Pump Efficiency Solutions

Pump Sequencing Optimization

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Abstract

The purpose of this document is to demonstrate the design, production, and testing of optimum pump sequencing logic for variable frequency drive (VFD) pumps in commercial heating ventilating and air conditioning (HVAC) systems. The product will be developed by Pump Efficiency Solutions (PES), which is a group of Cal Poly students working on their senior project. The product is being developed for Trane, an industry leader in large scale HVAC systems. MATLAB™, Microsoft Excel, Pump System Improvement Modeling Tool™ (PSIM), and fluid mechanics hand calculations were used during software development. Next, we converted the program into Trane's graphical programming language (TGP) and applied these algorithms to a MP580 Controller.

There were three separate phases to the project. The phases, each lasting one quarter, can be designated as conceptualizing, modeling, and programming. During the design conceptualizing PES gathered information on commercial HVAC systems and VFD pumps which can be implemented into these systems. We then modeled a simple system using PSIM and developed a series of optimization algorithms within excel to optimize the quantity of the pumps for a given system load (flow-rate) and pressure requirements. The completion of the model represented the end of the conceptualizing phase and beginning of the modeling phase.

For the second phase of the project, we took the analysis from Excel and used it to develop a general algorithm which can be applied to a variety of different systems. Essentially, it incorporates pump curves for the specific pumps selected for a system and calculates the theoretical best number of pumps to run for maximum system energy efficiency at a given load. This algorithm can be adaptable to any system and will be incorporated into Trane's pre-existing system control software. The program will have permanent inputs based on the components and geometry of the system in addition to dynamic inputs that define the current operating conditions due to a transient load. The outputs of the program will be number of pumps that should run in order to match the load and minimize power consumption.

In the programming phase, we translated our MATLAB™ program into a series TGP files to make the algorithms compatible with the controller. To simulate changes in system head and flow rate, we connected two potentiometers to the controller. Both MATLAB™ code and MP580 controller simulation successfully calculated the optimum number of pumps to operate given any system inputs within a standard operating range.

Introduction

First off, let us introduce ourselves as Pump Efficiency Solutions. We are a group of three Cal Poly M.E. students who are working together on our senior project. During this yearlong project, we studied pump sequencing and optimization as specified by Trane and our university, California Polytechnic State University San Luis Obispo (Cal Poly). Our names are John Allan, Kyle Nekimken, and Spencer Weills.

Formal Problem Definition

The project entails developing a set of algorithms which will maximize efficiency in building cooling systems. This will be done by optimizing the pumping system for a given load (flow-rate and pressure) on the water side of an industrial HVAC system. Our end goal is to deliver a set of algorithms which will be easily applied to multiple buildings by field technicians.

The major stakeholders are Trane, ourselves, and Cal Poly. Trane, because they will invest time and resources into the project and in turn will receive a practical and functional deliverable. We consider ourselves stakeholders because aside from being graded on our performance, our reputations are dependent on the success of this project. Of course Cal Poly has a vested interest because they will not only contribute resources to the project, but they want to see their students succeed and help the university's reputation as one of the leading undergraduate engineering universities in the country.

Objectives

The main objective of this project is to deliver a user friendly, self explanatory, and practical program to Trane that meets all of the specifications defined in our QFD (Appendix A). These objectives come from the engineering specifications which are the parameters that need to be met in accordance with our customer's requirements.

The program's main objective is to take, as an input, characteristics of an existing or proposed HVAC system, including pumps, piping system specifications, and minimum flow and pressure requirements. The program's algorithms use the required load with given system parameters to control the number of operating pumps to meet the required flow rate and operating pressures through the system. Variable frequency drive (VFD) motors can run at an effectively infinite number of frequency denominations, and it is assumed that all pumps in the system are driven by VFD's. Each of these frequencies produces a different pump curve, which corresponds to a different operating point. The program dynamically scales the pump curves to maintain the optimum running frequency for the system's pumps. Additionally, the program accounts for frictional losses based on the piping and geometric parameters as defined by the Darcy-Weisbach equation (Figure 5).

The output delivered by the program specifies the number of pumps needed to achieve the lowest power input while still meeting the flow rate and operating pressure requirements. In a system with multiple pumps, this is accomplished by optimizing the sequencing of the pumps in such a way as to

keep each pump closest to its best efficiency point thus lowering the input power to each pump. The outputs of the program are simply the number of pumps that should be operating the pumps' frequency. The program must be flexible enough to allow for process variation due to different pump types which may have significantly different shaped operating curves as well as a wide variety of detailed variable inputs due to particular pump or chiller characteristics and orientations. If the best way to optimize a given system is to add an additional pump, then the program should be able to determine the effect of the new pump. The program must also clearly specify the required input variables

The program (or associated documentation) must clearly and completely demonstrate the physical principles upon which the program relies. The program should be able to produce dynamic performance curves and clear, useful, results as the number of pumps, the system load, and operating pressure requirements change. Any assumptions inherent to the calculations must be stated. Any background information that the user may need should be listed as well.

The program must easily interface with Building Automation Systems (BAS), which is Trane's user interface program. A technician should be able to look at a graphical building design, easily input the variables into the program, and get results back without any difficulty. For this to be possible, the program must be easily navigable and the input process must follow a logical path. Further, the results produced must be provided in a clear and concise manner to avoid confusion.

Though industrial HVAC systems involve a significant amount of thermal analysis, our project is more focused on the water side of the system (more specifically the pumps). Thus we are not focusing on the heat transfer occurring in the system. Instead we are concentrating more on the fluid-dynamics side of system modeling and defining our water side load as the flow rate required by the overall system to deliver proper flow rate.

Project Management Plan

The project can be divided into four main sections: researching, modeling, programming, and implementation. Although the project is a collaborative effort, each group member had specific tasks he coordinated. Background research was shared equally between all three members since it was important for everyone to have an understanding of chilled water systems. Additionally, writing and editing reports was a collaborative effort. For the remaining tasks, Kyle Nekimken was in charge of the modeling segment, Spencer Weills oversaw programming, and John Allan coordinated the implementation. For each subsystem, the leader acted like the project manager while the other two members were supporting engineers helping to implement each task. Our preliminary schedules, including deadlines for our deliverables, are in Appendix E in the form of Gantt Charts.

Background

In this day and age of limited energy resources, the need and demand for improved efficiency in industrial HVAC systems is growing exponentially since these systems account for a large fraction of total energy usage. In the United States, our total annual energy consumption was approximately 100 quads (10^{15} BTU) in 2006 according to the U.S. Department of Energy. Of this energy, 40% was consumed by buildings with about 1/3 of this powering the HVAC system. This brings the energy to around 13 quads. Within HVAC systems, about 40% of this energy is spent on pumping. This means that about 5×10^{15} BTU of energy is spent solely to run HVAC pumps. Therefore any improvements in pump system efficiency will have a significant on overall energy consumption. One of the most simple, but still intricate, ways to improve efficiency is through pump sequencing optimization.

Pump sequencing basically defines how many pumps should operate to achieve maximum energy efficiency, while still maintaining the desired system performance. As far as VFD pumping goes, this means pump sequencing and speed regulation. Since there are an infinite number of operating speeds, it is essential that the pump is managed such that the system is always at the most efficient level.

Current State of the Art

Designing a pump sequencing optimization method is something that has been addressed before. There are already a small number of black box systems and field programmed systems available for purchase from HVAC companies. However, none of these systems have verifiable evidence to support their claims of energy efficiency. The companies that do offer products only claim increased efficiency, but they do not offer any sort of documented evidence which illustrates how they make the system more efficient nor to what extent they are more efficient. Surprisingly enough, the HVAC industry as a whole has left the topic of our project very lightly explored. As energy efficiency has become even more important in light of the current energy crisis, more companies are looking for ways to improve their HVAC systems. In an industrial cooling system, pumps use a large fraction of the total energy expended, which further highlights the need for improved pumping controls.

We plan defined a set of adaptable algorithms to work for a variety of industrial cold water systems. To accomplish this, we first researched pump systems and then came up with a set of algorithms based on pump efficiency curves and governing equations. The scope of our project does not include the chiller operation, heat transfer optimization, or any airside components of HVAC systems.

Types of Systems

The industry has significant experience with Primary-Secondary chilled water systems. These chilled water systems are arranged using two loops as illustrated in Figure 1 below. The primary loop contains chillers which are sequenced on and off as the load rises and falls. When a chiller is operating, it is provided with a constant chilled water flow (gpm) regardless of the required cooling load (tons).

The secondary loop has separate pumps which only provide enough pressure to induce the required flow though the distribution system, cooling coil, control valves and other system accessories. In a

properly operating variable flow secondary system the flow (gpm) varies infinitely and is directly related to the system load (tons) requirement. In most systems, the secondary or “distribution” pumps are installed in a manifold configuration. For a given system fluid flow and pressure requirement, it may be possible to operate one, two, three, or N pumps to meet the system load. The operation of this type of system is the focus of this project.

The interconnection of the two loops features a “by-pass” or “decoupler’ line. The purpose of the decoupler is to hydraulically isolate the operation of the primary and secondary loops. Since the decoupler is simply an open pipe, it allows the flow and pressures in each loop to act completely independently. The Primary-Secondary system was developed to provide for significant system pumping energy saving versus an all constant flow distribution system. Its flexibility, efficiency and robust operating characteristics make it a popular system configuration.

As true of any system with a Primary-Secondary configuration, there are operating conditions that cause wasted energy. When the building’s cooling load is small, the chiller receives water that is pre-cooled from the excess water passing through the decoupling pipe. The chiller unloads efficiently as its return water temperature drops, which is not a source of inefficiency. However, the excess water that is cooled and short circuited though the by-pass pipe does no useful work. Elimination of by-pass flow would reduce the total pumping energy required by the system.

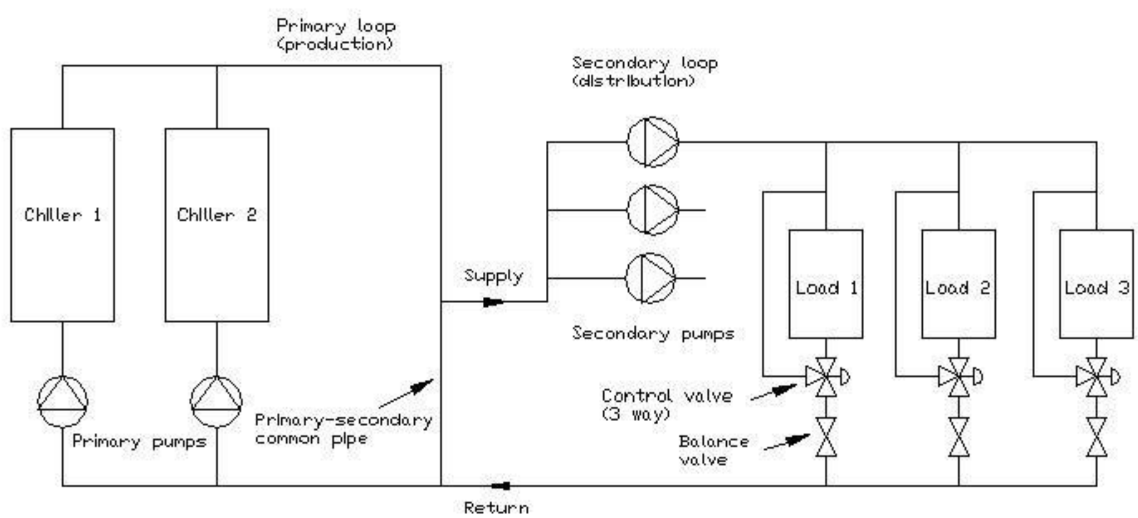

Figure 1. Primary-Secondary System

Variable-Primary Flow pumping systems may provide a significant advantage over Primary-Secondary systems by reducing energy requirements. This is due to the elimination of the dedicated chiller pumps and the associated decoupler pipe flow.

The key operational difference between Primary-Secondary and Variable Primary Flow systems is that in a VPF system, the flow is not only infinitely varied though the distribution loads, but it is also varied

within limits though the chillers. This provides pumping energy savings since the excess by-pass flow is eliminated at many loads. By-Pass flow is still required at some part load conditions to ensure that the flow does not drop below the chiller's minimum allowed flow, which results in laminar flow and therefore reduced heat transfer. The pumps in a Variable-Primary Flow system are often configured and operated exactly like the distribution pumps in a Primary-Secondary system. The final outcome of this project will be directly applicable to this system's pumping configuration.

Modeling

Reading through several of Trane's chiller design documents, we have gained a reasonable understanding of chilled water cooling systems. In particular we have concentrated our research on the implementation of VFD pumps within systems. We have studied three different ways to control VFD pumps: at a constant pressure differential, a constant flow rate, and a variable flow rate. In HVAC applications, it is most common to use variable flow arrangements because it allows for frequent fluctuations in the system load. By sequencing the pumps and regulating pump speed, a HVAC system can achieve lower energy consumption.

The model serves two purposes: to further our comprehension of chilled water systems and to aid us in determining the necessary parameters to measure when sequencing the pumps. In choosing these parameters, we will emphasize the simplicity of instrumentation and taking measurements. Providing a simple method for collecting data meets our objective to create a user friendly program.

Additionally, the model will help us identify ways to optimize energy efficiency. We will calculate system energy consumption and cooling capacity that corresponds to the optimal pump sequence. This model will provide a starting point for programming the sequencing code, but we will continue to modify the model as our project moves forward.

Requirements

In a closed loop pumping system, the pump manifold must produce a sufficient amount of pressure to maintain circulation. This pressure needs to overcome frictional losses in the system due to piping, fittings, and a variety of valves. Thus, the pumps must generate a specific pressure drop across the pump headers based on operating conditions. Control valves at each air handler determine the chilled water flow rate according to the cooling requirement. For example, when cooling demand is low, the control valves close thus reducing the flow rate. Likewise, the required pumping pressure decreases with cooling demand. This variability in operating conditions results in an infinite number of possible operating points for the pump manifold.

Unlike a simple linear system, a system with multiple control valves will not have a single system curve to designate the possible operating points. Instead, there is an area containing the set of operating points that can occur. To determine the boundaries of this area, we eliminated operating points that cannot occur. First, we calculated the system's maximum level (when all the control valves are completely open). Conversely, when there are no control valves the minimum flow rate and head occur. In between these points the boundary of the system is based on which part of the building requires chilled water. Cooling loads at the far end of the system define the upper boundary while loads near the pumps create the lower boundary as shown in Figure 2. The figure does not intersect the origin due to the frictional losses in the piping that will be present even when the flow rate is zero or minimal through the airside components.

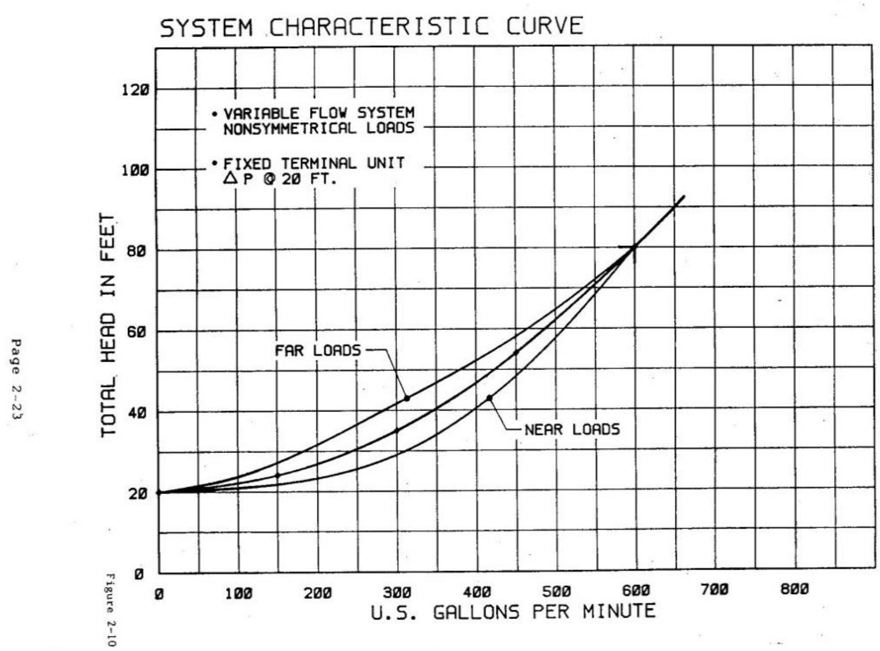

Figure 2. Representation of the system area for a variable flow system from ASHRAE

Although there will be a definitive pressure differential across the pump headers, this is not equivalent to the actual pump head. Since there are losses between the pump headers due to strainers, valves, and pipe connections, the pumps must produce a slightly greater head to achieve the desired system pressure. The magnitude of the losses is directly related to the system's flow rate. These losses should be taken into consideration when determining the optimal pump sequence. By dividing the flow to more pumps, each portion of the pumping manifold receives less flow rate thus lowering frictional losses, but the fluid flow must then pass through more components. We will take this into consideration when determining if it is beneficial to turn on an additional pump.

For our model we developed a simple two pump cooling system. Along with the pumps, this system included piping and the evaporator component of the chiller. We modeled the head losses across the system for different flow rates in order to develop a system curve. The system curve represents the pressure loss across the pumps for a given range of flow rates. From this system curve we can identify the flow and pressure that the pumps must be able to provide for the system load.

We then modeled the pump side of the system and developed a series of pump curves. These were based on the 60Hz pump specifications from the manufacturer. The curves showed the head that the pumps provide under different given loads (flow-rates). We next modified the curves for different frequencies from 60Hz to10Hz.

Based on the system and pump curves, our model then needed to find the number of operating pumps in order to minimize power consumption for a given loading condition.

Conceptualization

A model system used for a simple analysis is given below. The system consists of two parallel pumps supplying flow to two parallel chillers as shown in Figure 3. A Peerless 8AE20 17 inch pump (Figure 4) was chosen since its pump curve best matches the system characteristics. Having two pumps in parallel allows for relative the same head production to occur at twice the flow rate compared to using one pump. Given the pump curve, the system losses are determined as follows. Calculate the piping losses as modeled by the Darcy-Weisbach equation in Figure 5. Add head loss due to the evaporator from the specification sheet provided by the manufacturer (Figure 6). Lastly, we approximated the heat exchangers as dropping approximately 10 ft. of head each at design flow and assumed the change in elevation is negligible since it is a closed system. From these parameters we obtained a performance curve for the system by calculating the head loss across each system component at the design flow rate.

This simple system is modeled at only a single flow rate to give a clear example of the analysis that goes into obtaining performance curves. The chosen design flow rate in this system is 5000 GPM, or 2500 GPM through each pump and chiller. In our program, as the flow rate in the system changes due to demand, the system and pump curves will change dynamically to achieve the best possible efficiency. Graphing this system curve with the pump curve, we can obtain the performance graph displayed in Figure 7. The point at which the two curves intersect is the operating point.

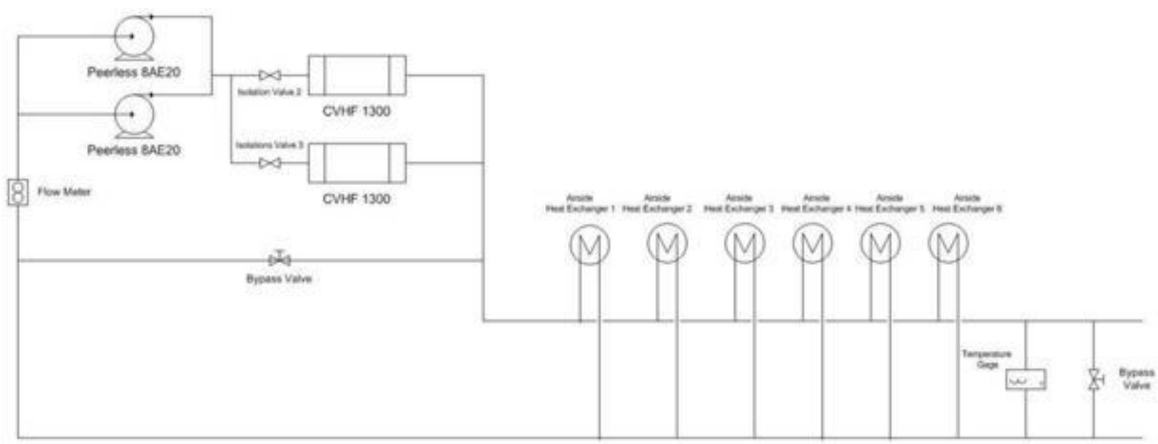

Figure 2. Variable Flow System Model

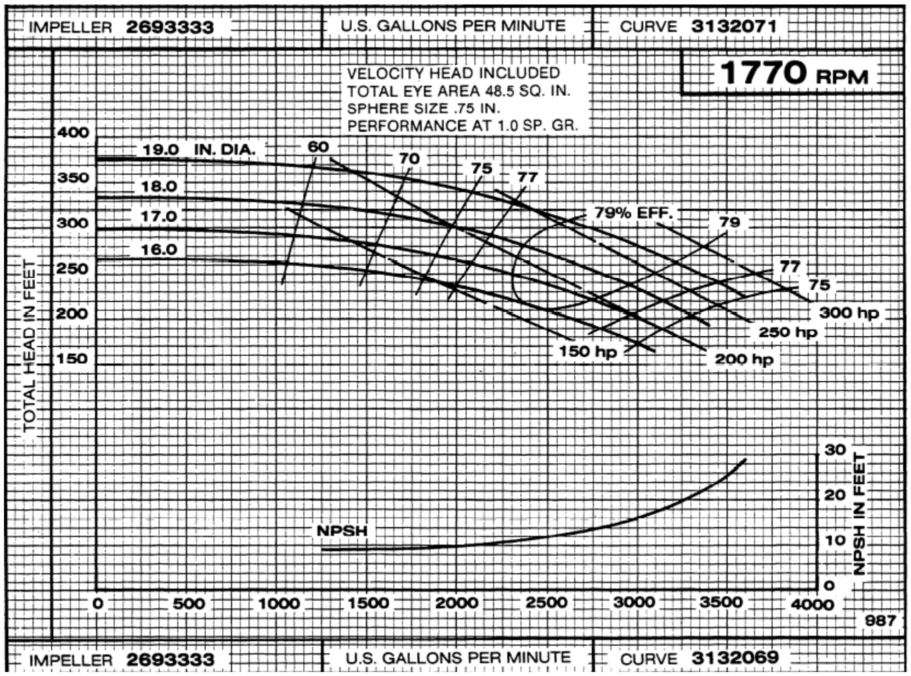

Figure 3. Peerless 8AE20 17" Pump Curve

$$h_{l_{total}} = \sum h_l + \sum h_{l_m} + \sum f \frac{L}{D}\frac{V^2}{2} + \sum \left(f \frac{L_e}{D}\frac{V^2}{2} + K\frac{V^2}{2} \right)$$

Figure 4. Darcy-Weisbach Equation

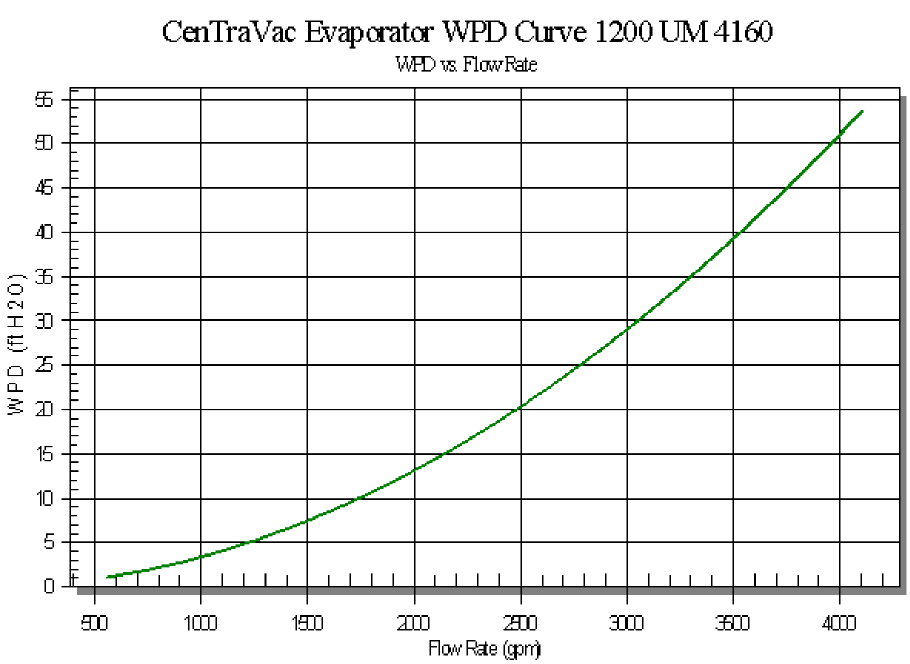

Figure 5. CVHF Evaporator Head Loss Curve

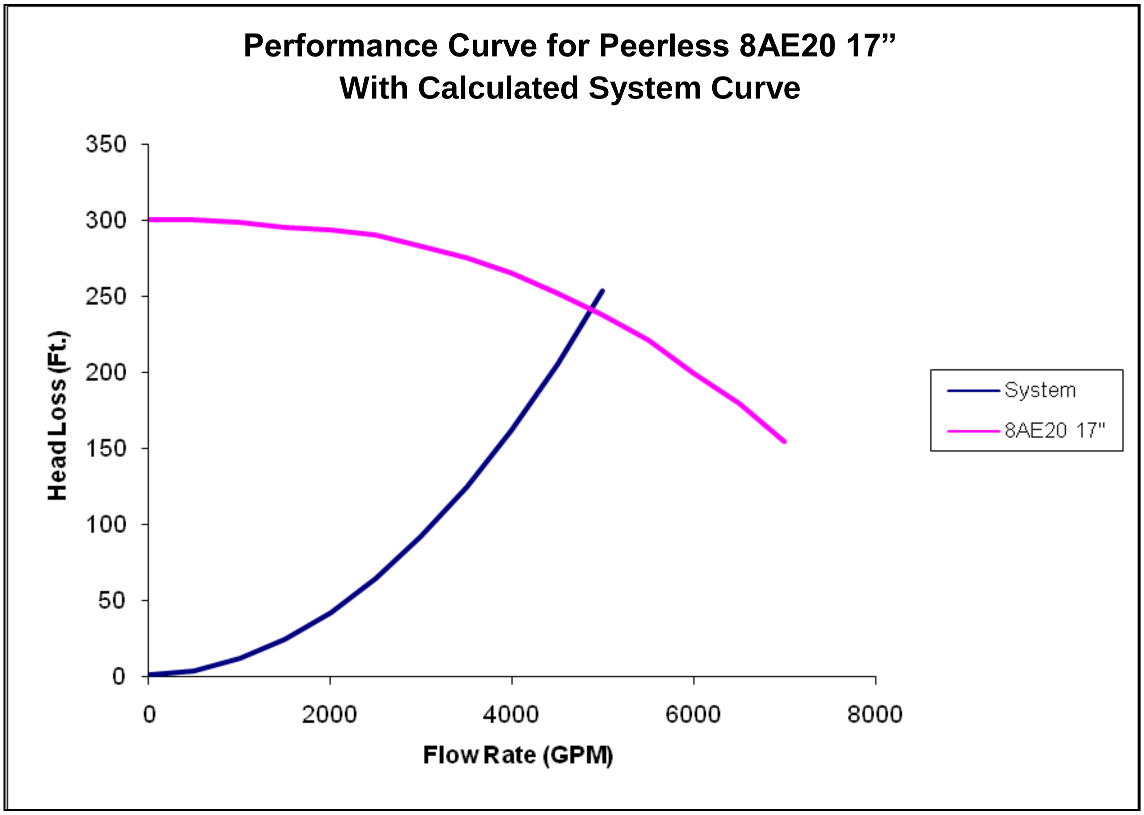

Figure 6. Performance Curve for Two Parallel Pump System

Verification of Model

To look at the flow through this system, we used the Pump System Improvement Modeling Tool (PSIM) which is a free software tool and an industry standard for pump system optimization. This program is useful because it allows the user to incorporate VFD pumps into the model. We used this model to find the pump energy required to deliver a specific amount of flow to the fan coil. We developed a variable flow system using PSIM that includes two chillers, two VFD pumps, several piping connections, and a general component that represents the load as shown in Figure 8 below. This software tool was used to model the same simple system as above so that we can confirm our results. This simulation is shown below.

To generate the system curve, PSIM requires user inputs to specify the head loss at different flow rates. The following specifications were selected according to the hypothetical system analyzed earlier in this section. We entered the head loss caused by the chiller using data from Trane for the CenTraVac Evaporator (Figure 6). Data for the pumps were obtained from pump curves in the Peerless Pump catalog (Figure 7). We decided to use 8 in. steel pipes throughout the system based on the expected maximum flow rate in the system. To model the fan coils, we assumed a head increase of 10 ft.

It is important to note that the resulting pump curve in Figure 9 matches very well with the pump curve developed using the simple pump system analysis (Figure 7). The purpose of this model is to show the system improvement associated with using VFD controls.

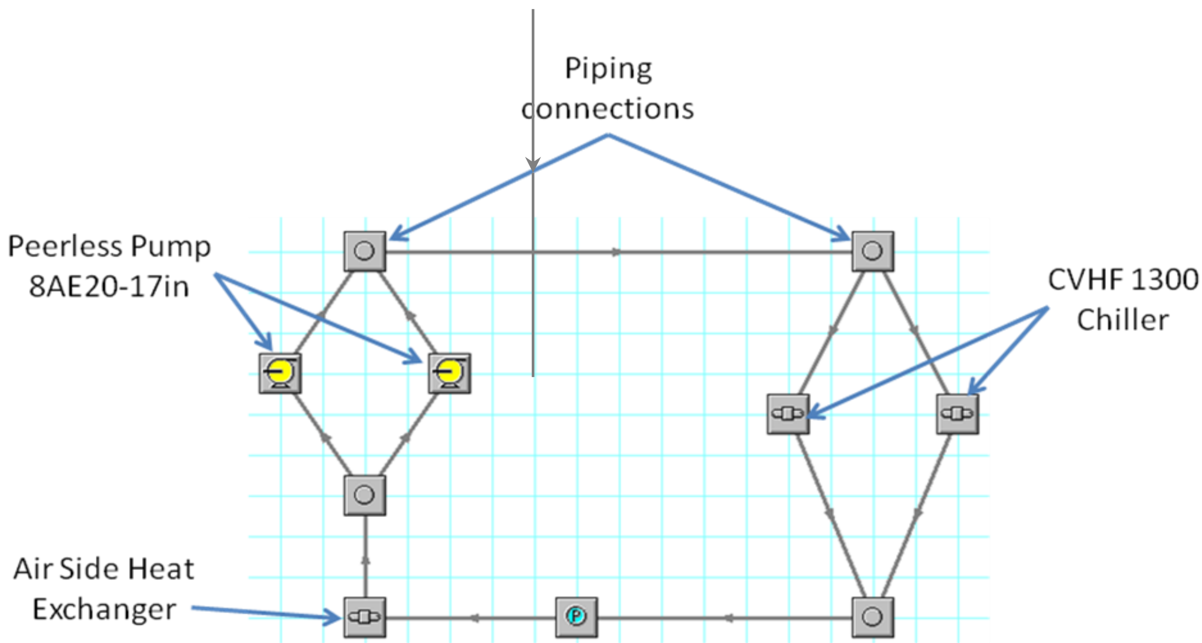

Figure 7. PSIM Model

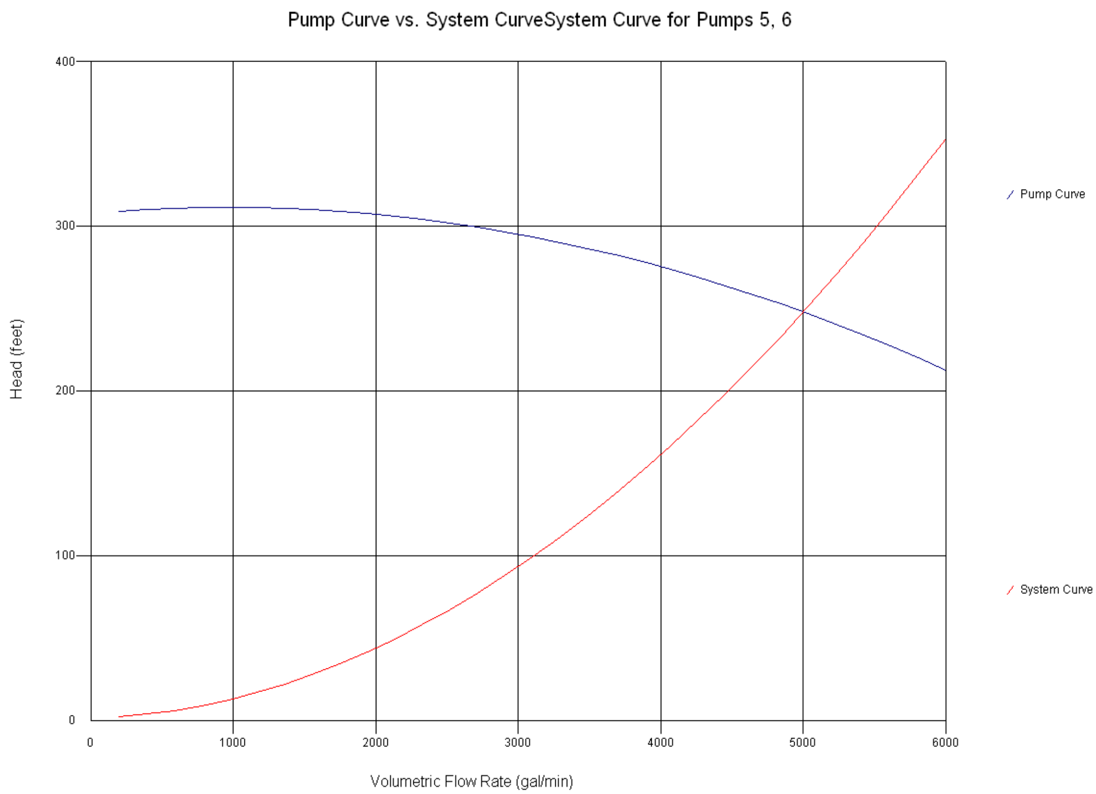

Figure 8. PSIM System and Pump Curves

Design Development

In creating our final product, we combined knowledge gained during modeling with fundamental principles from Fluid Mechanics. In this segment, we created a simple analysis in Microsoft Excel.

Program Overview

Currently, we have developed a set of algorithms to find the optimum number of pumps that should be running at any time based on the key system parameters chosen earlier. We started with a simple program containing three pumps. This program can be modified to accommodate a variety of applications with any number of pumps. Figure 10 below displays a simple flowchart which demonstrates how the program operates.

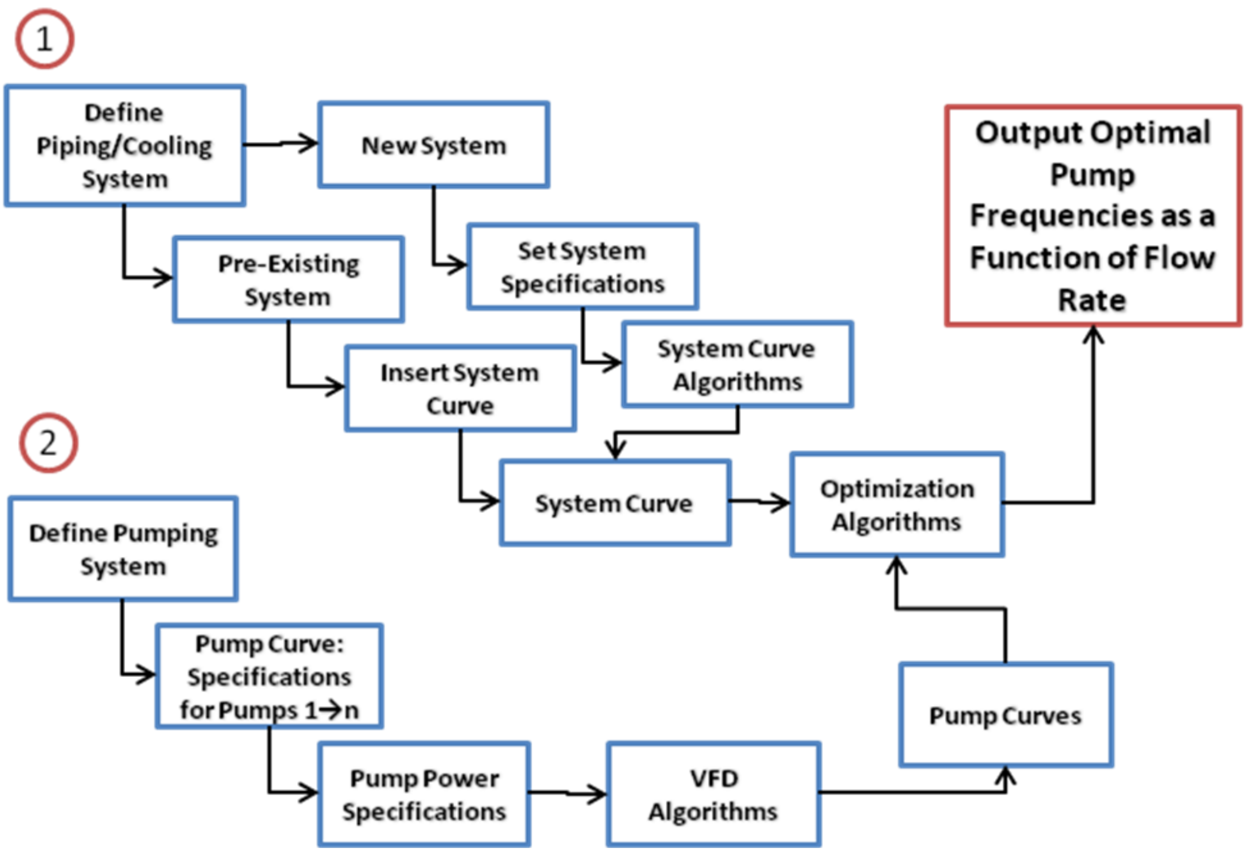

Figure 9. Program Flowchart

The two separate components represent the model from the system side and the pump side. Since it is necessary to optimize pumping to meet a particular system load, we initially generate the system curve through a series of user inputs. In reality, the behavior of an HVAC system is represented by an operating area, but this program is intended to be a simplified proof of concept. . For the 'Set System Specifications' section, the user will model the water side of the system using our excel program. This includes piping and component specifications, as a function of flow rate. The 'System Curve Algorithms' will calculate head loss across the pumps in the system as a function of the flow rate. I

Generating the second curve involves modeling the pumping portion of the system. When the user 'Defines the Pumping System' they will input the number of pumps and the manner in which they are connected (Series or Parallel). They will then be prompted to insert the 'Pump Curve Specifications' for each individual pump. The pump curve provided by the manufacturer shows the head generated as a function of flow-rate at the nominal frequency of 60Hz. The user must also input the 'Pump Power Specifications' from the manufacturer. The 'VFD Algorithms' will then develop a series of pump curves for frequencies from 30Hz-60Hz for each pump which plot head vs. flow rate in addition to the power consumed and efficiency for each point.

The 'Optimization Algorithms' then combine the pump curves and system curves. The algorithms solve for the most efficient operating frequency for each pump in order to match a load required by the system on the system curve. The final result is the number of pumps, and running frequency that provides the least power consumption as a function of system load (flow-rate).

In contrast to other pumping systems, closed circulation systems must only overcome losses due to friction. Since the pump constantly drives water through the system, elevation changes are not an issue. The system's losses relate directly to the flow rate in the system. For flow through pipe sections, losses due to friction depend on the pipe geometry, fluid properties, and flow regime. Our pipe losses were calculated using the Darcy-Weisbach Equation in Figure 5 and the equation below for friction factor. The equation in Figure 11 gives the head increase as a function of flow rate.

$$f = \frac{0.25}{\left[\log_{10}\left(\frac{\in}{3.7D} + \frac{5.74}{Re^{0.9}}\right)\right]^2}$$

Figure 10. Swamee-Jain equation for friction factor with turbulent flow

Additionally, we developed a system curve based on the specifications for the CenTraVac Evaporator using data from Trane (See Figure 6). Combining these curves results in an overall system curve that specifies the flow requirements the pump must meet.

For pump curve data, we used specifications from Peerless Pumps for the 17 in. 8AE20 pump at 1770rpm. After entering the head and power requirements for varying flow rates, we created a quadratic fit. Next, the head and power were calculated for frequencies from 60Hz-30Hz. According to the rules of similarity from fluid mechanics, as the frequency decreases, flow rate decreases proportionally. Similarly, the pump head decreases by the second power and power decreases by the third power. This demonstrates why optimal pump sequencing is essential since power is reduced with frequency by the third power.

The efficiency for each operating point was calculated using the following equation where Q is flow rate in GPM, head is in feet, and P_{in} is in HP.

$$\eta = \frac{\frac{QH}{3960}}{P_{in}}$$

Figure 11. Pump efficiency equation

Sample Analysis

An example of pump optimization is shown below. The purpose of this analysis was to develop the equations necessary for a more advanced system that operates on a system area as opposed to a system curve. We analyzed a system using our excel optimization program to demonstrate the energy savings possible by pump sequencing. This analysis used a simple system composed of one pump and one chiller as shown in Figure 13.

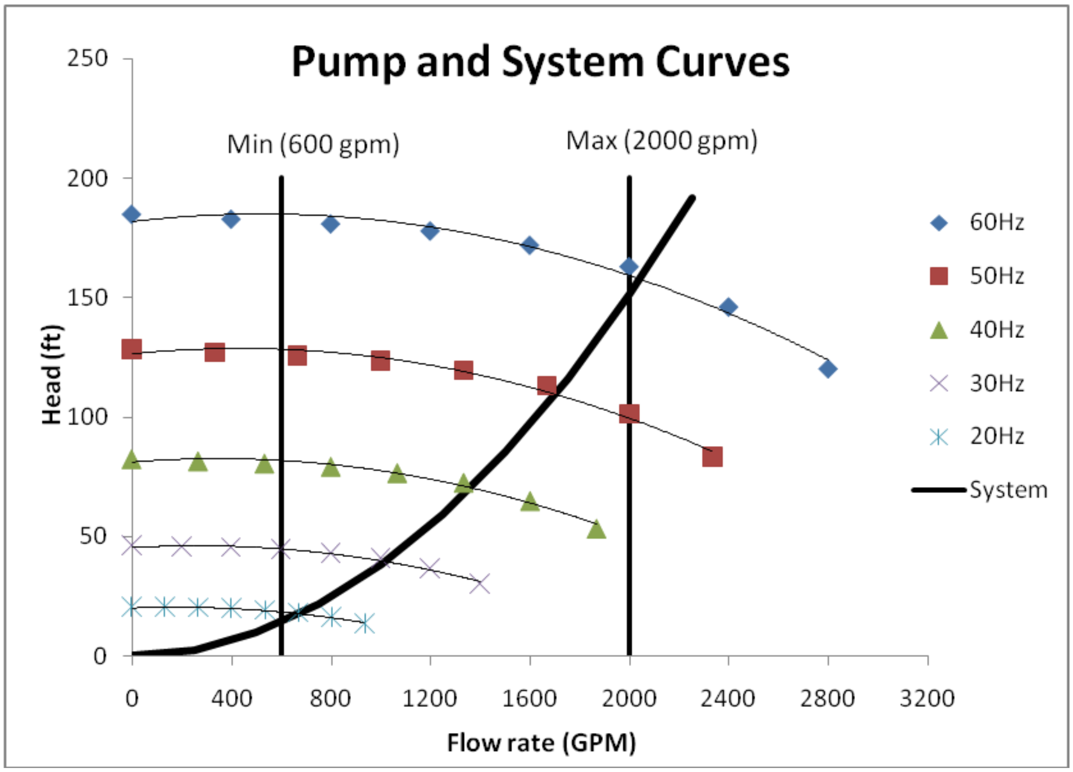

Figure 12. Sample Pump and System Curves

System	Flow rate (gpm)	600	1000	1200	1400	2000
	Head (ft)	15	40	58	79	160
Const. Speed	Frequency (Hz)	60	60	60	60	60
	Power Consumed (HP)	65	74	78	83	95

VFD	Frequency (Hz)	20	30	40	50	60
	Power Consumed (HP)	4	12	27	53	95

Table 1. Optimization results for a VFD pump compared to a constant speed pump.

Table 1 shows our preliminary optimization results in the form of power consumed as a function of flow rate. The VFD pump used approximately 50% less energy over the range of the load. This is a result of setting the frequency to meet the required load. Please note, for simplicity we used a pump that only ran at intervals of 10 Hz.

Final Design

Below is a description of how we put together our MATLAB™ algorithms. This section explains the key parts of our final produce. Also, it describes the process of converting our algorithms into Trane's graphical programming language.

Governing Pumping Equations

Based on the pump curves, we were able to generate pump curves in the form seen below with H corresponding to head, and Q corresponding to flow rate. We kept the units in H and Q in feet and GPM respectively. Data for the pump curves is taken directly from the manufacturer's pump curves.

$$H = aQ^2 + bQ + c$$

Then we generated polyfits based on the pump curves for energy consumption (E) and flow rate Q in units of horsepower, and GPM. This equation can be seen below.

$$E = a^{'}Q^2 + b^{'}Q + c'$$

For pumps with varying frequency (Hz), these equations will scale according to the pump similarity laws as seen below.

$$Q_{vfd} = \left(\frac{f}{60}\right)Q$$

$$H_{vfd} = \left(\frac{f}{60}\right)^2 H$$

$$E_{vfd} = \left(\frac{f}{60}\right)^3 E$$

We incorporated the similarity laws into the polynomial equations to create the primary governing equations.

$$\left(\frac{60}{f}\right)^2 H_{vfd} = a\left[\left(\frac{60}{f}\right)Q_{vfd}\right]^2 + b\left(\frac{60}{f}\right)Q_{vfd} + c$$

$$E_{vfd} = a'\left(\frac{f}{60}\right)Q_{vfd}^2 + b'\left(\frac{f}{60}\right)^2 Q_{vfd} + c'\left(\frac{f}{60}\right)^3$$

MATLAB™ Program

At the beginning of the program, the user specifies system parameters such as the number of installed pumps, pump and energy data from manufacturer, and the primary pipe diameter in the system. All these inputs will remain constant at a particular HVAC system and must only be entered once. Next, the program specifies the current operating conditions, which are measured in the system. We chose to use pressure differential across the pump header, current number of pumps in operation, and the running

frequency of these pumps as transient inputs. Each of these inputs can be measured inexpensively and reliably, which were the main deciding factors for selecting them. We determined measuring the system's flow rate was too unreliable to base our algorithms on this parameter. Instead, we back calculated the flow rate using the governing equations given above. In our code, the flow rate is calculated twice. The first time uses the pressure difference across the header while the second equation uses the change in pressure directly across each pump. The only difference between these calculations is the inclusion of minor losses between the header and each pump.

In the next part, we investigated every possible pumping sequence. The program assumes that all pumps are the same model and all operate at the same frequency, which ensures that the all pumps are as low as possible on the energy curve. We established limits on frequency and flow rate to avoid unattainable values. In our case, the options were running one pump, running two pumps, or running three pumps, but this will vary for different systems since the number of options equals the number of pumps available. For each possible case, we calculated the frequency and pumping power required to meet the current load. Comparing these results, we identified the option with lowest energy consumption.

MATLAB™ To Trane Graphical Programming (TGP)

The final goal of our project was to implement our algorithms within one of Trane's controllers. In order to implement our MATLAB™ code on Trane's MP580 controller, we had to translate the code we had written to Trane's proprietary software. Trane's software is a simple, logical, language that does not have the capability to perform many of the operations common to more in depth programming languages like MATLAB™. Because of this, we made some adaptations to allow our algorithms to be implemented on the controller. An illustration of the challenges faced in the transition is shown by the following two figures which represent the same equation to calculate the operating flow rate of a system written first in MATLAB™ and then in TGP.

```
Q_op = N_op*(-60*C(2)/f_op - (3600*C(2)^2/f_op^2 -...
    (4*3600*C(1)/f_op^2*(C(3)-3600/f_op^2*H_sys)))^.5)/(7200*C(1)/f_op^2);
```

Figure 13: Operating Flow Rate Calculation in MATLAB™ code

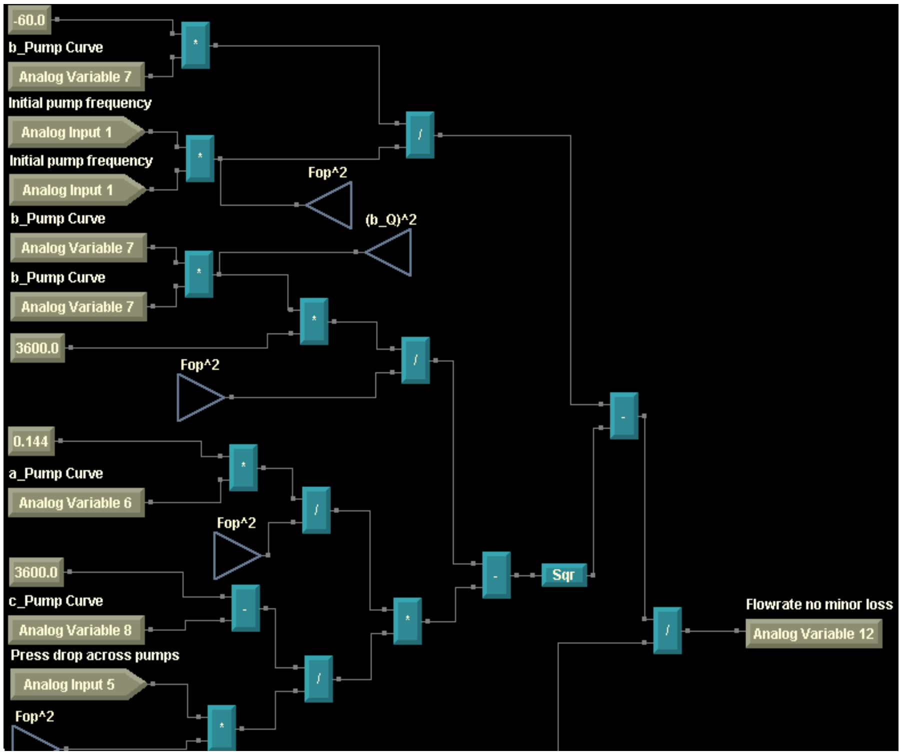

Figure 14: Operating Flow Rate in TGP (Partial Diagram)

In our MATLAB™ program, we used a loop to run energy usage calculations for one, two and three pumps and selected the optimum number of pumps for a given operating parameters. In order to implement this operation in the TGP code, we had to create a separate programs for each calculation and a forth to compare results of the first three.

Technician Implementation

In order for a technician to use our software in an existing system, it is necessary to provide the program with a description of the pumps it will be controlling. This is done by creating a curve fit line using data points from the manufacturer's pump curve. Below are instructions for this procedure:

1. Define eight to ten points along the length of the given pump and energy curves
2. Insert the coordinates of those into three columns of an excel file, flow rate (x-axis) in the first column, and the values of head and energy consumption that correspond to the chosen flow rate values.
3. Create a graph with the points. One series of Head vs. Flow Rate, and one of Energy vs. Flow Rate.
4. Using the "Add Trendline" function, add a second order polynomial fit trendline to both curves and check the "Display Equation on Chart" box on under the options menu.

5. The coefficients of these equations will define the Flow and Energy coefficients required for the controller programming. The equations are in the form

$$y = a\_Q \cdot x^2 + b\_Q \cdot x + c\_Q$$ (For the Head equation)

$$y = a\_E \cdot x^2 + b\_E \cdot x + c\_E$$ (For the Energy equation)

Note: For the "a" coefficients of both Head and Power, the program has a built in multiplying factor of 10^5 because the Trane program only allows a limited number of decimal points. When entering these values move the decimal to the right five spaces before entering in the TGP.

Program Design and Debugging

Integral in the design process is testing and verification. During the development of our TGP algorithms, we simultaneously compared the results to the MATLAB™ sequencing program. After completing our program, the last step is to apply our algorithm to a MP580 controller.

As we developed the programming algorithm we essentially incorporated the building and test phase into a single phase. This is because in order to continue building the algorithm into software we were progressively testing and debugging the software as we worked. The final result of this was software which was relatively simple to use, as well as being functionally tested throughout the writing process.

Conclusions

Using a variable frequency drive in an industrial HVAC system with proper pump sequencing provides significant energy savings. This procedure involves varying the number of pumps running in a system, as well as the frequency to dynamically optimize the energy usage as the cooling load increases or decreases. We first developed models using PSIM and Excel to demonstrate the potential savings associated with pump sequencing and to help develop the necessary algorithms. Our end goal was to develop a non-specific program that can calculate the optimum number of pumps that should be running for any given system characteristics. We completed this task in both MATLAB™ and Trane's graphical programming language. This program uses pump and energy curves, as shown in our implementation section, and is infinitely adjustable by changing the input frequencies to the motors. As the system pressure and flow rate requirements change, the program calculates the optimum frequency and number of pumps to be running in the system. The challenge of the program's algorithms was to control this pump sequencing in such a way as to maintain the lowest energy consumption as possible.

To optimize the energy efficiency of the entire system, chiller and air-side considerations need to be included. Our project defines the optimal pump sequencing based on flow rate requirements. Since pumps expend approximately 40% of the system's energy, addressing pump sequencing will have the greatest effect on overall efficiency. A follow up project would be to create an algorithm for sequencing chillers and incorporate heat transfer of the system though it would have a lesser effect on system efficiency.

Another important follow up is field testing of the algorithms. The algorithms work on a theoretical level, but we were unable to implement them into an actual control sequence for a large scale pumping system. To be completely certain of their effectiveness, it is critical to actually test the algorithms in the field and determine how effective they are.

The algorithms developed are capable of controlling up to three pumps in a HVAC system. With these algorithms, we hope that Trane will be able to achieve large gains in efficiency of their systems. This gives them an advantage in the HVAC industry as no standard currently exists for the sequencing of variable frequency pumps.

As Trane further develops their graphical programming language, these algorithms should become more useful. With the current version of TGP, the simple algorithms become overly complicated due to program limitations, but as Trane further develops the software the algorithms can be integrated more completely. Overall, the project was a great success, and we accomplished our goals of defining a general set of pump sequencing algorithms. These algorithms can be used for many systems with VFD pumps in parallel configurations and can optimize the sequencing of these pumps for maximum energy efficiency.

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Appendices

Appendix A: QFD

The QFD gives a graphical description of how we take the costumers requirements and translate them into engineering requirements. This method allows us to organize our engineering goals such that all of the costumers' requests will be fulfilled.

Pump Efficiency Solutions Costumers: Controls Technician, Controls Design Engineer, Lee Cline & Dale White	Customer Requirements	Engineering Requirements												Benchmarks		
		Weighting (1 to 5)	MATLAB™ Coding	Overall Savings Output	Implementation Cost	Validation of Results	Modifiable Interface	Works with Current Systems	Interface with BAS software					Canned Systems	Existing Algorithms	
Customer Requirements	User Friendly	4	3				9	9	9					2	1	
	# of Pumps to Run	5	1	9	3	3								1	1	
	List of i/p's & o/p's	3	9				9							1	1	
	Adaptable	5	1				9		1					1	1	
	Documentation	3	3			9								2	2	
	Saves Energy	5		9				3						2	2	
	Calibration	3	3			9			3					1	2	
	Specific System Info	3	3			3		9						1	2	
	BAS code Compatible	4	3						9							
	Units															
	Targets		8													
	Benchmark #1															
	Benchmark #2															
	Importance Scoring		88	90	15	78	108	78	86	0	0	0	0			
	Importance Rating (%)		81	83	14	72	100	72	80	0	0	0	0			
● = 9	Strong Correlation		1	2	0	2	3	2	1	0	0	0	0			
○ = 3	Medium Correlation		4	0	1	2	0	1	1	0	0	0	0			
Δ = 1	Small Correlation		2	0	0	0	0	0	1	0	0	0	0			
Blank	No Correlation		1	6	7	4	5	5	5	8	8	8	8			
	Total		8	8	8	8	8	8	8	8	8	8	8			

Table 2-QFD (House of Quality)

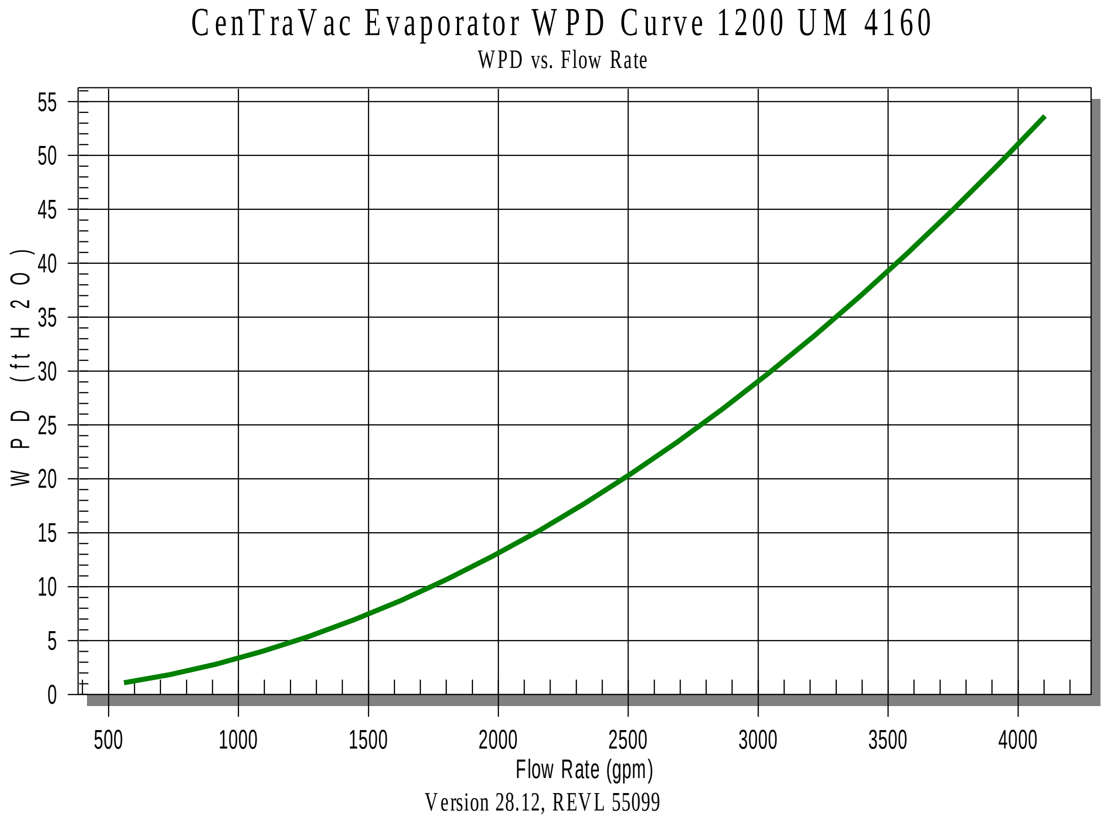
Appendix B: List of Vendors

Trane Commercial – Provided chiller specifications which we modeled (UVHF1300 Chiller)

Peerless Pumps – Provided pump specifications which we modeled (8AE20 17"Pump)

Pump Systems Matter – Provided PSIM software which we used for modeling.

Appendix C: Vendor Supplied Component Specifications and Data Sheets



Flow Rate	WPD
559.6	1.08
736.8	1.85
914.0	2.82
1091.2	3.99
1268.4	5.36
1445.6	6.93
1622.7	8.70
1799.9	10.66
1977.1	12.81
2154.3	15.16
2331.5	17.70
2508.7	20.44
2685.9	23.37
2863.1	26.49
3040.3	29.80
3217.5	33.30
3394.7	36.99
3571.9	40.87
3749.1	44.95
3926.3	49.21
4103.5	53.66

FCLT-LAX	MODL-CVHF	NTON-1300	CNIF-ADPV
INDP- NO	SRTY-UPIR	HRTZ- 60	VOLT-4160
ENCL-STD	SMPP- NO	DMP- NO WWUO-YES	
CPKW-745	CPIM-291	EVSZ-142L	EVBS-1420
EVTM-IMCU	EVTH- 25	EVWP- 2	CDSZ-142L
CDBS-1420	CDTM-IMCU	CDTH- 28	CDWP- 2
TSTY-STD	ORSZ-1810	AGLT-NONE	TEST-AIR
TTOL-AIR	FTST-YES	ASTT-NO	

Figure 15: Trane UM 4160 Chiller/Evaporator Curve

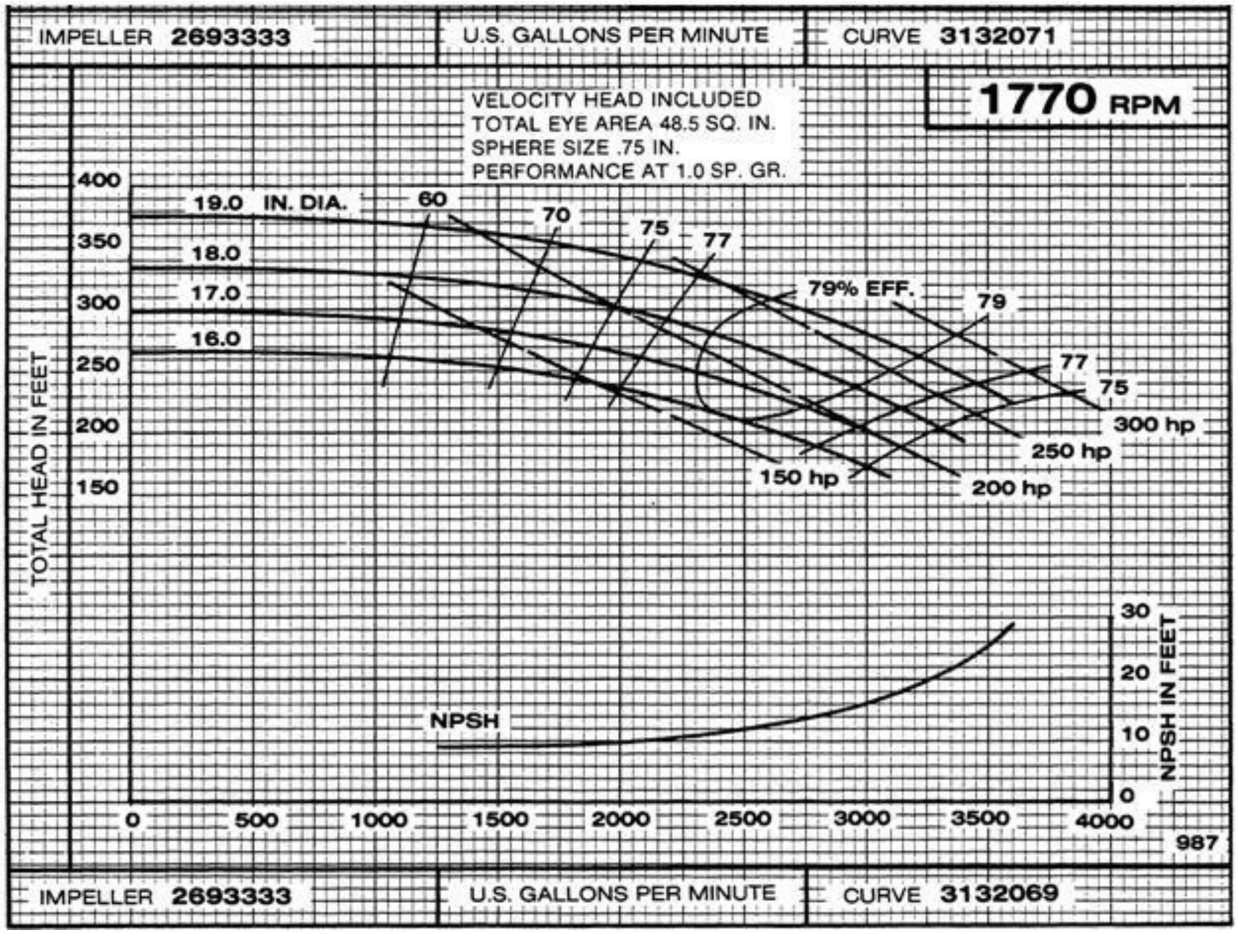


Figure 16. Peerless 8AE20 17" Pump Curve

Appendix D: Programming Code

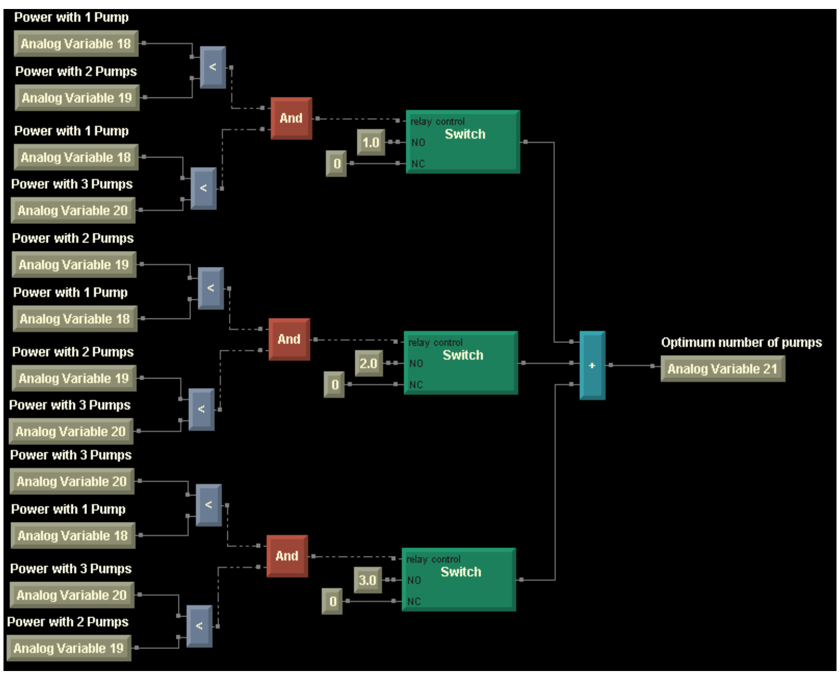
MATLAB™

```
% Pump Sequencing Code in Matlab
% Finds the number of pumps to minimize power consumption
%
% Input: Pump curve data points
%        Pipe Diameter
%        Number of available pumps
%        Operating conditions
%
% Output: Number of pumps to operate
%         Operating frequency
%         Power Consumption
clear all
close all
clc
```

```
%***Enter Data (Flow,Head,Power)***
D = [0 100 12 ; 500,82,15 ; 600,80,16.5 ; 700,75,17.5 ; 800,70,19 ; 900,60,19.1 ; 1000,50,19.1 ;
1100,35,19.2 ; 1200,20,19.2];
C = polyfit(D(:,1), D(:,2), 2); % Generate Pump Curve (a,b,c)
P = polyfit(D(:,1), D(:,3), 2); % Generate Power Curve (a',b',c')

%***Pipe diameter (inches)***
Dia=10;

%***Enter number of pumps in system***
n=3;

%***INPUT Operating***
f_op = 40;
N_op = 2;
H_sys = 11;

%Approximate Flow based on system head to be used for minor loss calculations
Q_op = N_op*(-60*C(2)/f_op - (3600*C(2)^2/f_op^2 - (4*3600*C(1)/f_op^2*(C(3)-
3600/f_op^2*H_sys)))^.5)/(7200*C(1)/f_op^2);

%Pump operating point with minor losses
H_op = H_sys + 10*Q_op^2/(N_op*2*32.2*(pi/4*(Dia/12)^2)^2*7.48^2*60^2);

%Re-calculate Flow based on actual head of pump
Q_op = N_op*(-60*C(2)/f_op - (3600*C(2)^2/f_op^2 - (4*3600*C(1)/f_op^2*(C(3)-
3600/f_op^2*H_op)))^.5)/(7200*C(1)/f_op^2);

%Set minimum head and flow
if (H_op>=10) && (Q_op>=600)

    % N Pumps
    for i=1:n
      Q(i)=Q_op/i;
      H(i)=H_op;

      %Set Max Flow Limit to the end of the pump curve
      if Q(i) < (D(9,1)*(f_op/60))

        % Solve for frequency
        f(i) = (-(60*C(2)*Q(i)) + ((60*C(2)*Q(i))^2 - 4 * C(3)* (3600*C(1)*Q(i)^2-3600*H(i)))^.5) /
(2*C(3));

      % Frequency Limits
        if (f(i)<=60) && (f(i)>0)
          % Solve for Power
          P_op(i) = P(1)*f(i)/60*Q(i)^2 + P(2)*(f(i)/60)^2*Q(i) + P(3)*(f(i)/60)^3;
```

```
            P_sys(i) = i*P_op(i);
          else
            P_sys(i) = 1000000; %causes this point not to be chosen
          end %end frequency limit

        else
          P_sys(i) = 1000000; %causes this point not to be chosen
        end %end flow limit

      end

[Power,Num] = min(P_sys);
fprintf('Running %i pump(s) at %6.1fHz gives a total system power of %6.2fhp',Num,f(Num),P_sys(Num))


else
  disp('Inputs are out of bounds');
end
```

TGP



Appendix E: Gantt Charts

Our Gantt Charts provide a detailed schedule of our project. They integrate the due dates for our deliverables with the development timeline of our design. Basically, the Gantt Charts demonstrate how the different project objectives lead into each other, and the charts lay out the sequence in which the project will be completed.

Winter Quarter 2009

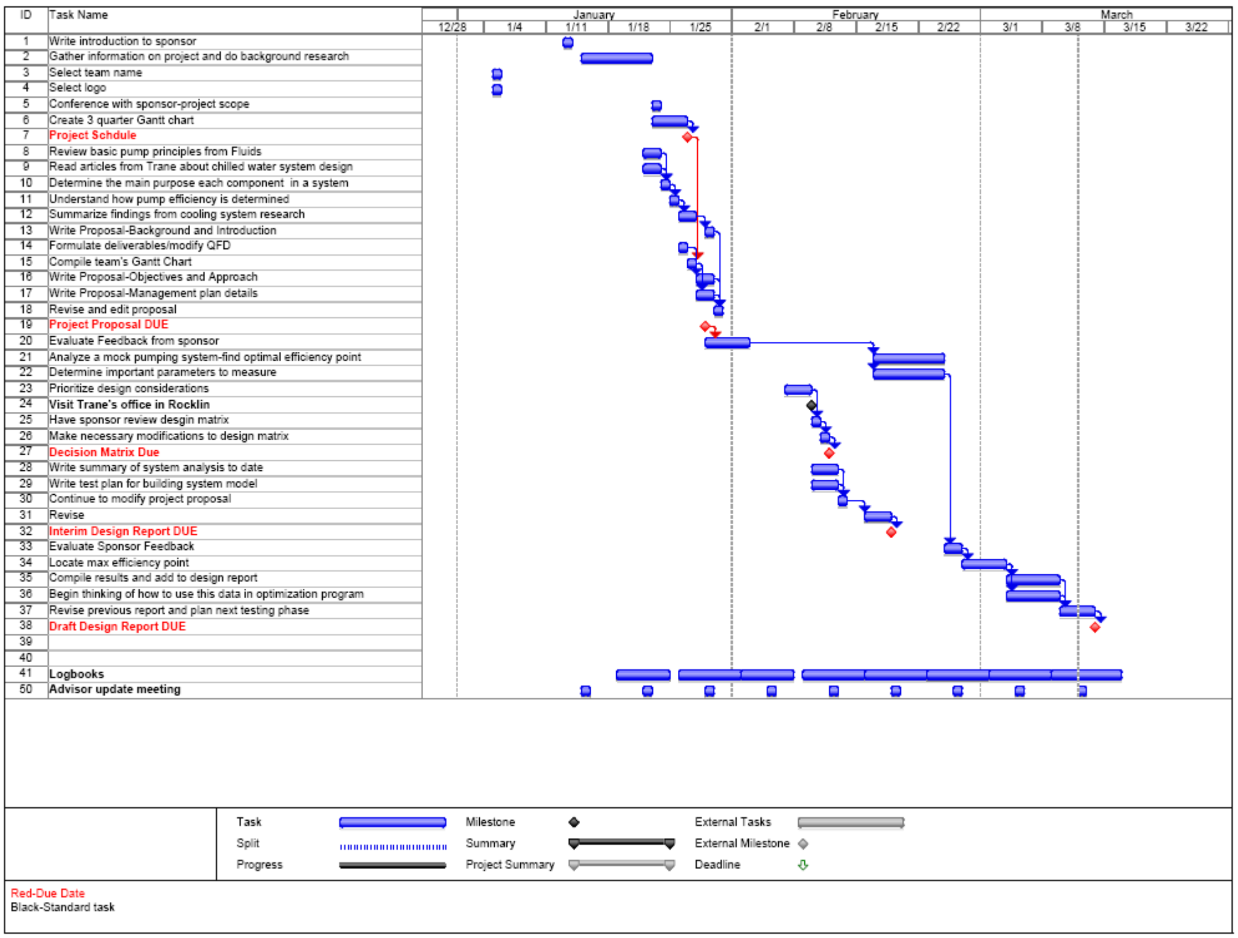


Figure 17. Winter 09 Gantt Chart

Spring Quarter 2009

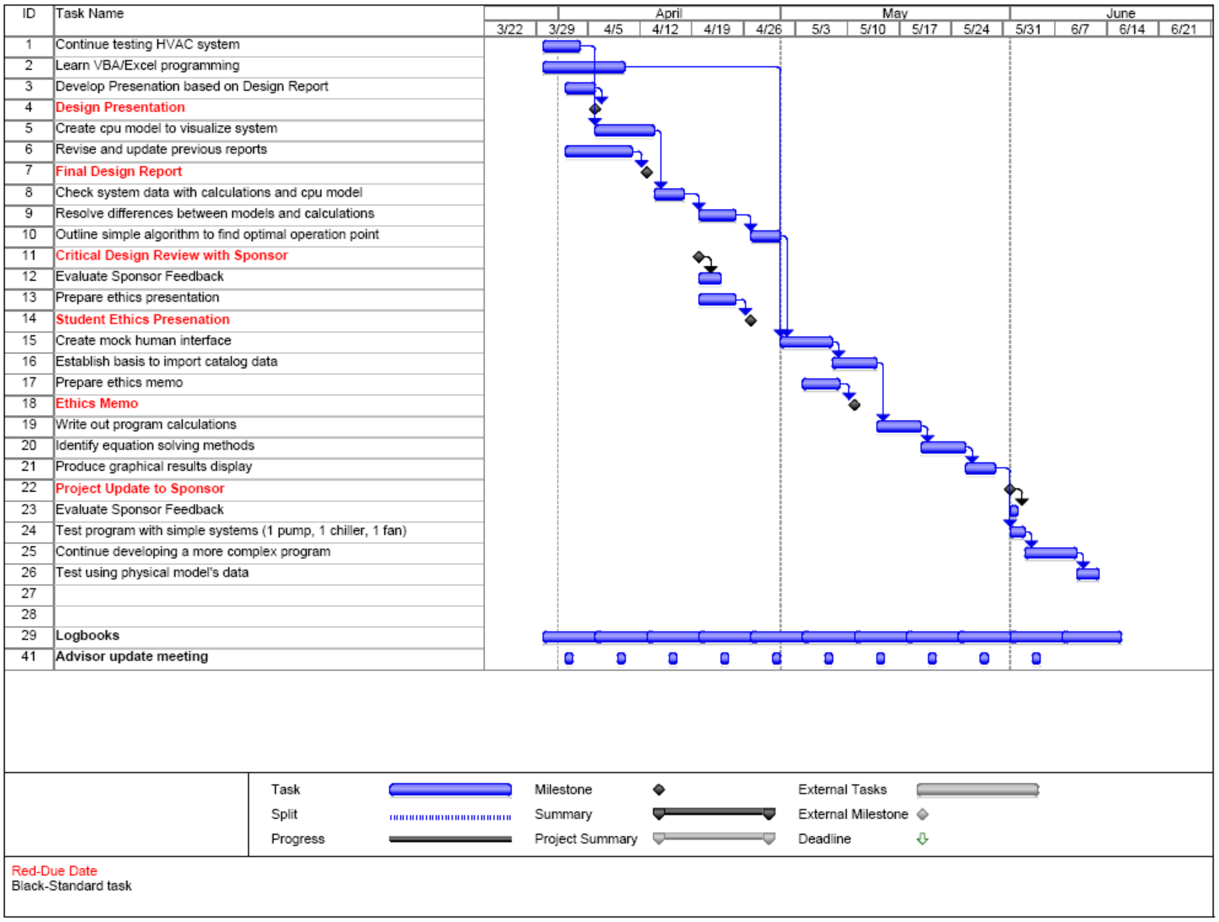


Figure 18. Spring 09 Gantt Chart

Fall Quarter 2009

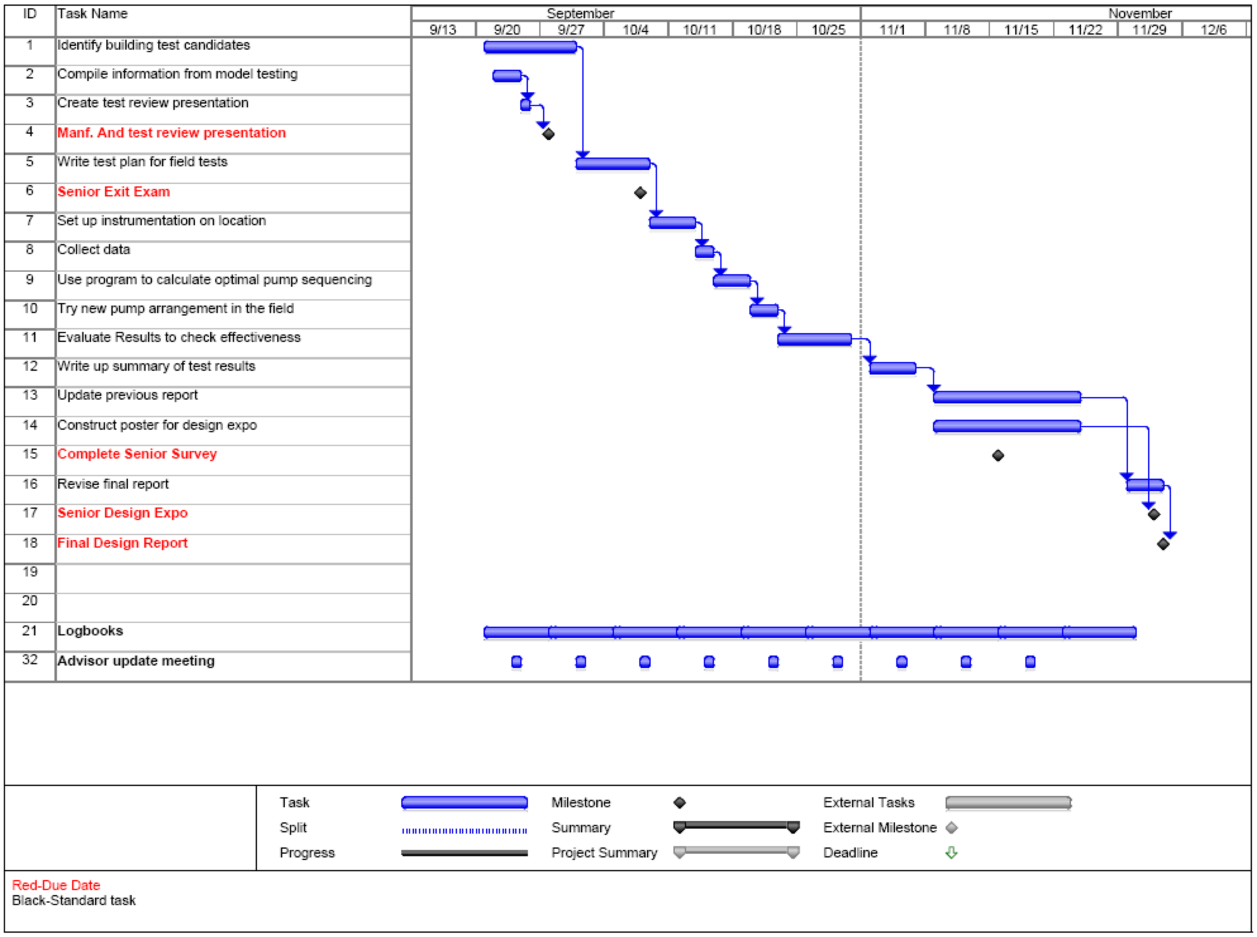


Figure 19. Fall 09 Gantt Chart