. Consult factory for further information.

4. **Temperature**
   Aluminum Elements
   350°F continuous operation (in air)
   400°F intermittent operation (in air)
   Stainless Steel Elements
   1600°F continuous or intermittent operation (in air)
   Hastelloy Elements
   900°F continuous or intermittent operation (in air)
   PVC Elements
   120°F continuous operation and 170°F intermittent operation (in air)
   Note: Corrosive resistant element maximum operating temperatures vary greatly with the concentration of the media in the process stream. Consult factory for further information.

5. **Humidity**
   All Elements
   0 to 100% non condensing

6. **Corrosion Resistance**
   Aluminum Elements
   Good salt, air, and mild acid gas resistance; excellent solvent and aromatic hydrocarbon resistance
   Stainless Steel Elements
   Good for sulfates, phosphates and other salts, as well as reducing acids such as sulphurous and phosphoric
   Hastelloy Elements
   Excellent resistance to strong oxidizers such as ferric and cupric chlorides, chlorine, formic and acetic acids, acetic anhydride, and salts.
   PVC Elements
   Excellent acid and alkalis resistance

7. **Instrument Connections**
   Aluminum Elements
   ¼" compression, suitable for use with thermoplastic or copper tubing; thermoplastic tubing requires the use of tubing inserts, which are supplied with the fittings
   Stainless Steel and Hastelloy Elements
   1/8-27 Female NPT
   PVC Elements
   1/8-27 Female NPT

FE-1000 Resistance to Airflow

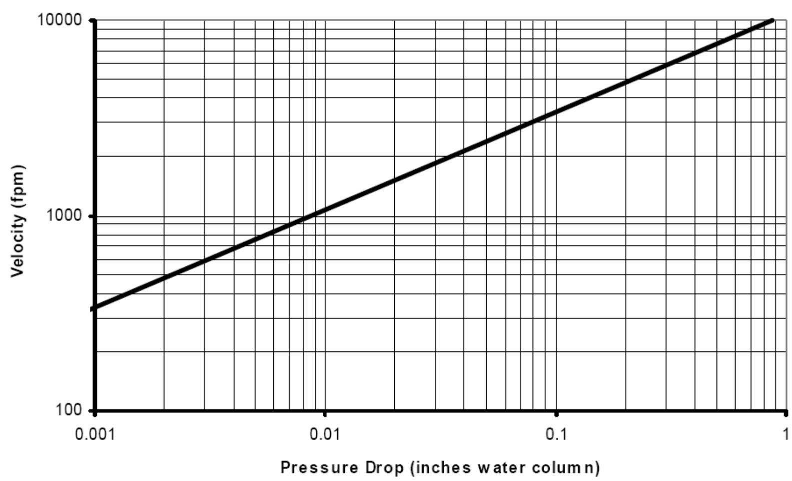


Figure B.10 Paragon Controls FE-1000 Sensing Element Specifications

PCI PARAGON CONTROLS INCORPORATED

Engineering Reference Table

VELOCITY VERSUS VELOCITY PRESSURE

V = VELOCITY IN FEET PER MINUTE P_V = VELOCITY PRESSURE IN INCHES H_2O

V	P_V	V	P_V	V	P_V	V	P_V	V	P_V	V	P_V	V	P_V	V	P_V
180	0.0020	620	0.0240	1060	0.0701	1500	0.1403	1940	0.2346	2760	0.4749	3640	0.8260	5300	1.7512
190	0.0023	630	0.0247	1070	0.0714	1510	0.1422	1950	0.2371	2780	0.4818	3660	0.8351	5350	1.7844
200	0.0025	640	0.0255	1080	0.0727	1520	0.1440	1960	0.2395	2800	0.4888	3680	0.8443	5400	1.8180
210	0.0027	650	0.0263	1090	0.0741	1530	0.1459	1970	0.2420	2820	0.4958	3700	0.8535	5450	1.8518
220	0.0030	660	0.0272	1100	0.0754	1540	0.1479	1980	0.2444	2840	0.5028	3720	0.8627	5500	1.8859
230	0.0033	670	0.0280	1110	0.0768	1550	0.1498	1990	0.2469	2860	0.5099	3740	0.8720	5550	1.9204
240	0.0036	680	0.0288	1120	0.0782	1560	0.1517	2000	0.2494	2880	0.5171	3760	0.8814	5600	1.9551
250	0.0039	690	0.0297	1130	0.0796	1570	0.1537	2020	0.2544	2900	0.5243	3780	0.8908	5650	1.9902
260	0.0042	700	0.0305	1140	0.0810	1580	0.1556	2040	0.2595	2920	0.5316	3800	0.9002	5700	2.0256
270	0.0045	710	0.0314	1150	0.0825	1590	0.1576	2060	0.2646	2940	0.5389	3820	0.9097	5750	2.0613
280	0.0049	720	0.0323	1160	0.0839	1600	0.1596	2080	0.2697	2960	0.5462	3840	0.9193	5800	2.0973
290	0.0052	730	0.0332	1170	0.0853	1610	0.1616	2100	0.2749	2980	0.5536	3860	0.9289	5850	2.1336
300	0.0056	740	0.0341	1180	0.0868	1620	0.1636	2120	0.2802	3000	0.5611	3880	0.9386	5900	2.1702
310	0.0060	750	0.0351	1190	0.0883	1630	0.1656	2140	0.2855	3020	0.5686	3900	0.9483	5950	2.2071
320	0.0064	760	0.0360	1200	0.0898	1640	0.1677	2160	0.2909	3040	0.5762	3920	0.9580	6000	2.2444
330	0.0068	770	0.0370	1210	0.0913	1650	0.1697	2180	0.2963	3060	0.5838	3940	0.9678	6050	2.2819
340	0.0072	780	0.0379	1220	0.0928	1660	0.1718	2200	0.3017	3080	0.5914	3960	0.9777	6100	2.3198
350	0.0076	790	0.0389	1230	0.0943	1670	0.1739	2220	0.3073	3100	0.5991	3980	0.9876	6150	2.3580
360	0.0081	800	0.0399	1240	0.0959	1680	0.1760	2240	0.3128	3120	0.6069	4000	0.9975	6200	2.3965
370	0.0085	810	0.0409	1250	0.0974	1690	0.1781	2260	0.3184	3140	0.6147	4050	1.0226	6250	2.4353
380	0.0090	820	0.0419	1260	0.0990	1700	0.1802	2280	0.3241	3160	0.6225	4100	1.0480	6300	2.4744
390	0.0095	830	0.0429	1270	0.1006	1710	0.1823	2300	0.3298	3180	0.6304	4150	1.0737	6350	2.5139
400	0.0100	840	0.0440	1280	0.1021	1720	0.1844	2320	0.3356	3200	0.6384	4200	1.0997	6400	2.5536
410	0.0105	850	0.0450	1290	0.1037	1730	0.1866	2340	0.3414	3220	0.6464	4250	1.1261	6450	2.5937
420	0.0110	860	0.0461	1300	0.1054	1740	0.1888	2360	0.3472	3240	0.6545	4300	1.1527	6500	2.6340
430	0.0115	870	0.0472	1310	0.1070	1750	0.1909	2380	0.3531	3260	0.6626	4350	1.1797	6550	2.6747
440	0.0121	880	0.0483	1320	0.1086	1760	0.1931	2400	0.3591	3280	0.6707	4400	1.2070	6600	2.7157
450	0.0126	890	0.0494	1330	0.1103	1770	0.1953	2420	0.3651	3300	0.6789	4450	1.2346	6650	2.7570
460	0.0132	900	0.0505	1340	0.1119	1780	0.1975	2440	0.3712	3320	0.6872	4500	1.2625	6700	2.7986
470	0.0138	910	0.0516	1350	0.1136	1790	0.1998	2460	0.3773	3340	0.6955	4550	1.2907	6750	2.8406
480	0.0144	920	0.0528	1360	0.1153	1800	0.2020	2480	0.3834	3360	0.7038	4600	1.3192	6800	2.8828
490	0.0150	930	0.0539	1370	0.1170	1810	0.2042	2500	0.3897	3380	0.7122	4650	1.3480	6850	2.9253
500	0.0156	940	0.0551	1380	0.1187	1820	0.2065	2520	0.3959	3400	0.7207	4700	1.3772	6900	2.9682
510	0.0162	950	0.0563	1390	0.1205	1830	0.2088	2540	0.4022	3420	0.7292	4750	1.4066	7000	3.0549
520	0.0169	960	0.0575	1400	0.1222	1840	0.2111	2560	0.4086	3440	0.7378	4800	1.4364	7100	3.1428
530	0.0175	970	0.0587	1410	0.1239	1850	0.2134	2580	0.4150	3460	0.7464	4850	1.4665	7200	3.2319
540	0.0182	980	0.0599	1420	0.1257	1860	0.2157	2600	0.4214	3480	0.7550	4900	1.4969	7300	3.3223
550	0.0189	990	0.0611	1430	0.1275	1870	0.2180	2620	0.4280	3500	0.7637	4950	1.5276	7400	3.4140
560	0.0196	1000	0.0623	1440	0.1293	1880	0.2203	2640	0.4345	3520	0.7725	5000	1.5586	7500	3.5069
570	0.0203	1010	0.0636	1450	0.1311	1890	0.2227	2660	0.4411	3540	0.7813	5050	1.5899	7600	3.6010
580	0.0210	1020	0.0649	1460	0.1329	1900	0.2251	2680	0.4478	3560	0.7901	5100	1.6216	7700	3.6964
590	0.0217	1030	0.0661	1470	0.1347	1910	0.2274	2700	0.4545	3580	0.7990	5150	1.6535	7800	3.7930
600	0.0224	1040	0.0674	1480	0.1366	1920	0.2298	2720	0.4612	3600	0.8080	5200	1.6858	7900	3.8909
610	0.0232	1050	0.0687	1490	0.1384	1930	0.2322	2740	0.4681	3620	0.8170	5250	1.7184	8000	3.9900

Above P_V Values Are Based On Standard Air Density Of 0.075 lbm/ft^3 Which Is Air At 68°F, 50% Relative Humidity, And 29.92" Hg.
The equation for converting air volume (Q) into velocity (V) and velocity pressure (P_V) is:

$$V = \frac{Q}{A} \qquad P_V = \left(\frac{V}{C}\right)^2 \times \rho$$

Where:
V = Velocity, in fpm
Q = Flow, in cfm
A = Area, in ft^2
C = 1096.7
ρ = Density of air, in lb/ft^3
P_V = Velocity pressure, in inches H_2O

Figure B.11 Paragon Controls FE-1000 Sensing Element Flow Table