Pumping Demonstration: The Control of Closed Loop Systems

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Abstract

The pumping system demonstration that was constructed displays closed loop pumping systems. It models a pumping arrangement found in a large building's heating, ventilating, and air conditioning (HVAC) system. Controlling flow rates efficiently in large systems is a common problem. Maximum capacity is rarely needed; when unnecessary, the flow must be slowed or otherwise regulated. This system allowed for testing different means of controlling flow rates. Through experimentation, measurements of flow rate, pressure, and power usage were taken for various methods of control. From this, it became clear that the use of variable frequency drives was the most efficient way to control the system's flow rates. This result was then generalized: in pumping systems the use of variable frequency drives to maintain constant pressure across the load provides for the most efficient means of operation.

Introduction

Closed pumping systems are used in the HVAC system of a building to control the flow of hot and cold water. Flow is increased when more heating/cooling is needed and is reduced when less heating/cooling is needed. With large buildings, large pumping systems are required. These pumping systems can require a large amount of energy to operate. Consequently, increased efficiency of system control can correlate to a large savings in energy. There is cost saving as well.

The pumping demonstration that was assembled models a portion of a closed loop system that would be found in a HVAC system. This demonstration allowed for the exploration of various means to control system flow. Measurements were taken to determine the most efficient method by which system flow could be controlled. Methods examined included: a throttling (choke) valve being turned to reduce flow rates; the use of an variable frequency drive keeping a set-point pressure constant across the system's pump; and the use of an variable frequency drive keeping a set-point pressure constant across the system's load.

Prior to this experimentation, it was known that the use of a variable frequency drive with pressure across the load being kept constant should provide for the most efficient means of controlling flow rates. The experiment sought to verify this and also provide a means to quantify the advantages of variable speed drives. With the demonstration that was built (a pumping system on a very small scale compared to that of a large building's system) it was hoped that enough energy savings could be measured with variable speed drive control to demonstrate its effectiveness.

To achieve these results, many problems needed to be understood and overcome. First, the pumping system required design and fabrication. Second, the system needed to have sensors for pressure, flow, and power consumption accurately placed in proper locations. With both of these tasks, it was important that the system be left flexible enough so that it could easily be adapted for different types of control. Third, system operation and pump curves needed to be established. To achieve this, the manufacturer's pump curves required verification and a maximum efficiency curve for the system needed to be determined. Finally, different means of controlling flow rates had to be measured and compared to the system's highest theoretical efficiency.

Methodology

System Design

Even though the system was very small with respect to the size of an actual HVAC system, it was complex nonetheless. Many different sections of piping were put in place to provide for different demonstrations, including the closed loop control that this project focused on. Consequently, many components were used in the completed pumping system.

The system was assembled in the Training Laboratory at Danfoss Graham in Milwaukee. There was limited space for the system as well, the design had significant size constraints. Also, due to the multitude of equipment donated to the project, many different diameters of PVC piping were required. Hence, the design included many adaptors. The pump, flow, and pressure transducers had inlet and outlet piping requirements to provide for a more laminar flow as well. Apart from such logistical considerations, the design had to be functional not only for my project but also for future uses of the project by Danfoss Graham (these are briefly discussed in Appendix E).

With such considerations in mind, the pumping system was designed. The design allows for a variety of demonstrations and lab experiments to be performed. In the heating/cooling closed loop demo, different means of controlling flow in a secondary pumping system can be compared in terms of power usage and efficiency. The pressure boost system demonstrates open loop pumping systems and allows the ability of drives to provide for more efficiency to be shown.

In addition to the demonstrations that the system was designed for, extra valves and a drain system were built in. The extra valves can be used to represent longer piping runs, a larger load, etc. The drain system was required to prevent things from growing in stagnant water if the system was left full.

This design was then implemented, leading to the creation of a complete system. Due to thorough planning, the construction of the demonstration went smoothly.

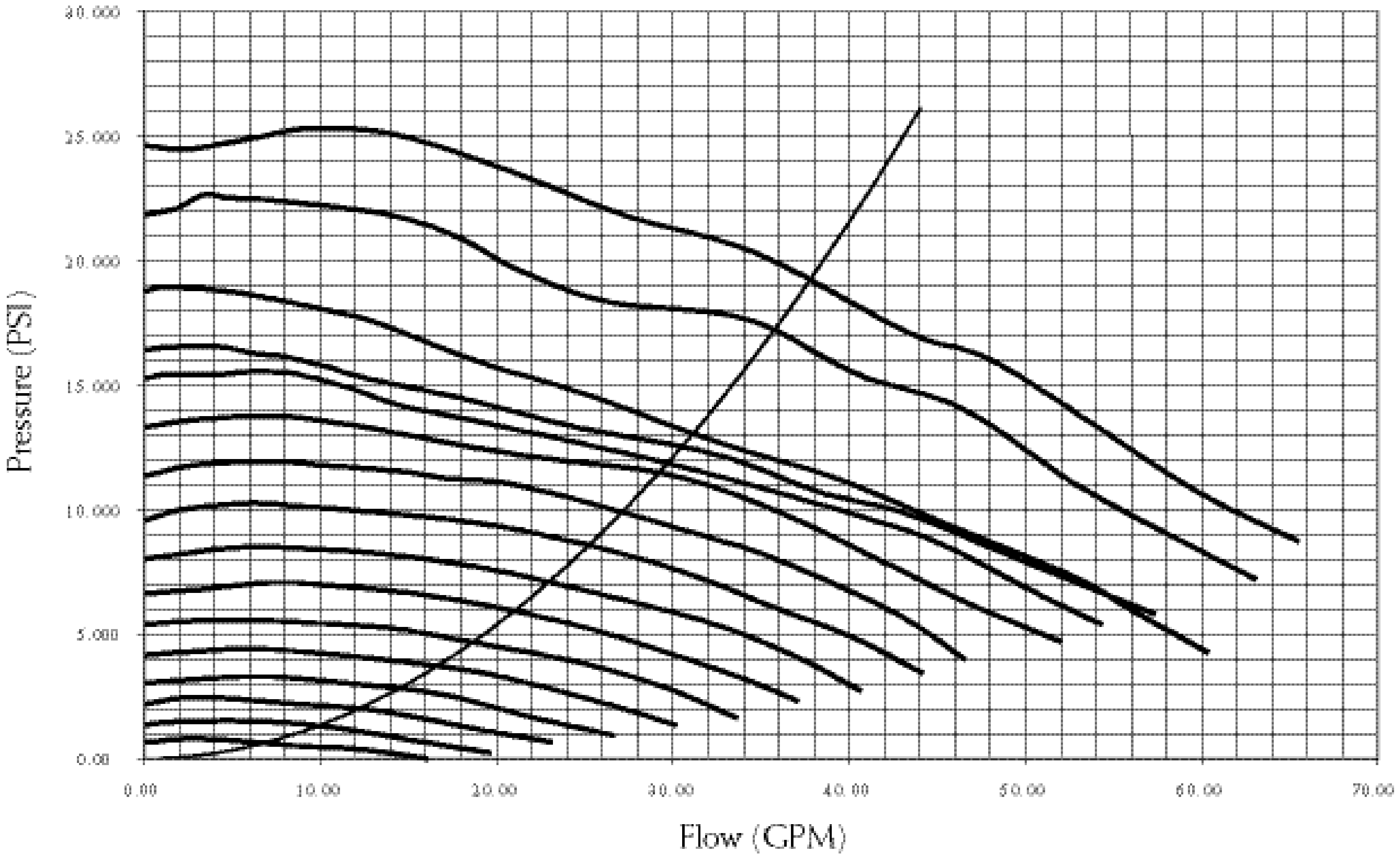
Experimentation

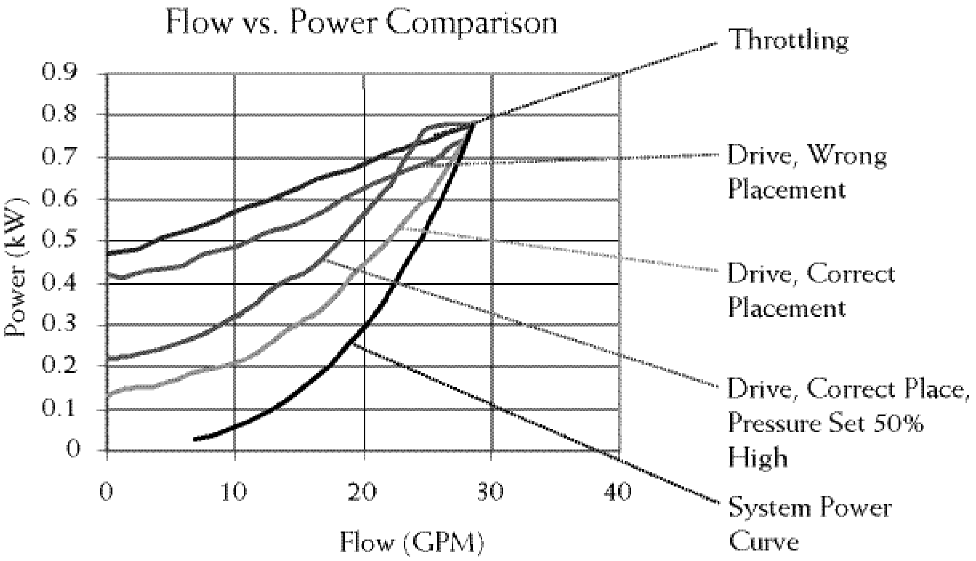
From this design, the closed loop experiments could be performed. For the various tests that were run, sensors required different positioning and different setups were required. These tests will be discussed here, while the results will be discussed later.

The first experiment that was performed was the determination of pump curves. These curves, which were created with the pump running at a set percentage of its maximum speed, plot pressure across the pump vs. flow rates. The pump was run at maximum speed with all valves open. At regular intervals flow was constricted (about 5 GPM less each trial) and pressure, flow, and power were measured. The pump was slowed until very few data points could be generated and flows were rather low, occurring at 25% of the maximum pump speed. From this data, pump curves could be plotted. Efficiency was also calculated at each flow rate. The points of maximum efficiency were noted, since these points are the ideal conditions that the pump should be operating at to achieve maximum power savings. Ideally, the system should be designed to allow for running near this maximum efficiency curve. In Appendix B, a sampling of the data from the pump curve experimentation is presented.

The second experiment involved finding the most efficient means to control flow in this pumping system. Four tests were conducted. In each test, flow, pressure, and power consumption were measured. First, a throttling system was simulated, where flow is reduced by closing down on a gate valve. Second, a drive was used with the pressure sensor across the pump, the wrong place to measure pressure. Placing the sensor here ignores that the pressure loss that occurs in the piping is dependant upon system flow rates. No matter the flow, in this placement the pump will still produce the needed pressure to satisfy the load at full flow conditions, when the maximum amount of pressure is lost in the piping. Hence, the drive doesn’t take advantage of the variable pressure losses in the piping, leading to inefficiencies. Third, a drive was used with the pressure sensor placed across the load – the correct placement. Finally, a drive was used with the pressure sensor in the correct position, but the drive was set at a pressure 50% higher than what would be required to fulfill the needs of the load.

Experimental Pump Curves with
Best-Fit Max Efficiency Curve





Flow vs. Power Comparison
Power (kW)
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
10
20
30
40
Flow (GPM)
Throttling
Drive, Wrong Placement
Drive, Correct Placement
Drive, Correct Place, Pressure Set 50% High
System Power Curve

Results

As the previous plot of power vs. flow for the different control methods indicates, the most efficient method of control of those tested is a variable frequency drive with the pressure sensor correctly applied. This verified the results that were expected with the experiment.

The energy savings of a correctly applied drive were calculated. From this, the payback time was determined, assuming that the two options were throttling control and the drive. The control system includes that was used for this includes: a VLT 6000 Drive with fuses and a MAMAC Pressure Sensor. The drive list price is $1,410, the sensor is $875. However, a customer commonly pays, at most, half of the list price. This totals the system cost at $1,143. This is the same control system that was used in the experimentation.

The calculations for the energy savings can be seen in Appendix D. In short, the energy savings of the drive control system will recoup the money invested in the drive in 4.4 years.

The power savings over time could easily justify the purchase of adjustable frequency drives. In many ways, this conclusion was surprising. The pumping system built was not very large and yet the drive could save enough power in a short enough period of time to justify its application. A larger system, such as an HVAC system of an industrial building, would even provide a more attractive payback since the price per horsepower of the drive drops and the price of the sensor would become less significant. Also, with a larger system the energy savings will be a higher net amount as well, leading to higher net monetary savings as well.

Appendix A: System Components and Acknowledgements

This project was of great interest in large part because of the many different pieces of equipment that were required, and that I would otherwise have been unable to use. I would like to thank the various people and companies that helped make the project a success.

Pump:

- ITT Bell and Gossett, Model 1536, _ HP, 3450 RPM, 2 7/8” trimmed impeller. Donated by Mike Hultgren of Bornquest Incorporated.

Flow Meters:

- Onicon Flow Sensor, Model F-1111. Donated by Bowen Ierna of Onicon Incorporated. The model is a single turbine insertion flow meter. The error is _____of actual flow.
- Danfoss Magflow Flowmeter, Model MAG 5000. Donated by Johnnie Jensen of Danfoss Water and Wastewater. This works on a principle of electromagnetic wave distortion in fluid flows. The flow meter error is ___.5% of actual flow.

Pressure Sensors:

- MAMAC Systems Pressure sensors. Two different styles were used: Model PR-264, a single point sensor, and Model PR-282, a differential pressure sensor. Supplied by Danfoss Graham.
- Danfoss Pressure Transmitter, MBS 3000. Two of these were used in the system. Donated by Johnnie Jensen of Danfoss Water and Wastewater.

Power Analyzer:

- Fluke 41B Power Harmonics Analyzer. Used for more accurate power measurements than the VLT Drive could provide. Supplied and setup by Ken Fonstad of Danfoss Graham.

Thermometer:

- Radio Shack Digital High-Low Thermometer. Supplied by Ken Fonstad of Danfoss Graham.

Variable Speed Drives:

- Danfoss VLT 6002. Two of these drives were employed. The drives were supplied, setup, VLT Software Dialog installed (software for PC control), and a control box from Ken Fonstad of Danfoss Graham.

Electrically Actuated Valve:

- Hawley and Company Limited, DuroTRON Division, Model D2S-1. Donated by Mark Chudecke of Climate Sales.

Heat Exchanger Coil:

- Donated by Mark Chudecke of Climate Sales.

PVC Piping and Related Components:

Note: A wide variety of pipe diameters were used because the donated equipment required a numerous different diameters of piping to connect up to. Adaptors between different pipe sizes were only used when necessary.

All PVC piping stock materials were supplied by Ken Fonstad of Danfoss Graham.

3" Diameter Piping: 10' section of pipe.

2" Diameter Piping: 10' section of pipe, 3 solvent unions, 1 T, 2 threading adaptors.

1 _" Diameter Piping: 10' section of pipe, 1 solvent union, 1 threading adaptor.

1.25" Diameter Piping: 10' section of pipe, 1 solvent union, 1 threading adaptor.

1" Diameter Piping: 4 10' sections of pipe, 2 elbows, 3 solvent unions, 2 Ts, 4 threading adaptors, 4 valves

_" Diameter Piping: 10' section of pipe, 2 couples, 6 elbows, 4 solvent unions, 4 Ts, 2 threading adaptors, 5 valves.

Adaptors: 3" diameter to 1 _" diameter. 2" diameter to _" diameter. 2" diameter to 1.5" diameter. 2" diameter to 1" diameter. 1 _" diameter to _" diameter. 1 _" diameter to 1" diameter. Two 1" diameter to _" diameter.

1" Diameter Flanges: 2.

_" Diameter Spigot: 1.

_" Diameter Garden Hose Valve: 1.

1/8" Diameter Brass Fittings: 3 couples, 2 elbows with connectors, 7 needle valves.

Brass Adaptors: 2 _" diameter to 1/8" diameter.

Container of Pipe Cleaner and Cement: 1 each.

Leak Sealant: 1 tube.

Appendix B: A Sampling of Pump Curve Data

Pump Speed (percent of 80 Hz)	Flow (GPM)	Pressure (PSI)	Power (kW)	Efficiency
100%	65.48	8.720	1.10	0.226
100%	59.19	10.96	1.05	0.269
100%	48.49	15.84	0.96	0.348
100%	43.41	17.09	0.94	0.344
100%	34.72	20.30	0.83	0.370

100%	27.22	21.83	0.76	0.340
100%	20.57	23.64	0.68	0.311
100%	14.47	25.03	0.62	0.254
100%	9.496	25.30	0.56	0.187
100%	5.987	24.89	0.52	0.125
100%	2.543	24.46	0.49	0.055
100%	0.000	24.61	0.46	0

Speed	Flow	Pressure	Power	Efficiency
95%	63.08	7.202	0.94	0.210
95%	53.34	10.82	0.89	0.282
95%	46.51	14.02	0.82	0.346
95%	40.52	15.42	0.78	0.349
95%	34.16	17.65	0.73	0.359
95%	26.38	18.34	0.65	0.324
95%	21.41	19.57	0.61	0.299
95%	17.67	20.99	0.57	0.283
95%	13.85	21.83	0.53	0.248
95%	7.638	22.39	0.47	0.158
95%	4.741	22.52	0.44	0.106
95%	3.440	22.66	0.43	0.079
95%	1.841	22.10	0.41	0.043
95%	0.000	21.82	0.41	0

Readings were taken at pump speeds ranging from 100% of 80 Hz down to 25% of 80 Hz. Speeds were decreased by 5% for each experiment.

Efficiency was determined in this manner: Efficiency = Power Out / Power In. 1 kW = 2297 gal/min*lb/in^2, a conversion factor. Hence: Efficiency = (PSI)(GPM) / (KW)(2297).

Due to space limitations in this report, a complete list of pump curve data could not be supplied.

Appendix C: Data Relating to Various Methods of Control

Throttling Valve (Choke Valve)

Speed (% of 80 Hz)	Flow (GPM)	Pressure (PSI)	Power (kW)	Efficiency
100%	28.54	21.69	0.78	0.345
100%	27.02	22.25	0.76	0.344
100%	25.84	22.66	0.75	0.340
100%	23.76	22.81	0.73	0.323
100%	21.16	23.08	0.70	0.304
100%	19.05	23.50	0.67	0.291
100%	16.42	23.92	0.65	0.263
100%	14.21	24.20	0.62	0.241
100%	12.75	24.34	0.60	0.225

100%	10.84	24.62	0.58	0.200
100%	8.573	24.76	0.55	0.168
100%	6.498	24.76	0.53	0.132
100%	4.414	24.64	0.51	0.093
100%	2.037	24.48	0.48	0.045
100%	0.000	24.18	0.47	0

Drive with pressure control across pump (wrong place) (pressure is kept constant, set at 21.69 psi – the correct amount of pressure across pump to supply the load at the maximum flow rate)

Speed (% of 80 Hz)	Flow (GPM)	Pressure (PSI)	Power (KW)	Efficiency
98%	28.33	21.69	0.75	0.357
98%	26.97	21.69	0.73	0.349
97%	25.82	21.69	0.70	0.348
96%	23.51	21.69	0.67	0.331
96%	20.91	21.69	0.64	0.309
95%	18.31	21.69	0.60	0.288
94%	15.54	21.69	0.55	0.267
93%	12.31	21.69	0.52	0.224
92%	10.11	21.69	0.49	0.195
92%	7.665	21.69	0.47	0.154
93%	5.406	21.69	0.44	0.116
93%	3.051	21.69	0.43	0.067
93%	1.181	21.69	0.41	0.027
95%	0.000	21.69	0.42	0

Drive with pressure control across main load (correct place) (pressure is kept constant, set at 8.6 psi -- measured from full flow)

Speed (% of 80 Hz)	Flow (GPM)	Pressure (PSI)	Power (KW)	Efficiency
100%	28.71	8.6	0.79	0.136
93%	25.68	8.6	0.63	0.153
88%	23.29	8.6	0.55	0.158
84%	21.55	8.6	0.49	0.165
79%	19.23	8.6	0.42	0.171
75%	16.70	8.6	0.334	0.187
71%	14.19	8.6	0.289	0.184
68%	11.72	8.6	0.232	0.189
65%	9.474	8.6	0.205	0.173
64%	7.589	8.6	0.192	0.148
62%	5.383	8.6	0.169	0.119
61%	3.554	8.6	0.154	0.086
61%	1.276	8.6	0.150	0.032
60%	0.000	8.6	0.131	0

Drive with pressure control across main load (correct place) (pressure is kept constant, se 12.9 psi -- 50% too high)

Speed (% of 80 Hz)	Flow (GPM)	Pressure (PSI)	Power (KW)
100%	28.74	8.740	0.78
100%	26.72	10.82	0.78
100%	24.57	12.9	0.76
96%	22.63	12.9	0.66
92%	20.49	12.9	0.58
89%	18.19	12.9	0.50
81%	15.63	12.9	0.43
81%	13.83	12.9	0.401
78%	10.91	12.9	0.334
76%	8.742	12.9	0.298
74%	6.696	12.9	0.270
73%	4.172	12.9	0.242
73%	1.463	12.9	0.222
73%	0.000	12.9	0.220

Appendix D: Energy Savings Calculations

Cost of Electricity	$0.10	/kW-hr

			Throttling Valve		Variable Speed	
hours/year	Flow (%)	Flow (gpm)	Power (kW)	Energy (kW-hr)	Power (kW)	Energy (kW-hr)
0	100%	28.0	0.78	----	0.78	----
263	90%	25.2	0.74	195	0.62	163
788	80%	22.4	0.71	559	0.53	418
1840	70%	19.6	0.67	1,233	0.43	791
2015	60%	16.8	0.65	1,310	0.32	645
2015	50%	14.0	0.61	1,229	0.29	584
1402	40%	11.2	0.59	827	0.24	336
438	30%	8.4	0.55	241	0.19	83
		Total:		5,594		3,021

Energy Savings Analysis		
Throttling Valve:	5,594	kW-hr
Variable Speed:	3,021	kW-hr
Energy Savings:	2,573	kW-hr
Cost Savings:	$257.31	
Drive Cost:	$1,143.00	
Payback:	4.4	years

Note: The duty cycle (number of hours per year that the system will be operating at a given flow), comes from a common approximation used in the HVAC industry.

Appendix E: Other Uses of the Pumping Demonstration System

As was alluded to previously, this pumping demonstration has the capability for other experimentation. Some of these possibilities will be briefly described.

The open loop part of the system, modeling pressure boost applications, has a pressure sensor mounted to it. With this, a similar experiment of determining the most efficient means to control flow through the open loop system can be performed. Again, the use of a variable frequency drive should provide for optimal control.

The closed loop system also has a bypass loop built into it. Diverting flow through a bypass loop is another way in which system flow can be controlled. This wasn’t included in this experiment primarily due to difficulties in the operation of the second flow transducer (a second flow transducer is required to determine how much water flows through the bypass as opposed to how much went through the load). Since this project was completed, the problems associated with the flow transducer have been corrected and the entirety of the closed loop system is operational.

Appendix F: Pictures

Since this project can't be seen in person, it can be difficult to envision. Consequently, a few pictures are being presented to assist in the understanding of the project.

The Heating/Cooling Demo loop slowly takes shape.