

Application of Optimization Techniques

in an HVAC System

by

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Abstract

This thesis presents the application of optimization techniques to a model of an HVAC system. Braun (1989) found that the power consumption of an HVAC system can be adequately described by a single quadratic curve. Optimal control settings can be found by minimizing power with respect to controlled variables,

The HVAC model used for this project was based on data gathered from an HVAC test facility at the Joint Center for Energy Management. The system was run at a wide variety of operating conditions, and the data were used to create performance curves for the power consumption of system components. The system model is comprised of several component models, which include the chiller, cooling coil, condenser fans, supply and return fans, and the chilled water pumps. These component models were linked together to form a system model that took six operating variables as input. The uncontrolled variables that were used as inputs are cooling load, sensible heat ratio, and outside air temperature. There are two continuous controlled variables, chilled water temperature and supply air temperature; and one discrete controlled variable, the number of operating condenser fans.

The model was run at many operating conditions. The results were curve fit to create a system optimization curve. Three curves were created, one for each discrete variable setting. By differentiating the curves with respect to controlled variables, the system power was minimized and optimal control settings were found.

The optimization curves do not accurately reflect all the system characteristics. For every load and sensible heat ratio, there exists a minimum allowable temperature difference between the chilled water temperature and the supply air temperature. For some operating conditions, the optimization curve recommended values that violated this constraint. By testing the model, data on the constraint were gathered. The constraint was described using a simple linear equation and was included in the optimization methodology.

Two simulations were performed using actual weather data to assess the energy and power savings that result from using optimal control. One simulation was performed with fixed control variable settings. The second run used optimization techniques. The model was run with weather data at a variety of operating conditions to generate initial operating data. The data were used to build an optimization curve, and the system was run using variable settings that minimized total system power. As more operating data were generated, the curve was updated. A comparison of the two runs showed that the optimal control methodology produced significant peak power reduction in this model, but produced minimal energy savings.

Acknowledgements

If I had known at the start how difficult this thesis would be for me, I wonder now whether or not I would have undertaken it. I know that I could not have succeeded without the Solar Lab as an office, a study hall, a computer lab, a play-pen, and a psychiatric resource. Thanks are due to Bill, Sandy, John, and Jack for creating and maintaining such a unique and lively place. Bill Beckman's insistence on clarity and explanation often sent me back to the drawing board to scratch my head and figure out what I was doing. John Mitchell's enthusiasm for my work kept me motivated at times when I seriously doubted my ability to succeed. As a team, Bill and John were the driving force behind the completion of my work, and are a formidable croquet team. While Sandy Klein and Jack Duffy were not present in the day to day tribulations of this project, Sandy's outstanding teaching skills, and Jack's constant availability around the lab contributed much to my studies.

Outside the lab, there are several individuals who were essential to this project. The Joint Center of Energy Management and its controls expert, Peter Curtiss, performed all the actual system set-up and testing for this project. High quality data is essential in experimental work and JCEM provided exactly that. Peter was always on the ball, with quick responses to my non-stop stream of questions and requests for data.

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Jim Braun deserves recognition for answering all my questions on optimization, and for writing a concise thesis on which I relied heavily for my work. Robert "Just Do It" Lanoue, my partner-in-crime on this project, played a large part in its progress. We struggled through the first half of the research together, and I'm not sure I could have made it through without him. Other Solar Lab players include Jeff aka TRNSYS Man, Jimbo, Doug, Paul, Todd, Krista, Dirk, Tammy, Ruth, Shirley and Maggie. I wish I could give everyone a paragraph to themselves, but sooner or later I've got to finish this thesis and start a real job.

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Nomenclature

\dot{m}	Mass flow rate of air
i	Enthalpy of air
T_{chw}	Chilled water temperature
T_{amb}	Ambient outdoor air temperature
T_{sa}	Supply air temperature
SHR	Sensible heat ratio
C_i	Curve fit coefficients
K_i	Curve fit coefficients
J	System power
f	Vector of uncontrolled variables
M	Vector of discrete control variable
u	Vector of continuous control variables
\hat{A}	Matrix of coefficients
\hat{b}	Vector of coefficients
\hat{C}	Matrix of coefficients
\hat{d}	Vector of coefficients
\hat{E}	Matrix of coefficients
\hat{g}	Coefficient

Introduction

1.1 Background and Objectives

The heating, ventilation and air conditioning (HVAC) system consumes a large percentage of the energy used by most commercial buildings. The central plant equipment can be operated at various control variable settings; often there are many different ways to run a system to provide the necessary amount of heating and cooling. Improved control of HVAC systems can reduce their energy consumption, thus saving both energy and money. With rising energy costs, it is increasingly important to examine HVAC energy consumption and how it may be reduced.

Braun (1989) outlines methods of modelling HVAC systems in order to obtain optimal control strategies. He modelled a large cooling system at the Dallas-Fort Worth Airport, and developed optimal control strategies for that system. He details methods of modelling individual components, as well as an overall system model. His method, which is the one used for this research, involves creating a single, overall quadratic equation of the system power as a whole, and minimizing it with respect to controlled variables. The result is a set of equations that produce an optimal control strategy for a given set of operating conditions. He found that performance curves are flat near the system optimum. Thus, an

approximate model of the system, such as the quadratic curves of system power, is sufficient to determine near optimal control strategies.

This thesis examines the control of a cooling system and the development of optimal control strategies to reduce total cooling system energy consumption. The specific HVAC plant used in this research is described in Section 1.2. Chapter 2 details the methods used to model the various components, the controls, and the system as a whole. Optimization procedures are described in Chapter 3, with discussion of curve fit generation and verification. Implementation of optimization methods into an HVAC system is detailed in Chapter 4. Finally, conclusions and recommendations based on this work can be found in Chapter 5.

1.2 Laboratory Equipment Description

The system analyzed in this study is located at the Joint Center for Energy Management (JCEM) in Boulder, Colorado. It is a test facility, designed to allow dynamic testing of HVAC equipment. It includes a full-sized HVAC system, four simulated zones where cooling or heating loads can be imposed on the system, and a complete direct digital control and data acquisition system. The facility was designed to simulate one floor, or 10,000 to 15,000 square feet, of a commercial office building. A simple schematic of the system is shown in Figure 1.1. The system does not contain some of the characteristics of a real building; however, the optimization techniques investigated with the JCEM system are applicable to real buildings.

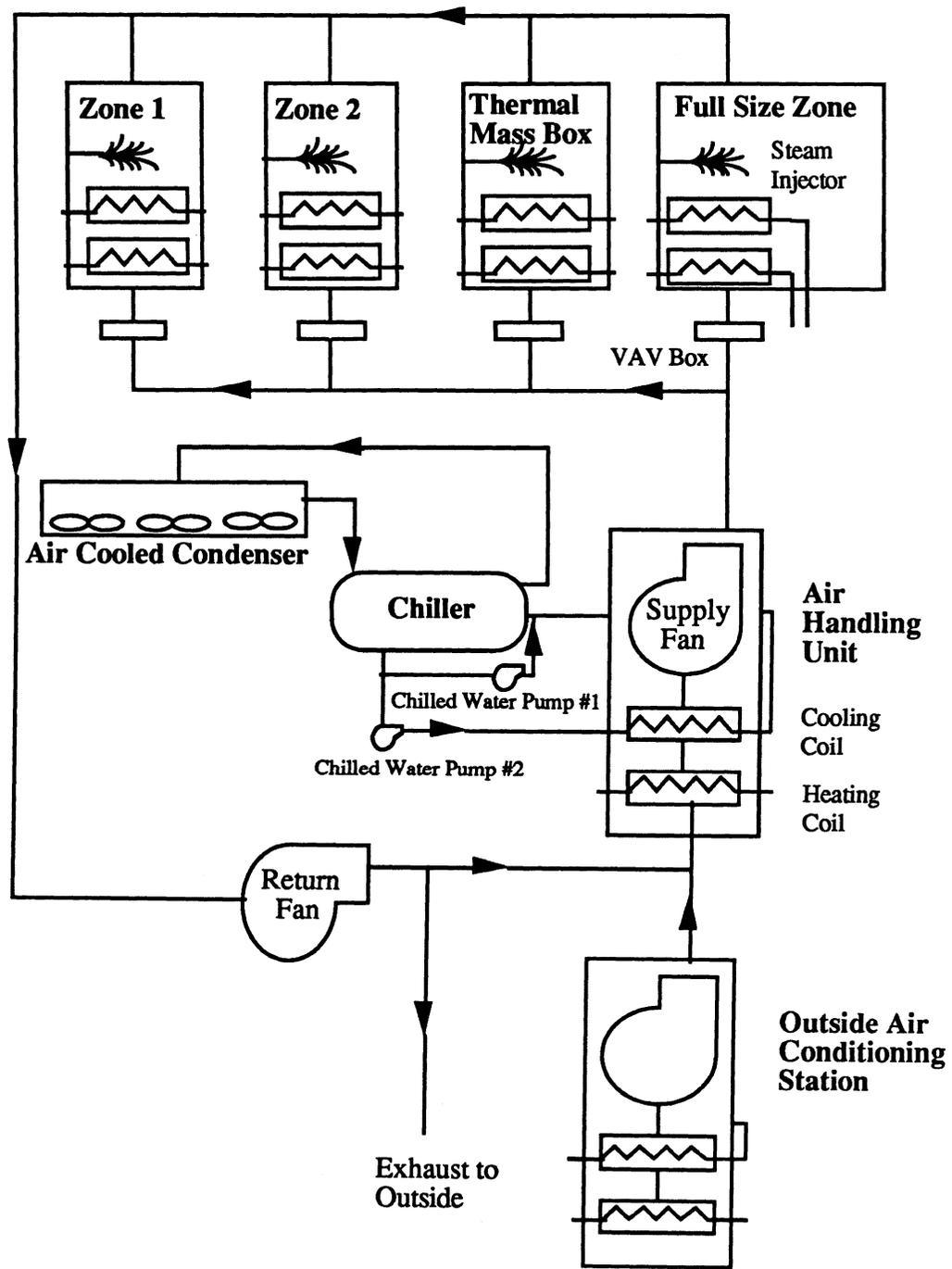


Figure 1.1: Schematic of HVAC Test Equipment at JCEM

The schematic shows the complete air loop, as well as outside air exhaust and intake. The chilled water loop to the air handling unit is also shown. Hot water piping to the air handling unit is not shown, as hot water was not used in the main air handling unit. None of the piping to the zones is shown, although hot water was used in the zones to impose a load on the system.

The equipment is monitored and controlled by an extensive energy management system. Direct digital controls (DDC) are used to control dampers, valves and other equipment. A 360 point data acquisition system allows sensor readings to be recorded as often as every two seconds. These points include output signals to valves, pumps and dampers; as well as sensor readings of temperatures flow rates, relative humidities and powers. Virtual points, which are values calculated from other points, can also be set up.

The cooling system contains a 50 ton reciprocating chiller. It has six cylinders, coupled into 3 stages, and the refrigerant used is R-22. The cooling coil is rated at 300 KBtu/hr, which is one-half the total capacity of the chiller. The associated condenser is air cooled with six fans, which are controlled in pairs, allowing two, four or six fans to operate at once. Two pumps are used to circulate the chilled water. One pump functions at a constant flow rate of 120 gpm, pumping water through the main piping circuit. The continuous flow of water protects against freezing in the main chilled water circuit. The second pump is modulated to control the water flow rate through a branch loop that serves the cooling coils.

An electric boiler, rated at 308 lbm/hr at 100 psig, provides steam and hot water. The hot water is used to impose a cooling load on the system. Heating coils in the zones provide

sensible load, with the steam injectors imposing latent loads. If the system was run in a heating mode, the boiler would be used to provide hot water to the heating coil in the main air handling unit. The chiller also has the capability of using a heat recovery condenser to provide hot water to the system, although this option was not used during this study.

The air handling unit contains the cooling and heating coils, a supply fan and filters. A diagram, showing a schematic of the sensors in the air handling unit can be found in Figure 1.2. Sensor locations are indicated by a circle labelled with the sensor number. The sensors allow temperature, humidity, and flow measurement to be made of the air entering and exiting the air handling unit. Virtual points have also been programmed to find other system parameters, including load and sensible heat ratio.

The supply fan is a 12,000 cfm variable speed fan with a motor outside the cold air stream so that no heat is transferred from the motor to the cold air. In the return duct, there is a 5 HP return fan with a motor located within the air stream. Dampers are used to control the exhaust air to the outside, and allow the system to take in the same amount of fresh air. The ducts are not insulated and there is heat gain to the ducts from the surrounding air. These heat gains are investigated in more detail by Lanoue (1991).

The system also has an air handling unit dedicated to providing desired "outside" air conditions. The unit pre-conditions the outside air so that different outside air conditions can be simulated. This air handling unit is only capable of conditioning the fresh air that is introduced into the system, and does not affect the outside air blown across the air cooled condenser. Because these tests were concerned with the operation of the chiller, and not with the amount of fresh air exchange, the outside air conditioning station was not used.

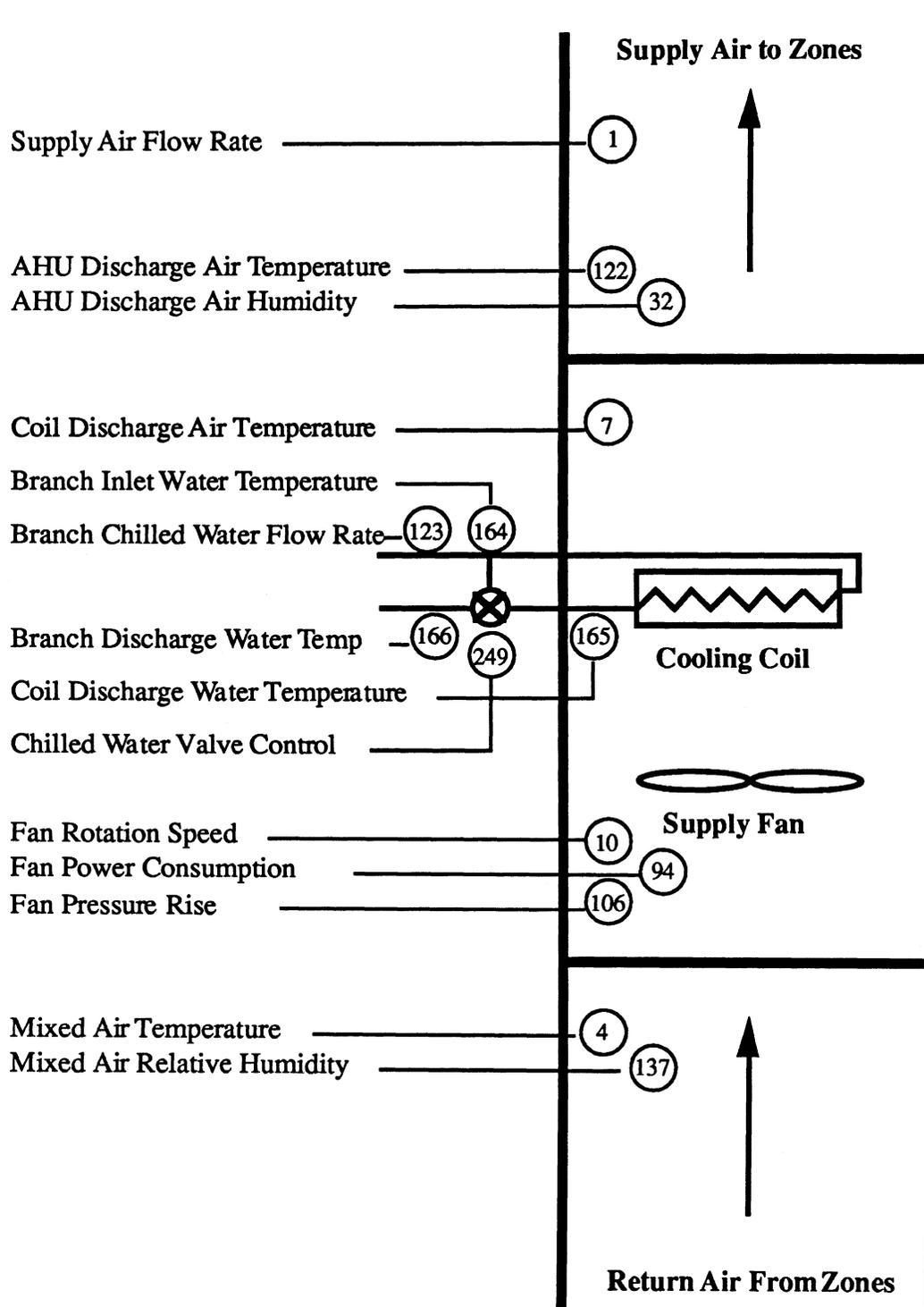


Figure 1.2: Diagram of Sensor Locations Within the Air Handling Unit

The facility is set up with four zones. The zones are equipped with cooling and heating coils, and steam injectors to impose sensible and latent loads on the system, respectively. Two of the zones consist only of coils and steam injectors. These are referred to as load simulators 1 and 2. A schematic, showing the instrumentation associated with load simulators 1 and 2 is shown in Figure 1.3. Sensor locations are represented by circles enclosing the sensor number. Supply air is ducted to the coils through a variable air volume (VAV) box, and the exiting air is exhausted into the return air duct. The only steam injector used in this study was the steam injector in load simulator 1. The remaining zones provided only sensible gains.

A third zone, called the thermal mass box, contains tall tubes that can be filled with up to 4 tons of water. The water serves to simulate thermal mass in a facility, and allows transient loads to be studied. For this research project, system loads were held steady and the tubes were kept empty. The fourth zone has capabilities for imposing solar loads, and room for equipment or people to be used to impose loads. This zone was not used.

The VAV system controls the air flow into each zone. Dampers control the flow such that the cold air entering the zone is just sufficient to meet the load. If desired, the VAV boxes can be set up to mix return air with supply air. This control method ensures that a constant amount of air is circulated through the zone, while varying the amount of supply air used. For these tests, no return air was used and the total flow to the false loads was modulated. The supply fan was modulated so that the zone loads were met.

The laboratory has the capability of being controlled in many different ways. For the purposes of this study, the supply air temperature is controlled to a specific set point. The

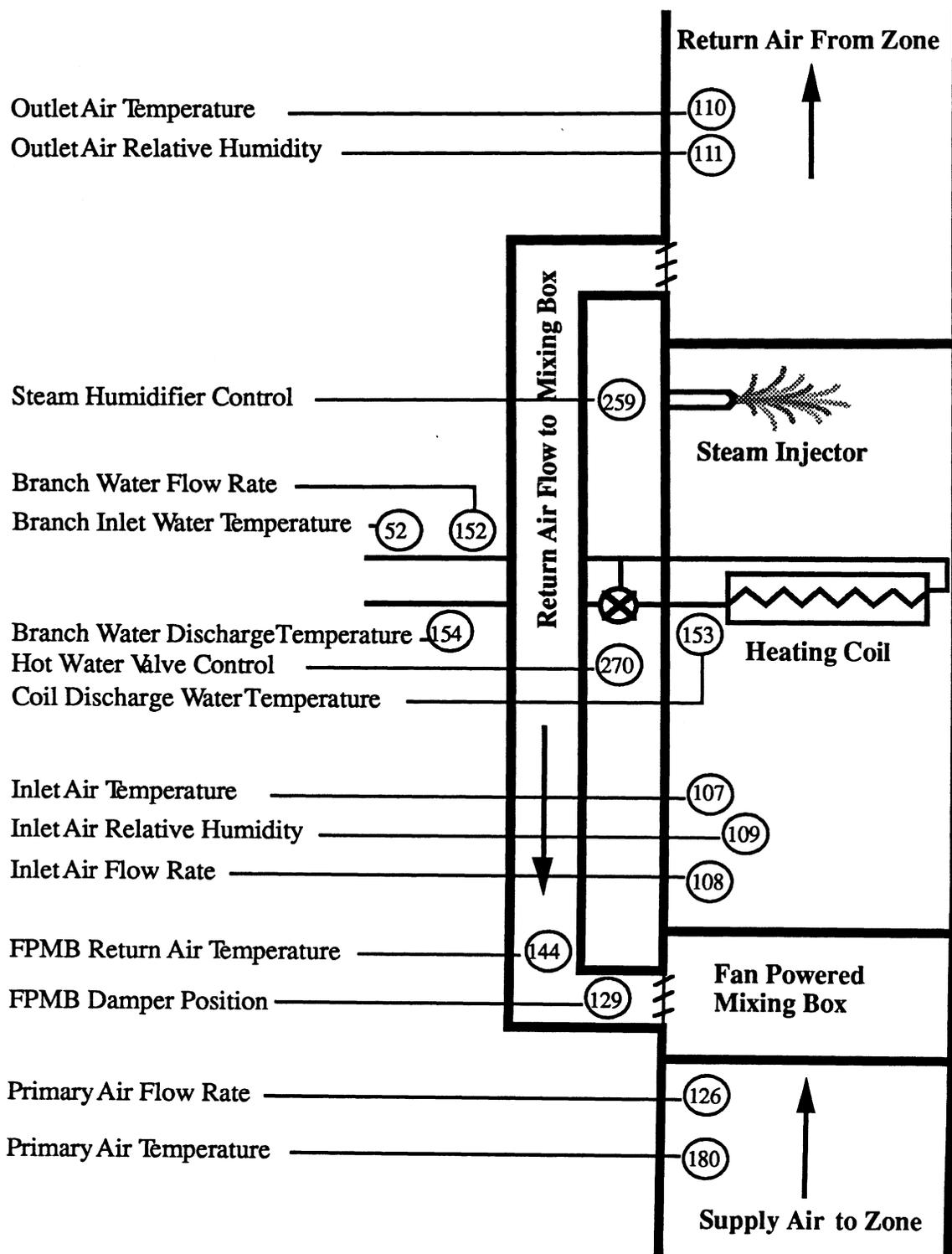


Figure 1.3: Diagram of Sensor Locations Within a Zone

chilled water flow rate through the cooling coil was controlled in order to obtain the desired supply air temperature.

Similarly, the VAV system modulates the air flow to maintain a constant "room" temperature. The supply fan can be modulated in two ways. To simulate a typical VAV system, the supply fan speed is modulated to maintain constant air pressure in the supply air duct. As the VAV boxes open and close, the duct air pressure begins to rise or fall. The supply fan speed is varied to maintain constant duct pressure. A second control method involves fixing the VAV dampers into a fully open position. The supply fan is controlled directly from return air temperature. If the return air temperature is too high, the cool air flow increases. For most of the tests, the second control method, which is not typical of VAV systems, was used. The data gathered at JCEM were used for two projects, the one presented here and that of Lanoue (1991). The tests performed by Lanoue required that the second VAV control method be used, which is suitable for the optimization methodology investigated in this research.

System Model

It is difficult to use a real system to run extensive tests. Real systems in operational buildings are not usually fully instrumented, and can not be shut down for installation of test equipment or equipment adjustment. It is easier to simulate a system by creating a computer model, and to run tests on the model, rather than on the original system. Modelling also allows the study of equipment or control changes that might be very expensive or time consuming if the changes were implemented on a full sized system. Because of the time involved to run a full test, and because weather can be a limitation in air conditioning studies, it was decided that the HVAC system at JCEM should be modelled.

The modelling tool initially selected to create the system simulation was TRNSYS. This computer program was designed to model thermal systems, including HVAC systems and solar hot water heaters. TRNSYS consists of a large library of system components that can be linked together into different system configurations. The system can then be fed operating data and run just like a real system. Component models consist of subroutines, which can be easily modified if needed.

While many of the subroutines in the TRNSYS library were used for the model, the level of system detail provided by the main TRNSYS driver program was not required for this study. In order to simplify the model, TRNSYS subroutines were linked together using a

simple driver program. Variables that were not investigated in this research, such as duct and plenum temperatures, were thus removed from the simulation.

2.1 Initial Data Collection

Manufacturers' data were used to provide the basis for the system model, including basic pump sizes, fan sizes, and maximum fluid flow rates. Some system operating data were required to validate the component models. To this end, the system was operated over as wide a range of operating conditions as possible. Data were taken over 5 minute intervals, and each test ran between 30 and 90 minutes in total duration. A computer program was written to allow rapid graphing of the data. Start up transients were identified from these graphs, and were removed from the data sets. The chiller sometimes cycled between stages, primarily at low loads. In this case, although the system no longer experienced start up transients, it was dynamic. For these runs, the data were averaged, excluding transients.

Throughout this thesis, the term "data point" is used for a single, 5 minute average. When two or more data points are averaged together, it will be referred to as averaged data. Often, changes in outdoor conditions caused the test settings to wander during the test. An example of this can be seen in Figure 2.1. Data points taken between 15 and 45 minutes were averaged together into a single value. Similarly, data points between minutes 50 and 70 were averaged together, and taken as a second value.

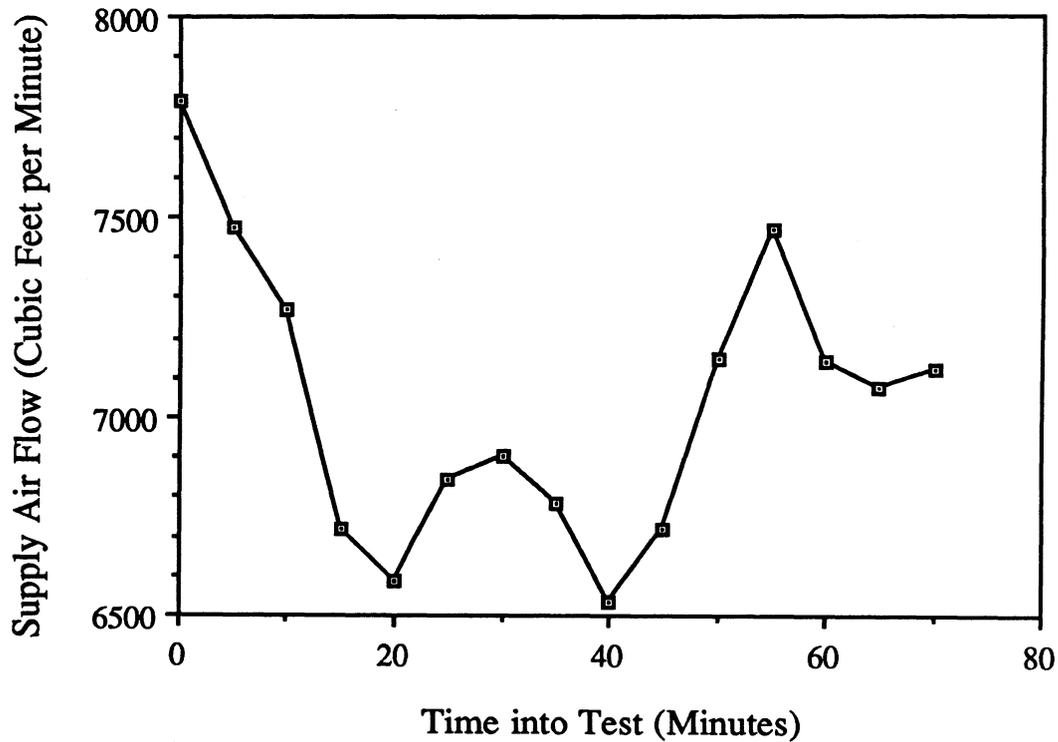


Figure 2.1: Sample Plot of Operating Data Taken at JCEM

2.2 Chiller Model

The chiller performance was modelled by creating a curve fit from historical chiller data. This method is limited in that it only provides power information. A mechanistic model might be able to find the maximum possible chiller load at the given operating conditions, for example. Because only power information was desired, and because chiller operating

data were available, the chiller was modelled with a curve fit. A copy of the subroutine developed to model the chiller can be found in Appendix A.

The chiller was monitored over a wide range of operating points, and a separate curve fit was created for chiller power for each condenser fan setting. The variables used for the curve fit were outside air temperature, chilled water set point and chiller load. The curves are of the form

$$\text{Power} = C_0 + C_1 (T_{\text{amb}}) + C_2 (T_{\text{amb}})^2 + C_3 (T_{\text{chw}}) + C_4 (T_{\text{chw}})^2 + C_5 (\text{Load}) + C_6 (\text{Load})^2$$

and were developed using a least-squares method.

The curves were visually checked for accuracy by plotting the actual chiller power against the chiller power calculated by the curve. This graph can be found in Figure 2.2. The plot used chiller data averaged over each run. All runs created for this research project are plotted, as well as some that were performed on the chiller with a similar chiller set-up that do not directly pertain to this research. A graph of chiller performance data is presented in Appendix H.

It is clear from the graph that the model does a good job in predicting the chiller power. The largest discrepancy is 1.86 KW, which results in an error of 7.3%. The root mean square (RMS) of the data is 0.795 KW. The variations in chiller data can be attributed to the nature of the data itself. Often the parameters were not steady over the entire length of the test, so averages were used. Some of the points represent 5 minute averages. If the

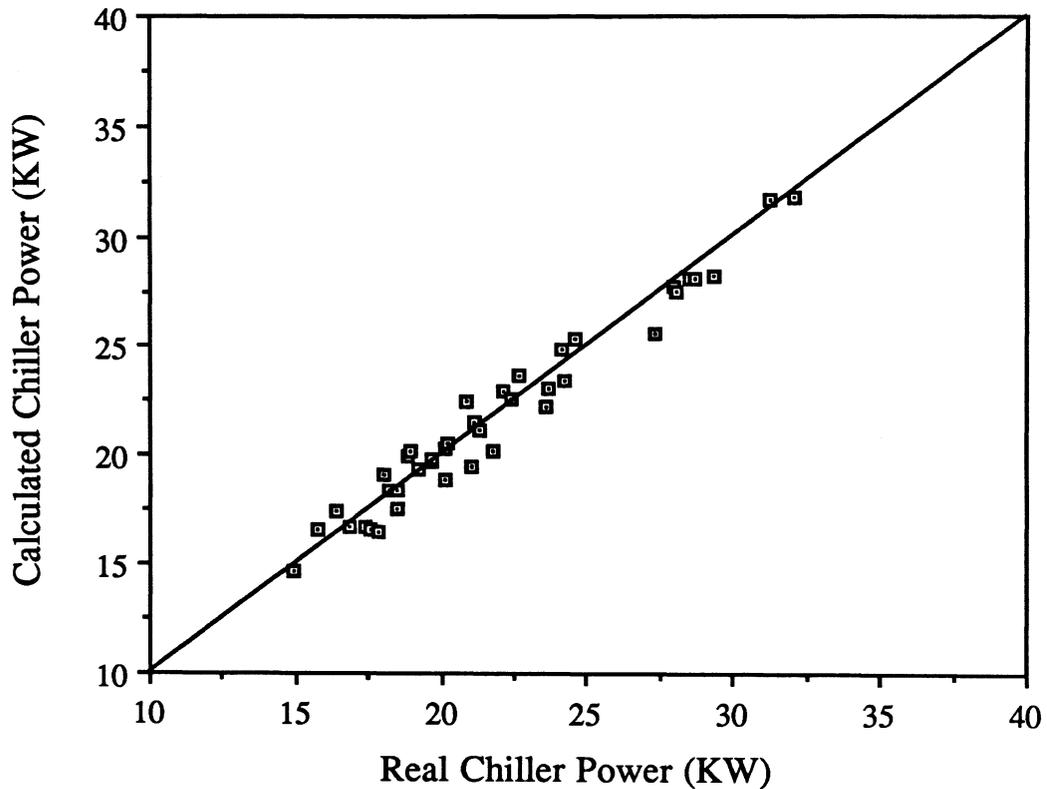


Figure 2.2: Graph of Modelled Chiller Power vs. Measured Chiller Power

parameters, such as outside air temperature, were changing slightly during the test, these transients may be responsible for some of the data spread.

The chiller model used average operating data at operating points where the chiller cycled severely. At higher loads, when the chiller cycling was not evident, six data points were selected from each run for the model curve input data. Each point consisted of a five minute average of data. At lower loads, a single, overall average of the chiller power as it cycled was used for each run. A total of 128 points were used for the chiller model.

2.3 Cooling Coil Model

The cooling coil was modelled using a subroutine developed by Braun(1989) that is one of the components in the standard TRNSYS library. The subroutine creates a very detailed model of the cooling coil. Coil dimensions and material properties are used to calculate pertinent dimensions. Specifically, the total external coil area, which is the area "wetted" by the air, is found from fin and tube dimensions. The total inside coil area, which is the area wetted by the chilled water, is found from the tube dimensions. The flow area of the air, used to find the air velocity, can be found from the external dimensions of the coil tubes and the internal dimensions of the air duct.

Using the inner pipe diameter, the Reynolds number of the chilled water is found. The Reynolds number is then used to find the heat transfer coefficient inside the coil tubes. Similarly, the air flow area, and the mass flow rate of the air are used to find the Reynolds number and the heat transfer coefficient of the air.

A heat exchanger analysis is performed. First, the coils are assumed to remain dry, and the total heat transfer is calculated. A second analysis is performed assuming that some water condenses from the air onto the cooling the coils. If the coil outlet water temperature is below the dewpoint of the inlet air temperature, the wet analysis is used. This heat exchanger model computes the outlet water and air conditions. Using these values, and the inlet water and air conditions, the sensible and latent loads are calculated.

Several changes were made in this model to replicate the actual test results from JCEM. If the water flow was assumed to always be turbulent, a more accurate result was obtained.

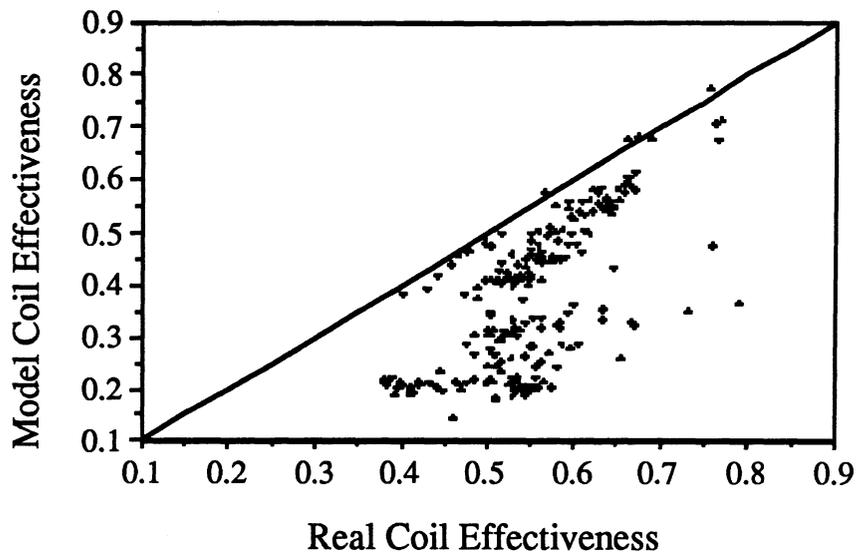


Figure 2.3: Graph of Cooling Coil Effectiveness Modelled with an Unmodified TRNSYS Subroutine vs. Measured Cooling Coil Effectiveness

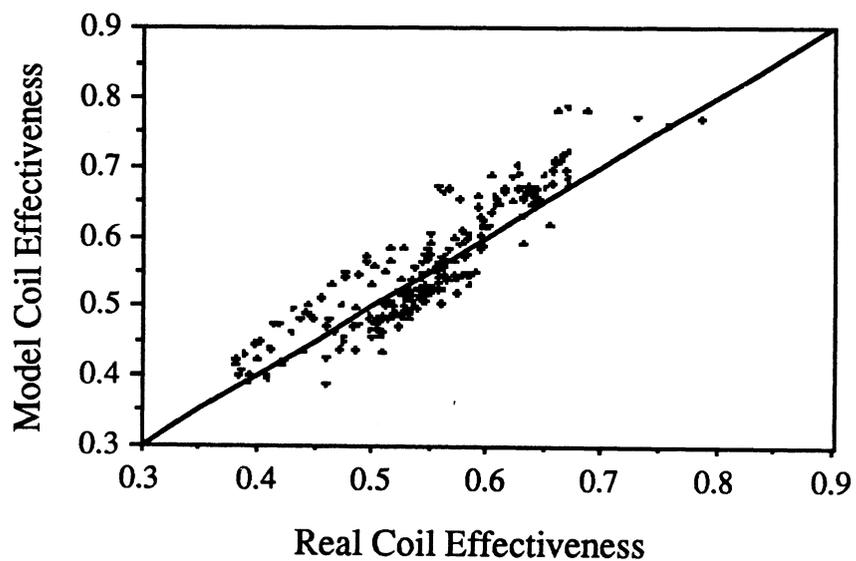


Figure 2.4: Graph of Cooling Coil Effectiveness Modelled with a Modified TRNSYS Subroutine vs. Measured Cooling Coil Effectiveness

Additionally, the heat transfer coefficient on the coils was increased by a factor of 1.5. The results of these changes can be seen in Figure 2.3 and 2.4. In Figure 2.3, the results from the unmodified subroutine are plotted against the actual test data. Most of the calculated results show a predicted coil effectiveness less than the actual value. The results of the modified subroutine are plotted against the measured results in Figure 2.4. By assuming that the chilled water was always turbulent, and by increasing the heat transfer coefficient directly by a factor of 1.5, the model has been improved to more accurately predict the test results.

There are several reasons why these changes might more accurately model the cooling coil. Because of the bends in the cooling coil piping, the water will probably never be truly laminar. Mixing of the water would occur, and the flow could be turbulent. Also, if the airflow over the coil is not uniform, the heat transfer coefficient may vary at different points on the coil surface.

2.4 Pump and Fan Models

The pump for the main chilled water loop runs at a constant speed. Serving as a circulating pump, it ensures that no localized freezing will occur in the chiller. Because the pump is constant speed, its power is constant, and was modelled as a constant 1.25 KW. The actual pump power ranged between 1.23 and 1.27 KW. With a total system power usually over 20 KW, this error in the pump power is negligible.

For the remaining pumps and fans, the operating data were used to create curve fits of the following form.

$$\frac{\text{Power}}{\text{Max Power}} = C_1 + C_2 \left(\frac{\text{Flow}}{\text{Max Flow}} \right) + C_3 \left(\frac{\text{Flow}}{\text{Max Flow}} \right)^2$$

Actual operating points and the curve fit derived from them are shown in Figures 2.5 and 2.6. for the supply fan and the return fan respectively. The same information for chilled water pump #2 is graphed in Figure 2.7. The coefficients and operating data for all pumps and fans can be found in Table 2.1.

	Pump 2	Return Fan	Supply Fan
	0.2006	0.2828	0.1938
C2	-0.6010	-0.9251	-0.7207
C3	1.3515	1.6578	1.4652
R²	0.998	0.996	0.998
Max Power	2.0 KW	3.0 KW	9.0 KW
Max Flow	30,000 #/hr	12,000 cfm	30,000 #/hr

Table 2.1: Parameters for Pump and Fan Curve Fits

In all of the curves, the power begins to increase with decreasing flow rate. In actuality, the curves should level off at very small flow rates. Examining the limit, at negligible flow rates, there will still be losses in the equipment that will draw power. The curve does not go through zero, but will level off. Because the fans and pumps never operate at such low flow rates, however, the accuracy of the curves in this region is unimportant. As shown by the graphs, the curves are accurate over the normal operating range of the equipment.

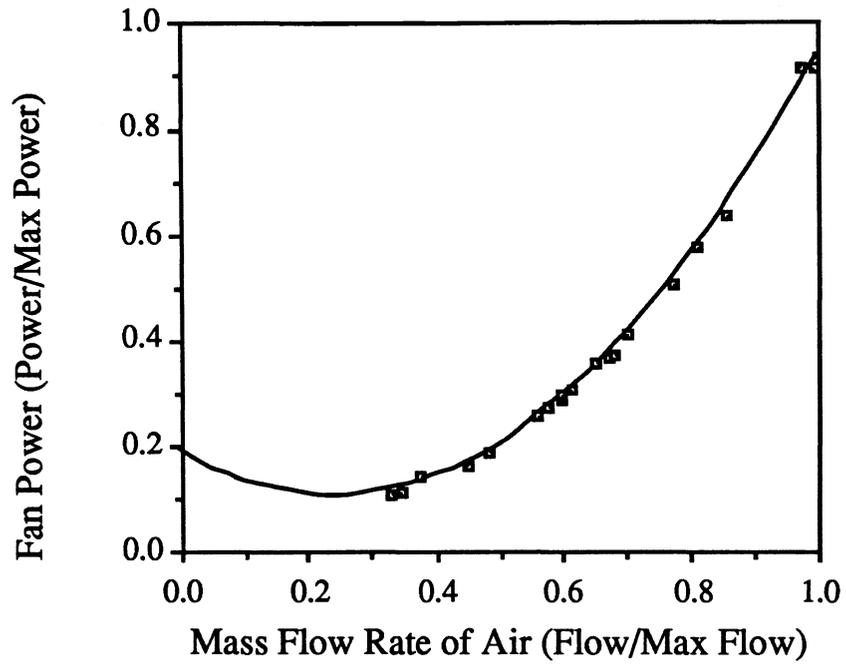


Figure 2.5: Graph of Supply Fan Power vs. Supply Air Flow

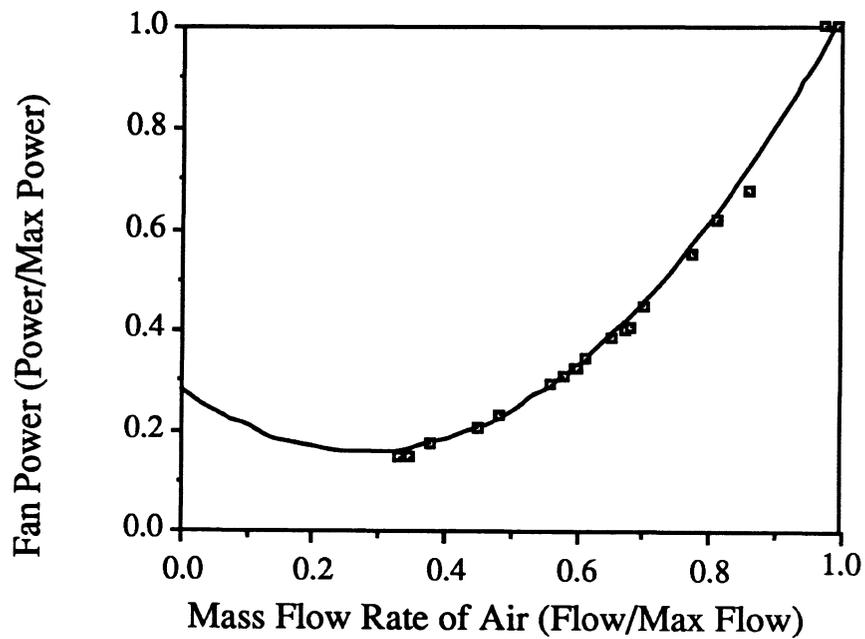


Figure 2.6: Graph of Return Fan Power vs. Supply Air Flow

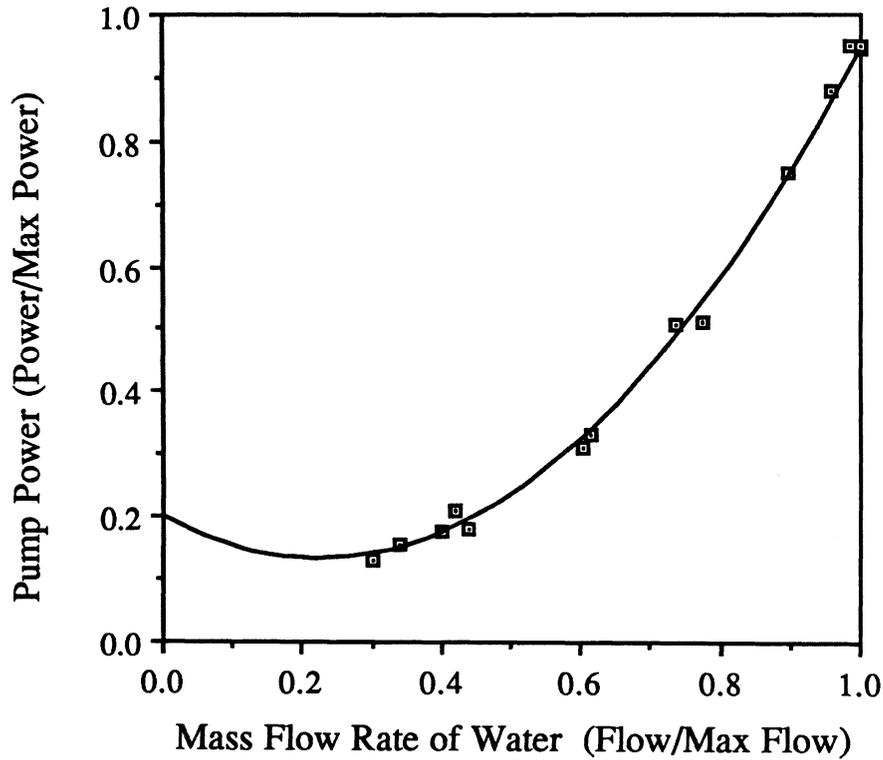


Figure 2.7: Graph of Chilled Water Pump #2 Power vs. Chilled Water Flow

2.5 Condenser Fan Model

The condenser fans are set with two, four, or six fans operating at one time. If the chiller cycles off completely, the fans are also shut off. While the fans are on, the power of the condenser fans is constant. If they cycle off, the average fan power over the averaged five minute data reading drops. For each fan setting, a graph was created that shows the measured fan power at various loads. The graph for four fans is shown in Figure 2.8.

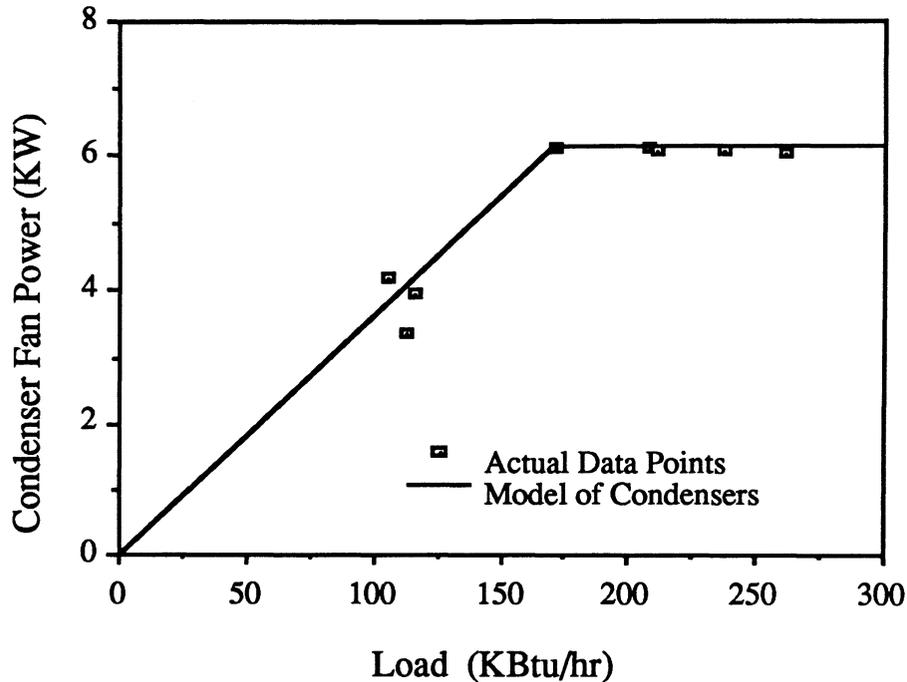


Figure 2.8: Graph of Condenser Fan Power vs. Load, Showing Model of Fan Cycling.

At high loads, the curve is approximated as a constant power. At lower loads, the curve is modelled as dropping off linearly after a specific load. Below a certain load, the chiller begins to cycle off, shutting off the fans. In the case of four fans, as shown, the curve begins to drop off after a load of approximately 170 KBtu/hr. The minimum load before cycling was found to be 180 KBtu/hr for two fans and 145 KBtu/hr for six fans.

2.6 Controls

Unlike a real system, the model assumed that, if possible, all control temperatures are met exactly. The chilled water temperature, supply air temperature, and room temperatures are assumed to be met exactly, and are assumed constant. Ideal, instantaneous controls are

also assumed. The supply air temperature was modelled as a controlled variable that could be set as desired. The supply air flow rate is then varied to meet the load. The chilled water temperature was also modelled as a controlled variable. The chilled water flow rate was varied to obtain the desired supply air temperature. The return fan is controlled in the same way as the supply fan. All of these control methods are the ones employed on the test equipment.

2.7 System Model

All of these components were linked together to form a complete model of the system with six system parameters as inputs: load, sensible heat ratio, ambient temperature, chilled water set temperature, supply air set temperature, and number of operating condenser fans. The FORTRAN program used to combine the component models is in Appendix B.

Some component models take these parameters directly as inputs. The condenser fan power, for example, is a function of only the condenser fan setting and the load. Similarly, the chiller model needs only load, chilled water temperature, and outside air temperature as inputs. The cooling coil component model treats load, sensible heat ratio and supply air temperature as outputs, and requires inlet air and inlet water conditions as inputs. Similarly, the pump and fan curves take fluid flow rate as an input, which is not one of the desired six inputs. If the return air temperature remains constant, the inputs that need to be determined are the supply air flow rate, the chilled water flow rate and the return air humidity.

The supply air flow rate can be determined directly from the six input parameters. Figure 2.9 shows the system load on a psychometric chart. By assuming a constant return air temperature, and by setting a supply air temperature, the total temperature change of the air is found. This temperature change represents the sensible portion of the load.

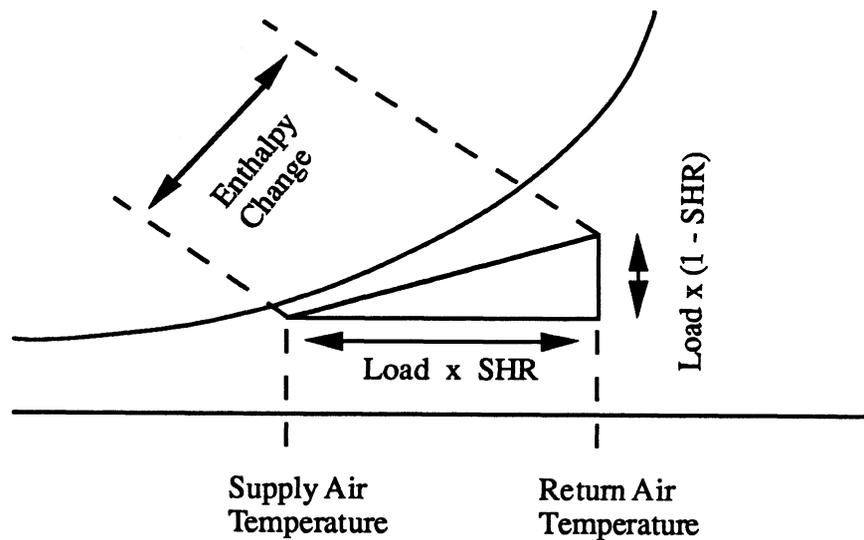


Figure 2.9: Psychometric Chart Showing Load Line

The sensible heat ratio allows the total load line to be found, and thus the total enthalpy change of the air, on a per unit mass basis, is calculated. The total system load is:

$$\text{Load} = \dot{m} (i_{\text{in}} - i_{\text{out}})$$

Where \dot{m} is the mass flow rate of air through the cooling coil and i is the enthalpy of the air. The flow rate of the air required to meet the load can thus be found directly. A subroutine was written to find the supply air flow, and is located in Appendix C.

Once the air flow rate has been found, the inlet air humidity and the chilled water flow must be calculated. These two cooling coil inputs are varied until the desired load and supply air temperatures result. First, maximum chilled water flow is assumed. The inlet air humidity is varied until the desired total load is achieved. These values of chilled water flow and inlet air humidity will cause a specific outlet air temperature, unlikely to be the desired supply air temperature. The chilled water flow rate is then set to its minimum value, and the inlet air humidity is varied until the desired load is found. Again, an outlet air temperature is found. If the desired supply air temperature lies between the values found at maximum and minimum chilled water flow, a chilled water flow rate is estimated, and a new outlet air temperature is found. This process continues until the desired load and supply air temperature is reached. Two separate subroutines were used to search for the operating conditions. One is used only when the sensible heat ratio is 1.0, and is found in Appendix D. The second, which is listed in Appendix E, is used when there is some latent load.

2.8 System Constraints

The real system is constrained in several ways. Fluid flow rates have set limits, determined by the operating range of the fans and pumps. The chilled water set temperature must be lower than the supply air set temperature. If there is not enough of a temperature difference between the two set temperatures, the supply air temperature will not be achieved.

The model needs to handle these constraints. If a constraint is not automatically imposed by the model, it needs to be added. If a constraint is built into the model, the model output should indicate that the system is constrained.

One important constraint that needs to be imposed on the model is the maximum supply air flow rate. The supply fan is rated for 12,000 cubic feet per minute, and can provide 12,500 cfm at maximum speed. After the air flow rate is calculated, the value is checked to ensure that it is below the 12,500 cfm limit. If not, the supply air temperature is stepped down incrementally until the load can be met with 12,500 cfm or less.

The cooling coil has physical constraints that are also handled by the model. Sometimes, for example, the cooling coil can not meet the desired load at the chilled water and supply air temperatures given. Even at maximum inlet air humidity and maximum chilled water flow, the total coil load may be less than desired. This usually occurs at settings that are far from optimum and will not occur often. The model does not try to adjust for the error, instead an error message is printed. Similarly, sometimes the coil load is higher than the desired load. Even at minimum chilled water flow and minimal inlet air humidity, the load is higher than desired. Rather than adjusting for the constraint, the model simply prints an error message.

A more common error is that the cooling coil cannot cool the air to the desired supply air temperature. In this case, the model will adjust the supply air temperature up slightly. The set temperature is increased until the temperature difference is sufficient or until some other constraint is reached.

2.9 Model Verification

Once the model had been completed, it needed to be checked for accuracy against real system data. Averaged data for each set of operating conditions were used. The operating

conditions were then applied to the model to determine if the resultant calculated power was the same as the measured power. Results are plotted in Figure 2.10.

The maximum error between the real power and the model is 3.13 KW, which amounts to 10.9 % of the total real power. This number is quite reasonable, as the largest error found within the chiller curves was 7.3%. The RMS of the data is 1.97 KW. Because of the errors associated with gathering real data, such as system transients, the model cannot be expected to predict system values exactly.

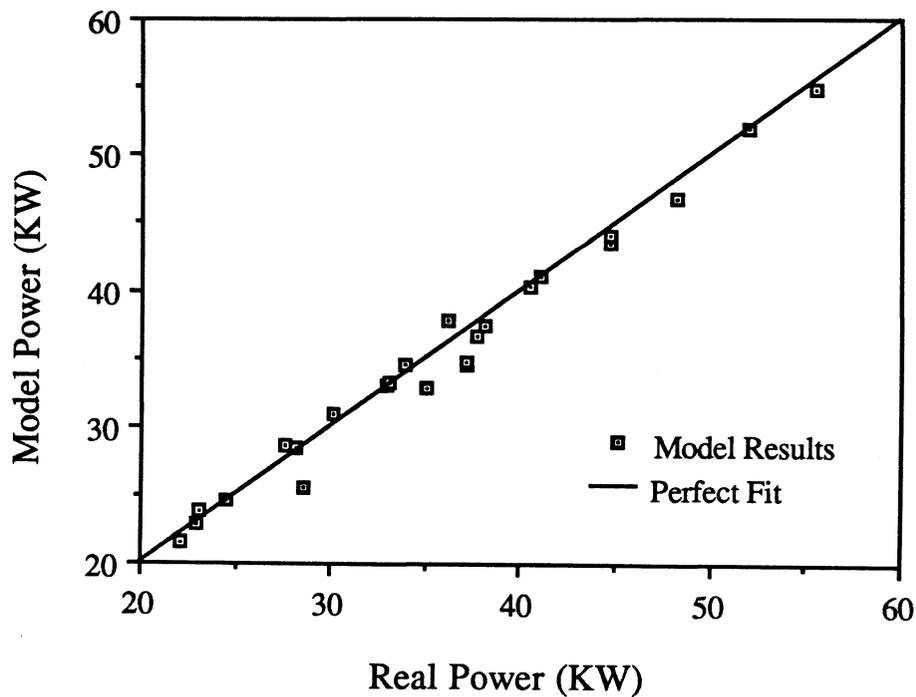


Figure 2.10: Graph of Model System Power vs. Measured System Power

Additionally, there may be discrepancies between the model results and the real system due to the way the real system is controlled. For example, there may be a range of chilled water flow rates that provide a supply air temperature close to the desired set point. If the chilled water flow is initially too high, it is reduced in order to meet the supply air set point. If the chilled water flow is initially too low, the flow will be increased. The final resultant chilled water flow may be different in these two cases, even though all other variables are held constant. Because the model assumes perfect and instantaneous control, the model may give an answer slightly different than either of the two measured above.

Optimization

A large HVAC system can be controlled in many different ways. Often there are several system configurations that could be used to meet the same load. A simple example involves a zone with a cooling load of 12,000 Btu/hr and variable air volume control. The load in this example is entirely sensible, and the room temperature is maintained at 72 °F. One possible way to meet the load is to provide 400 cfm of cool air at 42 °F. The load can also be met by providing 800 cfm of air at 57 °F. One way to choose which settings to use is to select the settings that give the lowest system energy consumption.

The JCEM cooling system has five power consuming components: the chiller, the supply and return fans, the condenser fans, and the chilled water pumps. The total power used by these components depends on various operating variables. Some of the operating variables, such as load, outside air temperature, and sensible heat ratio, can not be controlled. Others, such as chilled water temperature, supply air temperature, and number of operating condenser fans, can be easily controlled. For any set of uncontrolled variables, there are many ways to set the controlled variables such that the load is met. The purpose of optimal control is to select values for the controlled variables that minimize the total system power.

3.1 System Curve Fit

Jim Braun (1989) showed that the total power consumption of large HVAC systems can be represented by a simple quadratic curve fit. The curve is shown here in matrix form.

$$J(\mathbf{f}, \mathbf{M}, \mathbf{u}) = \mathbf{u}^T \hat{\mathbf{A}} \mathbf{u} + \hat{\mathbf{b}}^T \mathbf{u} + \mathbf{f}^T \hat{\mathbf{C}} \mathbf{f} + \hat{\mathbf{d}}^T \mathbf{f} + \mathbf{f}^T \hat{\mathbf{E}} \mathbf{u} + \hat{\mathbf{g}}$$

J is the overall system power. It is a function of \mathbf{f} , the vector of uncontrolled variables; \mathbf{M} , the vector of discrete variables; and \mathbf{u} , the vector of continuous controlled variables. $\hat{\mathbf{A}}$, $\hat{\mathbf{C}}$, and $\hat{\mathbf{E}}$ are coefficient matrices; $\hat{\mathbf{b}}$ and $\hat{\mathbf{d}}$ are coefficient vectors; and $\hat{\mathbf{g}}$ is a scalar. This equation is actually a set of curves, with one curve for each combination of discrete variable settings. Discrete variables are any variable that can only be changed in discrete increments, such as the number of fans or chillers operating at once. The system at JCEM has only one discrete variable: the number of operating condenser fans.

Braun found that this expression can accurately predict the system power, especially at settings close to optimum. The system curve can then be differentiated with respect to the controlled, continuous variables, and set equal to zero. Solving the resultant equation for the controlled variables yields the control settings to minimize the total system power.

In this research project, a slightly different equation was used to fit the system curve. The curve is still in a quadratic form, but some of the terms have been removed, reducing the number of coefficients required to create a curve fit. A full quadratic curve fit would require 27 coefficients to be determined for each discrete variable setting. For this revised curve fit, only 17 coefficients must be found for each discrete variable setting.

The curve was originally created using a statistics program called MINITAB. Model-generated operating data were used, in which each curve fit variable was varied over a wide range of operating conditions. One feature of MINITAB is that it identifies the relative statistical importance of each term of a curve fit. Using the MINITAB criteria, ten terms were removed. By eliminating some of the less important terms, the curve will be less accurate, but will require fewer coefficients. The revised curve is the following:

$$\begin{aligned}
 \text{Power} = & C_0 + C_1(\text{Load}) + C_2(\text{Load})^2 + C_3(\text{SHR}) + C_4(\text{SHR})^2 \\
 & + C_5(T_{sa}) + C_6(T_{sa})^2 + C_7(T_{amb}) + C_8(T_{amb})^2 + C_9(T_{chw}) + C_{10}(T_{chw})^2 \\
 & + C_{11}(\text{Load})(T_{sa}) + C_{12}(\text{Load})(T_{chw}) + C_{13}(\text{SHR})(T_{sa}) + C_{14}(\text{SHR})(T_{chw}) \\
 & + C_{15}(T_{sa})(T_{chw}) + C_{16}(T_{amb})(T_{chw})
 \end{aligned} \tag{3.1}$$

Power refers to the total system power, load to the total system cooling load, and SHR is the sensible heat ratio. C_0 thru C_{16} are the curve fit coefficients. T_{amb} and T_{chw} are the ambient outdoor air temperature and the chilled water set temperature, respectively.

One primary advantage of this method of optimization is that no system modelling is required. Only system operating data are needed to create the curve. This method could ideally be applied to an existing HVAC system. Historical operating data would be used to create a curve fit, and the expression would be used to derive an optimal control strategy.

3.2 Creation of Initial Curve Fit

The quality of a system curve fit is a result of the amount and range of data available from which to generate the curve. When the HVAC system is newly installed and no historical

operating data is available, the system must be operated without knowledge of optimal settings. Once some operating data have been generated, an initial curve fit can be created and used to determine optimal control settings. Later, data generated with the control strategy, along with the initial operating data, are used to refine the system curves. Each successive curve fit incorporates additional operating data, and is more accurate.

In this research, the computer model was used as the HVAC system. Initially, system power values were generated with the computer model over the wide range of operating conditions shown in Table 3.1. This table also includes the range of operating data taken at JCEM to create the system model.

Variable	Curve Input Data		JCEM Data	
	Max	Min	Max	Min
Load (KBtu/hr)	275	120	308	106
Sensible Heat Ratio	0.9	0.7	1.0	0.7
Outside Air Temperature (°F)	90.0	50.0	91.4	40.6
Supply Air Temperature (°F)	60.0	50.0	60.0	49.5
Chilled Water Temperature (°F)	48.0	40.0	49.9	39.0

Table 3.1: Range of Operating Conditions Used to Create Initial System Curve

Care was taken to ensure that all variable settings used in the runs were within the ranges used to create the model. In the case of outside air temperature, only a few tests were performed at very low outside air temperatures. Because data were sparse below 50°F, the range of curve input was limited to values above 50°F. Ranges for load and sensible heat ratio were also reduced due to sparse data near the range limits. The values from the model were curve fit in the form of Equation 3.1, using least squares techniques.

Once created, the curve fit of system power was compared with values generated from the model. Two comparisons were made to verify the curve fit. First, the operating conditions used to create the curve fit were inserted back into the curve. If the curve fit was perfect, the system power calculated from the curve would match the model output exactly. The actual results of this comparison are shown in Figure 3.1.

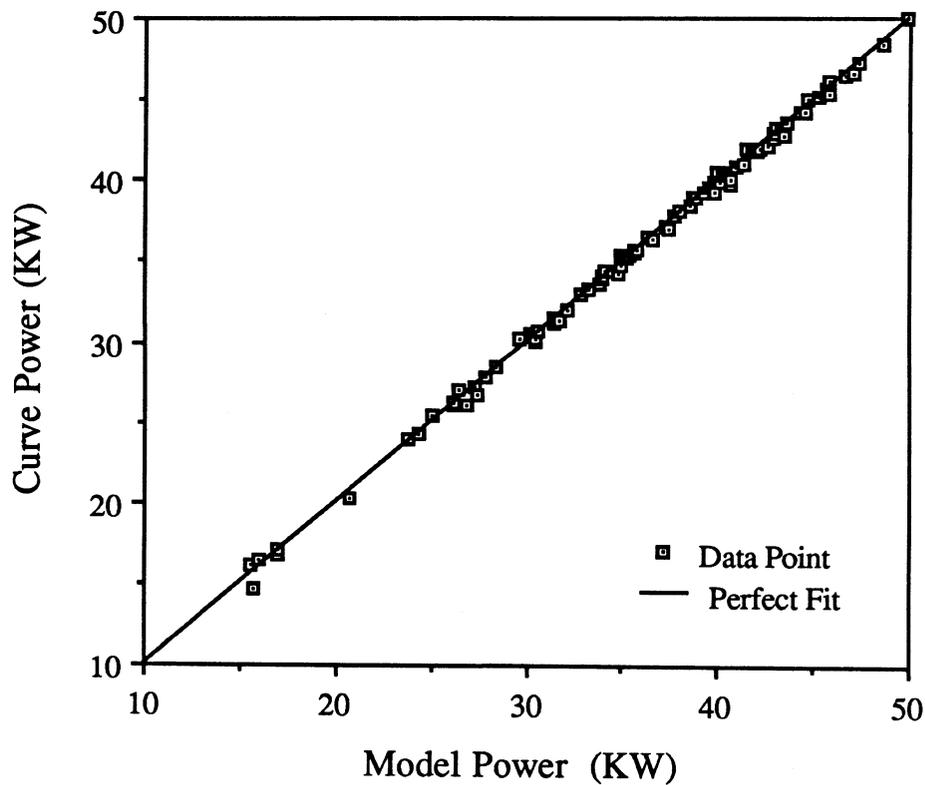


Figure 3.1: Comparison of Power Calculated from Curve Fit vs. Power Used to Generate Curve Fit.

Because all of the points are clustered tightly around the center line, it is clear that the curve fit is good. The maximum error is 1.1 KW which represents a percentage error of 7.0%. The RMS value is 0.30 KW. This graph, however, only shows that the curve accurately represents the values used to create the graph. Figure 3.1 does not verify the ability of the curve to interpolate operating conditions that were not specifically used to generate the curve.

The second comparison used new operating conditions to compare the curve with the model. The variables settings were within the ranges used to generate the curve, so the results should be valid. These results are graphed in Figure 3.2.

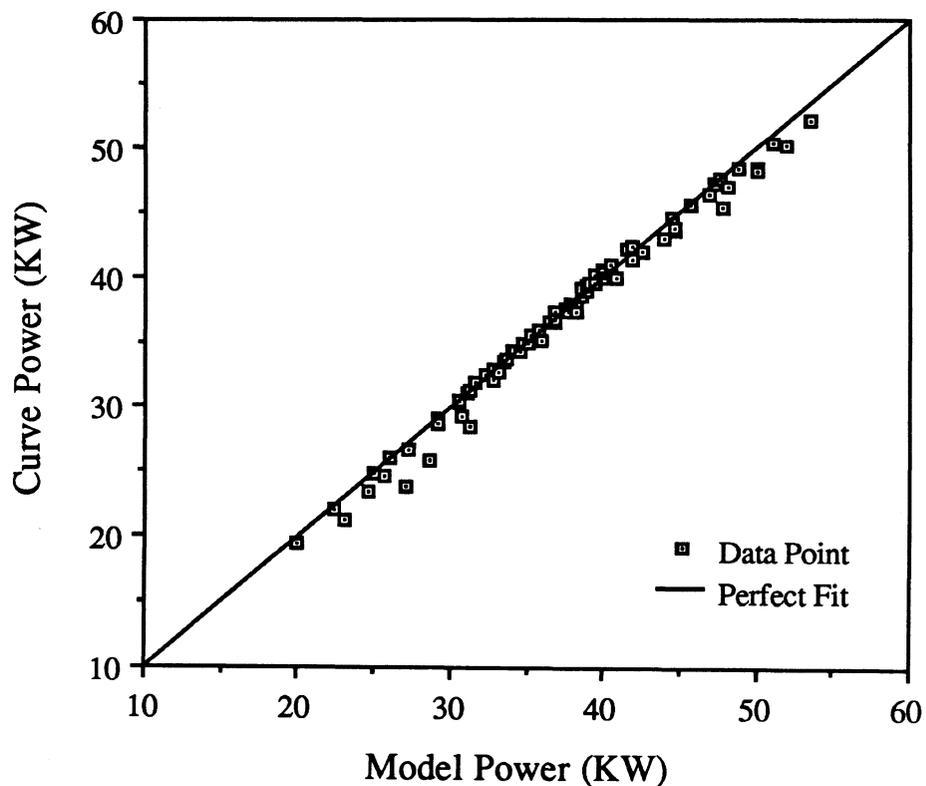


Figure 3.2: Comparison of Model Power with Curve Fit Power

These values still show a good fit. As expected, the points do not cluster as tightly as in Figure 3.1. The maximum error in this graph is 3.34 KW, or 12.3%. The RMS value is 0.86 KW. In the center of the graph, where the curve fit is best defined, the accuracy of the curve is still quite good. At higher or lower powers, larger errors occur. If more data points were used to generate this curve, and more points were used at the extremes of the operating range, the curve fit would be improved. In an actual installation, the curve would be refined in time as more data were gathered.

3.3 Creation of Control Strategy Using Curve Fit

Once the system curve fit was created and verified, it was differentiated with respect to the two continuous controlled variables; supply air temperature and chilled water temperature. The following two equations resulted.

$$\frac{\partial \text{Power}}{\partial T_{sa}} = C_5 + 2 C_6 (T_{sa}) + C_{11}(\text{Load}) + C_{13}(\text{SHR}) + C_{15}(T_{chw})$$

$$\frac{\partial \text{Power}}{\partial T_{chw}} = C_9 + 2 C_{10} (T_{sa}) + C_{12}(\text{Load}) + C_{14}(\text{SHR}) + C_{15}(T_{chw}) + C_{16}(T_{amb})$$

Solving these equations for the controlled variables yields the following equations:

$$T_{sa} = \frac{- [C_5 + C_{11}(\text{Load}) + C_{13}(\text{SHR}) + C_{15}(T_{chw})]}{2 C_6} \quad (3.2)$$

$$T_{chw} = \frac{- [C_9 + C_{12}(\text{Load}) + C_{14}(\text{SHR}) + C_{15}(T_{sa}) + C_{16}(T_{amb})]}{2 C_6} \quad (3.3)$$

These equations can be solved at any operating conditions to give the optimal settings for chilled water temperature and supply air temperature. These equations are used in a subroutine that finds the optimal control variable settings for a given set of operating conditions. A listing of the subroutine is shown in Appendix F.

The optimization methods outlined above are demonstrated in the following example with only one continuous controlled variable and one discrete variable. The outside air temperature is fixed at 75.0 °F, with a load of 200 KBtu/hr and a sensible heat ratio of 0.8. For this example, the chilled water temperature is held constant at 40.0 °F. Optimization techniques are used to determine the ideal supply air temperature and the optimal number of condenser fans.

Inserting these operating conditions into the equations for supply air temperature, the recommended set temperatures are found at each fan setting. These temperatures, as well as the estimated power consumption, can be found in Table 3.2. For this example, the minimum power is obtained at a supply air temperature of 51 °F, with four condenser fans.

Number of Fans	Supply Air Temp (°F)	System Power (KW)
2	46.8	37.0
4	51.1	34.8
6	50.7	39.1

Table 3.2: Optimal Supply Air Temperature Settings and Associated System Powers Calculated from System Curve

These results can also be seen by graphing the system curves and selecting the optimal supply air temperatures and fan settings from the graphs. The curves are shown in Figure 3.3. Clearly, the optimal setting of a supply air temperature of approximately 51 °F with 4 condenser fans closely matches the exact value shown in Table 3.2.

The system curves must also be compared with the true model behavior, to ensure that the curves accurately represent the model. The model was run at the same operating conditions used with the curve fit in this example. The supply air temperature was then varied, so that the optimum setting could be determined using simple search techniques. A graph of the model system power at various supply temperatures is shown in Figure 3.4. This graph shows that the true model optimum of 51 °F at four condenser fans is accurately reflected in the system curves.

Unlike the curve, the model has specific constraints on the range of feasible supply air temperatures. There is a minimum temperature difference that must exist across the cooling coil for the load to be met. For this example, the model required a temperature difference of at least 9 °F across the cooling coil. As a result, supply air temperatures were limited to values above 49 °F. For consistency, the curve results in Figure 3.3 are plotted with dotted lines when unrealistically low supply air temperatures are shown.

Comparing Figure 3.3 and Figure 3.4, it can be seen that the curve predicts the system behavior at 4 fans and 6 fans much more accurately than at 2 fans. All the curves predict the total system power with reasonable accuracy, however the optimal supply air setting is more accurately determined at settings of 4 and 6 fans. The system curves are known to be more accurate close to the system optimum, and often do not perform well far from the

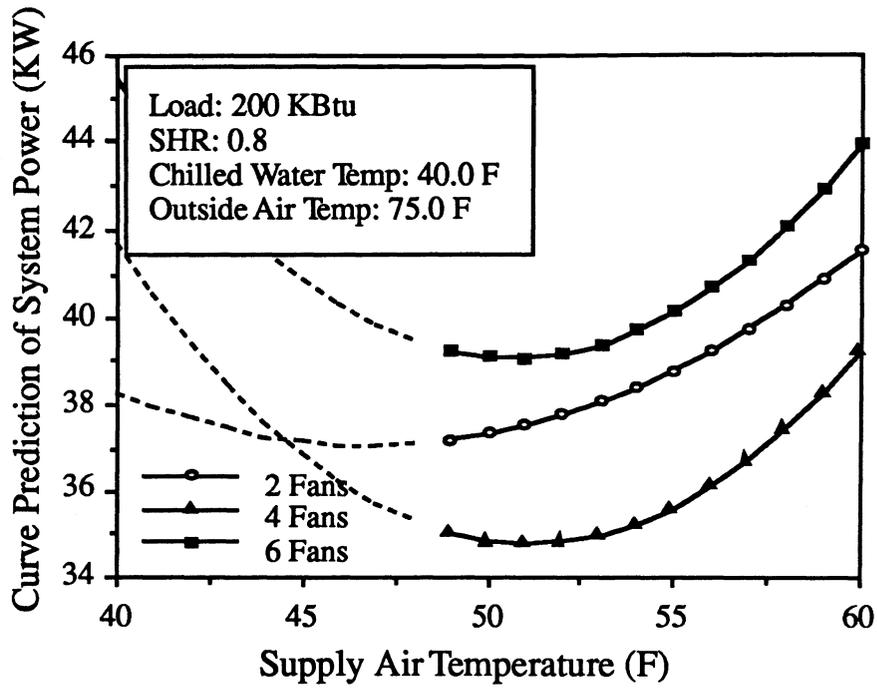


Figure 3.3: Curve Prediction of System Power vs. Supply Air Temperature

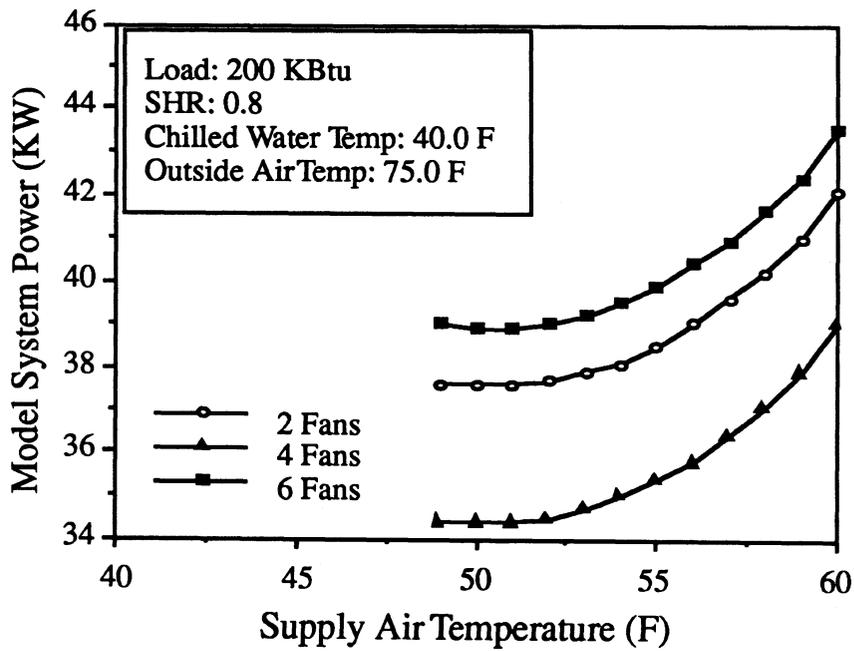


Figure 3.4: Model System Power vs. Supply Air Temperature

optimum. The inability of the 2 fan curve to predict the system minimum may be because any supply air temperature would be far from optimum with a setting of two condenser fans.

3.4 Curve Constraints

When the supply air temperature and chilled water temperature are both optimized as controlled variables, constraints arise on the allowable control settings. At some operating conditions, especially at fan settings far from optimal, it is common for the control strategy to recommend settings that are not physically possible. Two basic types of constraints exist. First, the recommended settings can be unreasonably high or low. A chilled water temperature of 20 °F, for example, is clearly not possible. Secondly, the settings of the two controlled variables can be impossible to implement simultaneously. An example of this constraint is a chilled water temperature that is higher than the recommended supply air temperature. These constraints must be built into the optimization scheme.

The model was designed to adjust the continuous controlled variables if the values given can not be implemented. If the supply air temperature can not be met with the given chilled water temperature, for example, the chilled water temperature is decreased until the supply air temperature and cooling load can be met. The resultant system power, however, may be far from optimal.

Each of the controlled variables has specific limits. The most important constraint on the chilled water set temperature is its lower bound. The chilled water temperature can not be less than 32 °F, or freezing occurs. Actually, a higher limit is usually set to ensure no

localized freezing occurs. At JCEM, the minimum chilled water set temperature is set at 39 °F. The optimization subroutine was modified so that if a chilled water temperature below 39 °F is recommended, the chilled water temperature is set to 39 °F. This temperature is then used in Equation 3.2, with the other operating variables, to determine a new optimal supply air temperature.

The supply air temperature is constrained by its maximum value. If the supply air temperature is too high, no cooling can be done. This constraint does not usually arise because at high supply air temperatures, very large amounts of air are required to obtain any cooling. The large fan power associated with these high set temperatures results in settings that are far from optimal. Thus, the control strategy curves rarely yield high recommended supply air temperatures.

The second type of constraint involves the interaction of the two controlled variables. A supply air temperature setting that is lower than the chilled water temperature is clearly impossible, although both the chilled water temperature and the supply air temperature may appear reasonable if viewed independently. This constraint is a function of the cooling coil, which requires a minimum temperature difference between the chilled water and supply air temperatures. The constraint must be quantified and supplied to the optimization subroutine.

In order to clearly define this constraint, the model was run at a variety of operating conditions. In each run, the supply air temperature was incrementally decreased while the chilled water temperature was increased. The settings were allowed to approach each other until the minimum temperature difference was found, below which the load could not be

met. The results of these runs are plotted in Figure 3.5. Additionally, system runs where the temperature difference was not forced to a minimum are also plotted in Figure 3.5. Both sets of values clearly show that there is a minimum possible temperature difference, which is a function of load.

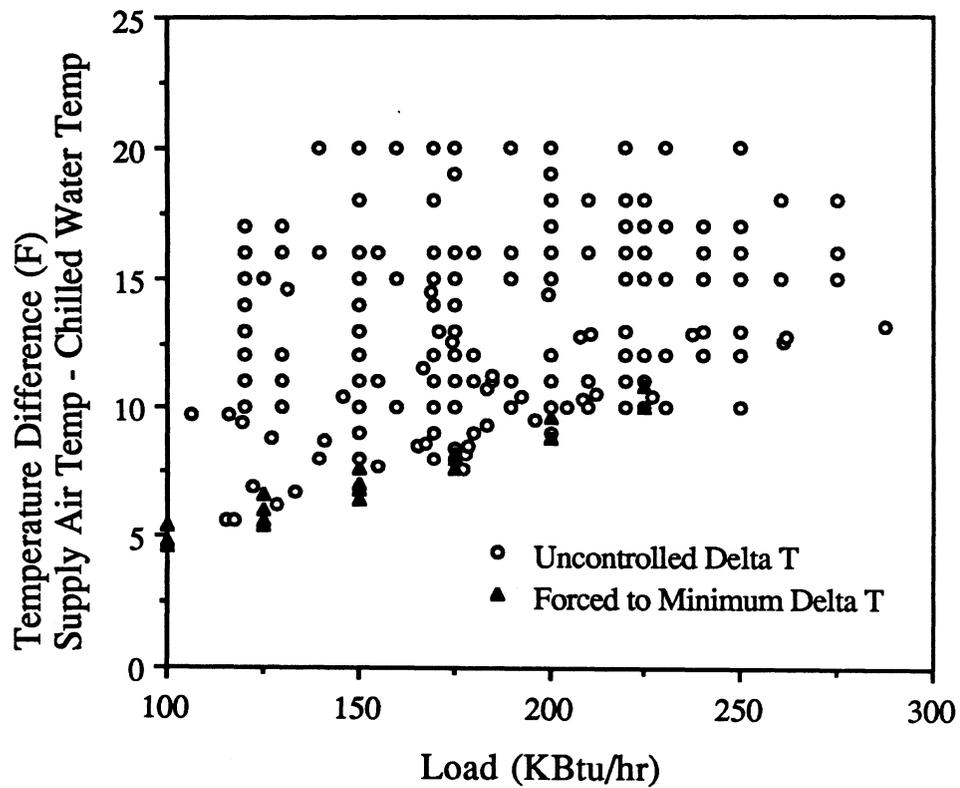


Figure 3.5: Difference Between Supply Air Temperature and Chilled Water Temperature vs. Load

The plot shows that, for a given load, when the temperature difference is forced to a minimum, the resultant temperature difference may be slightly different for different sets of operating conditions. At a load of 150 KBtu/hr, for example, there are several different

values plotted for the minimum temperature difference. Further attempts to describe the constraint revealed that the minimum temperature is also a function of sensible heat ratio.

The constraint was then quantified using the following equation.

$$T_{sa} - T_{chw} = K_0 + K_1(\text{Load}) + K_2 (\text{SHR}) \quad (3.4)$$

This equation predicts the minimum required difference between the supply air temperature and the chilled water temperature within approximately 1.5 °F. It is possible that the difference could be more accurately predicted if a more complex curve was used. Because this curve may be difficult to determine for a real system without extensive testing, an effort was made to keep the curve as simple as possible.

Once the constraint curve was developed, it was incorporated into the optimization procedure. At any particular set of operating conditions, the minimum difference between the supply air temperature and the chilled water temperature is calculated using Equation 3.4. The optimal control settings are then calculated using Equations 3.2 and 3.3. The recommended supply air and chilled water temperatures are checked to ensure that the temperature difference is larger than the minimum difference calculated from the constraint.

If the recommended settings are not acceptable, a new calculation takes place. Equation 3.4 is solved for the supply air temperature and substituted back into Equation 3.1. This yields a new system power curve that includes the required constraint. As before, the curve is differentiated with respect to the controlled variable, producing Equation 3.5, shown below.

$$\begin{aligned}
\frac{\partial \text{Power}}{\partial T_{\text{chw}}} = & C_5 + 2 C_6 (T_{\text{chw}} + K_0 + K_1 (\text{Load}) + K_2 (\text{SHR})) \\
& + C_{10} + 2 C_{11} (T_{\text{chw}} + K_0 + K_1 (\text{Load}) + K_2 (\text{SHR})) \\
& + C_{12} (\text{Load}) + C_{13} (\text{Load}) + C_{14} (\text{SHR}) + C_{15} (\text{SHR}) \\
& + 2 C_{16} (T_{\text{chw}} + K_0 + K_1 (\text{Load}) + K_2 (\text{SHR})) + C_{17}(T_{\text{amb}})
\end{aligned} \tag{3.5}$$

Chilled water temperature is the only controlled variable, because of the implementation of the constraint. This equation can then be set equal to zero, and solved to find the recommended chilled water temperature. Once the chilled water temperature is found, Equation 3.4, which defines the minimum difference between supply air temperature and chilled water temperature is used to determine the optimal supply air temperature.

After the optimization procedure was defined, the revised methodology was verified through testing using the computer model. A specific set of operating conditions was selected. The load was set at 200 KBtu/hr, with a sensible heat ratio of 0.8. The outside air temperature was 75.0 °F. With these variables held constant, the model was run with a large range of supply air temperatures and chilled water temperatures. Both controlled variables were varied in 1 °F increments between 40 °F and 60 °F for all three fan settings.

Some of the resultant operating strategies were unfeasible in that they violated the system constraint. Running all conceivable combinations of controlled variables ensures, however, that all viable combinations of the controlled variables were run. The optimal control variable settings for each fan setting were then found. These values, along with the optimal settings found using the curve fit and constraints, are shown in Table 3.3.

	Supply Air Temp (°F)	Chilled Water Temp (°F)	System Power (KW)
2 Fans - Curve without constraint	47.1	41.8	37.0
2 Fans - Curve with constraint	48.7	40.0	37.2
2 Fans - Model	50.0	40.0	37.6
4 Fans - Curve without constraint	54.6	52.7	32.4
4 Fans - Curve with constraint	55.1	46.4	33.3
4 Fans - Model	54.0	45.0	33.7
6 Fans - Curve without constraint	51.4	45.2	38.5
6 Fans - Curve with constraint	51.9	43.2	38.8
6 Fans - Model	52.0	42.0	38.7

Table 3.3: Comparison of Actual Model Optimum with Optimum Found Using System Curve and Constraints.

The recommended temperature settings are not exact because of the simplicity of the constraint curve. The difference between the minimum power predicted by the curves and the actual optimum power is small. At a setting of 4 fans, there is 1.1 °F, or 2.0%, difference between the recommended supply air temperature and the actual optimum set point. Similarly, there is a 1.4 °F, or 3.1% difference between the recommended and actual chilled water temperature. The resultant difference in power is only 0.4 KW, or 1.2%.

The importance of the constraint curves is very well demonstrated by the results listed in Table 3.3 for four fans. Without the constraint curve, the recommended supply air temperature and chilled water temperature differ by less than 2 °F. When the constraint is implemented, the temperature difference increases to 8.7 °F, and the actual model optimum shows a temperature difference of 9 °F.

A breakdown of the total optimum at each fan setting is shown in Figure 3.6. The system powers are the same results presented in Table 3.3 for optimization performed with a constraint curve.

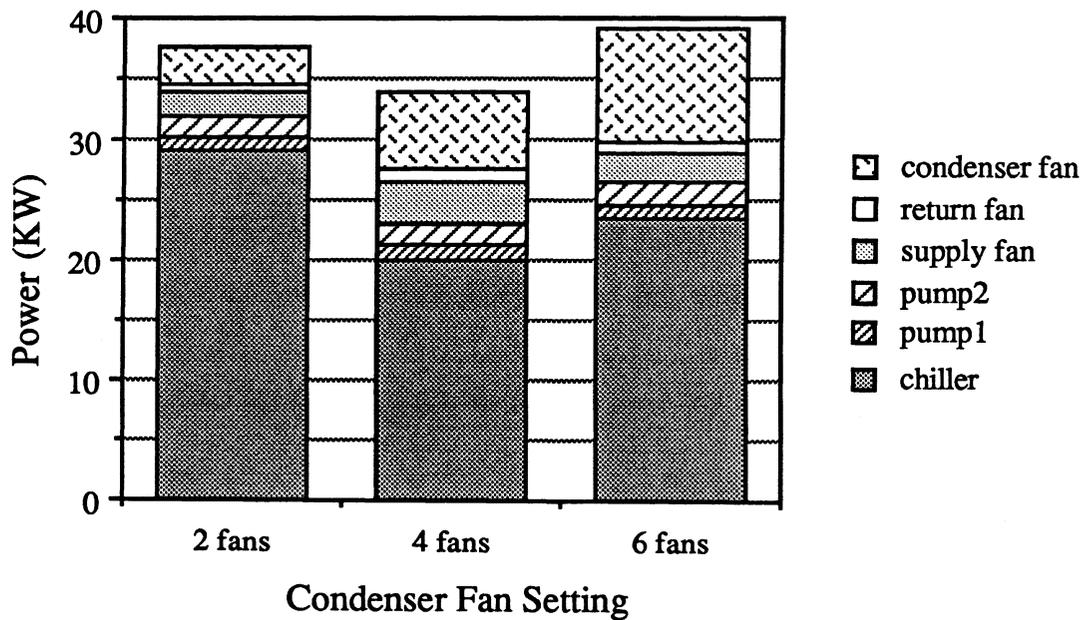


Figure 3.6: System Power Breakdown by Component

As the number of condenser fans is increased, the condenser fan power increases. The reduction in chiller power associated with switching from two to four condenser fans is large enough that the condenser fan power increase is offset by the decrease in chiller power. If additional condenser fans are added, however, there is no additional reduction in chiller power.

Because the optimum supply air set temperature is different for each fan setting, the supply fan power also varies. With four fans, the supply air temperature is higher than at settings of two or six fans, so the supply fan power is also higher. The increased supply air temperature allows a higher chilled water temperature set point, which is responsible for some of the decrease in chiller power.

It is important to remember that Equation 3.4, which describes the supply air and chilled water constraint, is linear. The curve is only designed to give settings that result in near optimal control. Table 3.3 clearly shows that system optimization methods using an overall curve fit, when augmented by well documented constraints, successfully minimizes the overall system power.

Application of Optimization Methods

A series of runs was set up to examine how effective the optimal control strategy might be if implemented into a real HVAC system. As before, the model was used in lieu of an actual system. Hourly outside air temperatures and humidity ratios were taken from a weather file and used to create hourly system loads and sensible heat ratios. The loads and sensible heat ratios were combined with control strategies to generate operating conditions for model input.

The HVAC model was run once without optimal settings, where supply air temperature, chilled water temperature and fan settings remained constant. A second run was done using optimal control techniques. The resultant system powers were then examined to determine the effectiveness of this optimization methodology.

4.1 Generation of Uncontrolled Variable Settings

The HVAC model requires six inputs: load, sensible heat ratio, outdoor air temperature, supply air temperature, chilled water temperature, and number of condenser fans. The three uncontrolled system variables; outdoor air temperature, system load, and sensible heat ratio, were based on information from the weather file. Hourly weather data were used to generate hourly system operating conditions.

The most important features of the input data are that a wide variety of operating conditions were experienced by the system, and that no inadvertent relationship between independent variables was created. The typical summer outdoor air temperatures must also fall within the operating ranges used to generate the model. In this case, data from Nashville, Tennessee were readily available, and met the necessary range criteria.

Outdoor ambient temperatures were taken directly from the weather file. High and low outdoor air temperatures were eliminated so that temperatures were always within the required range. At outdoor air temperatures below 50.0 °F, it was assumed that there would be no chiller load. The outdoor temperature was included in the input file, but the system load was set to zero. At temperatures above 90 °F, the temperature was reduced to 90 °F. This ensured that all ambient temperatures fell within the outdoor air temperature range used for the system model. The cooling season was assumed to run from May 1 through September 30.

A sensible heat ratio independent of any other variables was derived from the outdoor humidity records. This was done to ensure the independence of all the curve fit variables. In a real building, internal gains, which are independent of other variables, effect the sensible heat ratio. At humidity ratios of 0.006 lb_w/lb_{da} or below, a sensible heat ratio of 0.9 was assumed. When the outdoor air humidity ratio is 0.014 lb_w/lb_{da} or above, the sensible heat ratio was set to 0.7. Linear interpolation between these two points provided sensible heat ratios for all other outdoor humidities. This system of generating sensible heat ratio gave values that vary from hour to hour, but that always remain between 0.7 and 0.9.

Three building cooling load profiles were developed. One was used for weekdays, and one for weekends. The third was used for Mondays, when a real building might have to be cooled down after a hot weekend. These three load profiles are shown in Figure 4.1.

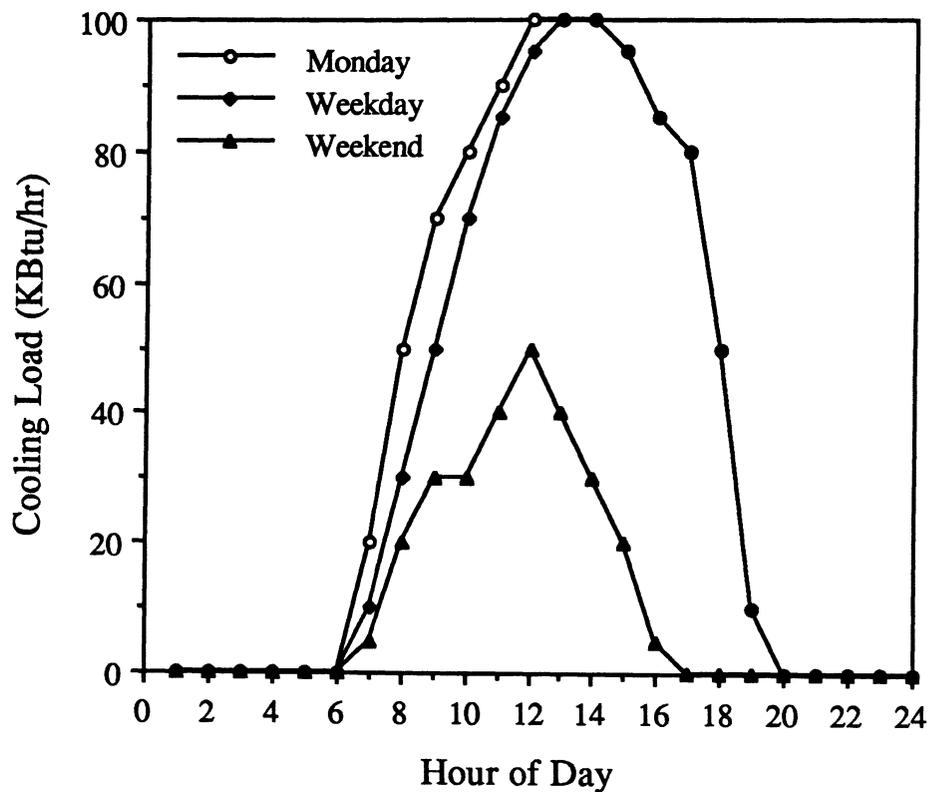


Figure 4.1: Plot of Load Profiles

They are designed to be added onto a base load that varies from day to day. The absolute values of the load profiles change daily, but the profile shapes do not. The same load profiles were used for both the fixed variable run and the optimization run, regardless of the control strategy.

In a real facility, the building load varies throughout the year, and the load is at least partially based on outdoor air temperature. For this test, the load was intentionally not directly related to the outdoor air temperature because both the building cooling load and the ambient outdoor temperature are independent inputs to the optimization curve. Any direct correlation between them might interfere with the curve fit, and thus the optimization methodology

To avoid relating the hourly load profile to the hourly outdoor air temperature, a base load was correlated to the outdoor temperature at midnight. This base amount was then added onto each hour of the daily load profile. As the weather changed seasonally, the system load slowly changed. There was no direct relationship in a given hour, however, between the load and the outdoor air temperature.

4.2 Selection of Controlled Variable Settings

Two different strategies were used to generate values for the controlled variables. One strategy used constant settings for each control variable. The other strategy involved using the optimization techniques outlined in Chapter 3.

4.2.1 Fixed Variable Settings

The first run performed was one in which all controlled variable settings remained constant. The chilled water temperature was set at 42 °F, with a supply air temperature of 53 °F. Four condenser fans were operational at all times. This run was designed to simulate constant controls with no optimization, and was used as the reference run.

It was not possible to find constant supply air temperature and chilled water temperature settings that worked for all operating conditions. Settings that worked for low loads, for example, would violate system constraints at higher loads. If conditions arose where the load could not be met with the specified variable settings, the model varied the settings slightly. If the supply air temperature was too low, and could not be met with the specified chilled water temperature setting, the chilled water temperature was decreased and the supply air temperature increased until a viable set point was found. For both the chilled water temperature and the supply air temperature, the maximum adjustment made was 1.3 °F.

4.2.2 Optimal Variable Settings

The second run performed used optimization procedures to determine the controlled variable set points. Part of the optimization technique includes creating a curve fit of system operating data. A run with constant controls can not be used to generate an optimization curve, because the curves include supply air temperature and chilled water temperature as variables. In order to get a curve fit, the control variables must be varied. For the first month of the optimization run, the controlled variable settings were varied throughout the test. This month of values served to map the system power.

For the month of May, the supply air temperature was varied each hour. It ranged from 50.0 °F up to 54.5 °F in 1.5 °F increments. Its value was simply stepped up 1.5 °F each hour. When a value of 56.0 °F was obtained, 50.0 °F was used instead. Similarly, the chilled water temperature was increased incrementally. Every four hours, it was increased by 1.0 °F, beginning with 39.0 °F, and with a maximum value of 43.0 °F. The number

of condenser fans was dependant on load. At loads less than 175 KBtu/hr, two fans were used. Four fans were used between loads of 175 KBtu/hr and 250 KBtu/hr, with six fans operating at loads above 250 KBtu/hr. By modulating all the operating variables, this mapping run produced data that could be used to generate a system curve. The operating data from the month of May was curve fit into an initial system optimization curve.

An attempt was made to create an initial curve fit using only the first two weeks of May data. When this curve was used for optimization, however, the optimization methodology maximized system power rather than minimizing it. The optimization techniques used in this project find the inflection point of the optimization curve. If the curve fit is good, the inflection point will be the system minimum. If not enough data is used for the initial curve fit, however, the inflection point may be a maximum.

If the initial curve yields maximum power set points, the data that is generated from the model will be far from optimal. When the data generated with maximum power set points was used to revise the system curve, the curve did not significantly improve. It is very important that the initial curve which begins the optimization procedure exhibits the same general trends as the actual system power.

Once the system curve was developed, the optimization began. The model was run though June weather data using the rough optimization curve from the first month's mapping run. The data from June, which should be near optimal, and the data from May, with no optimization, were then combined and a revised optimal curve was created. This process continued until all the cooling season weather data had been run. At the end of each month,

all previous operating data were curve fit, and the revised curve was used for the next month.

It should be recognized that the month of May was never optimized. In a real system, the initial data used to create an optimization curve must be gathered before the optimization can begin. In a simulation, it is possible to use later data from June, and retro-actively optimize May. Because this would be impossible to perform on a real system, May was not optimized during the simulation.

The final results of these tests were two sets of operating data. One, the reference run, used no optimization methods. The second simulated an optimal control strategy being built. It began with non-optimal data and used the data to create a system curve. It then updated that optimization scheme monthly.

4.3 Results

Once each simulation was complete, the total system energy consumption and maximum power were found for each month. The power consumed every hour was summed for each month to determine the total kilowatt hours of energy consumption. These results are presented in Table 4.1. May was not included because it was not optimized in either of the two runs.

In every month, both the maximum power and the monthly energy consumption are less when optimization techniques are used. The total energy savings are not large, only 1042 KWh, or about 1.8%.

Month	Fixed Set Points		With Optimization	
	Max KW	KWh	Max KW	KWh
June	55.6	13928	51.9	13743
July	59.0	15662	53.6	15405
August	57.7	15356	53.2	15070
September	55.1	13142	51.4	12860
Total		58120		57078

Table 4.1: System Power and Energy Consumption With and Without Optimal Control.

The reason that there are only small energy savings is due to the condenser fan setting. For the non-optimal run, the condenser had four fans operating at all time. For many operating conditions, this is the optimal fan setting. Often, there is a limited range of possible supply air and chilled water temperature set points. Regardless of what settings are selected for these variables, they are not far from optimal. For most operating conditions, the constant variable settings of the reference run are near-optimal, so for most hours, the power consumption with constant control was close to the power consumption with optimal control.

The impact of the optimization is more clearly seen in the peak power reduction. For the month of July, the maximum power draw is reduced by 5.4 KW when optimization is performed, which is a decrease of 9.2%. At high loads, the fixed variable settings are not close to optimal. The constant control case was run with four condenser fans, and at high loads, six fans is the optimal setting. Even though six fans consume more energy than four, the additional condenser air flow reduces the chiller power sufficiently to off-set the increase in fan power. Thus, the total system power is reduced.

A more graphic example of the savings can be seen in Figure 4.2. A two day period is plotted, showing the system power with and without optimization. Both days have sensible heat ratios of 0.9. The second day experiences a maximum ambient temperature 5 °F higher than the first day; 90 °F instead of 85 °F. Also, the cooling load is slightly

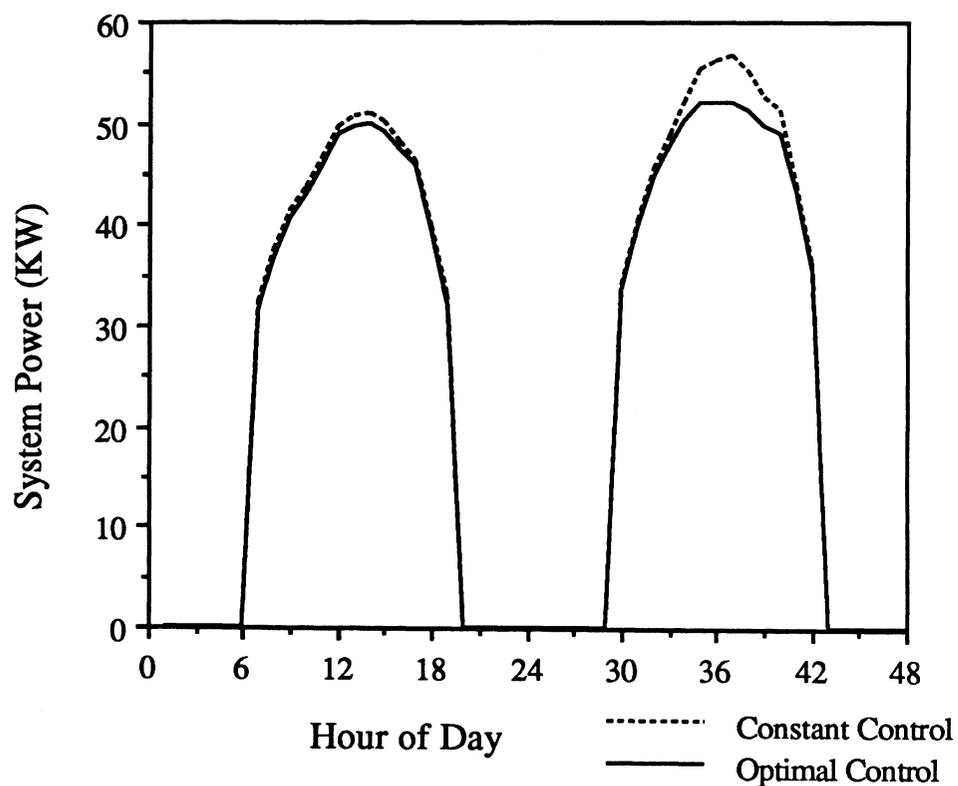


Figure 4.2: Two Day Comparison of Optimal Control Results and Fixed Control Results

higher for the second day, with a maximum of 280 KBtu/hr instead of 269 KBtu/hr. At lower loads during the first day, the non-optimal settings consume almost the same power as the optimal settings. Clearly, the constant variable settings are near optimal. At higher

loads during the second day, the power consumption with optimal control is almost 10% lower than the power consumption with non-optimal control. At these higher loads, switching to six condenser fans is responsible for the majority of the decrease in the system power.

4.4 Requirements for Implementation

The previous section indicated that if this strategy could be successfully implemented into a real system, energy and power savings would result. There are several processes that can be performed on a model that may be more difficult to perform on a real system. These include the generation of data for an initial system curve, and the documentation of system constraints.

In order to create an initial system curve fit, operating data must be gathered. It was explained in Section 4.2.2 that the controlled variables must be modulated for an accurate curve fit to result. If this optimization methodology were implemented with a real system, a scheme would need to be developed to vary the supply air set temperature, the chilled water temperature, and the number of condenser fans. A start-up control strategy is required that spans as wide a range of operating conditions as possible. If the initial system curve fit does not exhibit the same behavior as the system, the curve fit may not improve as additional operating data are generated.

The constraint curve, which is necessary for this optimization methodology, must also be quantified. The optimization requires a curve that describes the minimum allowable difference between the chilled water temperature and the supply air temperature. This curve

was originally developed by testing the system model at various loads and sensible heat ratios. Testing would need to be done in advance for this optimization methodology to be used. The curve describing the constraint was intentionally kept simple, so that it would be easy to document in a real system.

Conclusions and Recommendations

5.1 Summary

The objective of this research was to apply optimization techniques developed by Braun (1989) to a model of the cooling system at the Joint Center of Energy Management (JCEM). Although the JCEM may not represent the performance of an HVAC system in an actual building, the methodology is applicable to actual buildings. A system model was developed, based on operating data from JCEM. The system model encompassed component models of the chiller, condenser fans, supply and return fans, chilled water pumps, and the cooling coil. These models were linked together to form a system model that takes six variables as input: load, sensible heat ratio, outside air temperature, chilled water temperature, supply air temperature, and number of condenser fans.

Once the model was developed, it was used to generate a wide variety of system operating data. Braun found that cooling system operating data can be curve fit to create a single curve that yields system power for a given set of operating conditions. The model values were curve fit, and the curve used to determine optimal control variable settings. A constraint on the chilled water and supply air temperatures was found that was not reflected in the optimization curve. A methodology for determining the nature of the constraint was developed. The constraint was documented, and included as part of the optimization.

Finally, the model was run under two control strategies, using real weather data. For one strategy, control settings were constant, simulating a system without an optimal control strategy. For the second strategy, optimization techniques were used. Model results based on real weather data were curve fit into an optimization curve. The model was then run with optimal controls, which gave more operating data. Periodically, the new operating data were included in the curve fit, updating the control strategy. Energy and power reduction due to optimization were then found by comparing the optimal run to the run with fixed variable settings.

5.2 Conclusions

The system model was developed based on operating data from JCEM. The operating data used for the model must include as wide a range of operating data as possible in order to develop an accurate model. The range of viability of the model is strongly dependent on the range of operating data used. Enough data must be gathered to make the curve fit meaningful. Several component models, including the chiller, fans, and pumps, consist primarily of individual performance curves. Care must be taken that the curve fit variables for these component models span a range at least as broad as the anticipated range for which the model will be used.

When the optimization procedure is started, operating data are used to create the initial optimization curve. This data must span a wide range of operating conditions, so that the overall shape of the curve displays the same trends as the actual system. If the curve fit demonstrates the same characteristics as the system, the fit will improve as more data are generated and the curve is updated. If the curve is inaccurate, the data that are generated

may not improve the curve. A poor initial curve may maximize power, rather than minimizing it.

There are details of system operation that are not well documented by the system curve. The curves used in this study may recommend temperature set points for the chilled water and the supply air which are physically impossible. For any specific load and sensible heat ratio, for example, there is a minimum possible temperature difference across the cooling coil. The curve may recommend a temperature difference less than the minimum. The minimum temperature difference was described using an equation separate from the optimization curve. When the recommended supply air and chilled water temperature did not meet the constraint, the constraint was imposed on the optimization. This constraint exists for all HVAC systems, however the optimal control settings recommended by the system curve may not always violate the constraint.

Documentation of this constraint was achieved through system testing. The system controls were set to increase the chilled water temperature and decrease the supply air temperature until the minimum temperature difference was found. A real system may need to undergo a brief period of testing to document this constraint before an optimization strategy can be implemented.

The results in Chapter 4 show that energy and power reductions are possible through the use of these optimization techniques. For the system model used in this research, the primary energy savings occur from selecting the optimal fan setting. Due to system constraints, the continuous variables were found to have a small range of possible values; thus, any set point that is selected is near the optimal value. Discrete variables had no such

constraints. Changing the discrete variable settings can have a large impact on the system energy consumption for this system. For this research, optimization reduced peak power significantly, but had only a small effect on overall energy consumption.

The results here, for several reasons, are conditional to the JCEM test facility. Some parasitic heat gains to the air stream that often occur in real systems are not included in the test facility. The energy savings do not include all the factors that might be important in an actual building. The air temperature entering the cooling coil was modelled as constant. In an actual building, at low air flow rates, the air temperature entering the cooling coil will be higher than at high flow rates, which will improve the effectiveness of the cooling coil.

5.3 Recommendations

Several further areas of research arose during the course of this research that were not thoroughly investigated in this project. Specifically, the best methods of initiating and building optimization curves and constraint curves have not been determined.

Data must be gathered to create an initial optimization curve. Ideally, data could be gathered through normal system operation. Also, the data would ideally include wide ranges of operation for all the system variables. It is currently unclear whether normal system operation will provide a satisfactory range of data to create initial curves. Further investigation needs to be done into the best way to collect data for the initial curve, and exactly how broad the range of initial data must be to create a viable initial system curve.

Once the performance curve has been generated, it should be updated periodically based on more recent system operation. A strategy for revising the system curves is a possible topic of further study. The total number of data points required for a good curve fit, as well as the frequency with which the curve should be updated, needs further investigation.

In this research project, the system curves were simplified to make initial curve generation easier. Less important terms were discarded, which reduced the required number of coefficients. The accuracy lost by reducing the curves is currently unknown. Once large amounts of data have been gathered, it may be possible to switch from the simplified curve to a more detailed curve for better accuracy. The system curve itself should be examined more thoroughly, so that the trade-off between simplicity and accuracy is well documented.

Similarly, documentation of system constraints was not researched extensively in this work. The need for a system constraint curve was researched, as well as the use of a constraint curve as part of the optimization methodology. In this research, one system constraint was the minimum difference between the supply air and chilled water temperature. A simple curve was used successfully in this project, although there may be better forms of the constraint curve.

As with the initial system data, the best method for collecting constraint data is unknown, and further research into gathering constraint data is needed. In this study, system testing was used to determine the constraint curve, although there may be a way to create adequate constraint curves from manufacturers cooling coil data, or from historical operating data.

The HVAC system model used for this research simulated only steady state conditions, whereas a real system experiences transients. Controls were assumed to be ideal and instantaneous, rather than dynamic. The effects of transients on the optimization methodology should be researched, including controls that require time to travel between control settings.

The results of this research are specific to the JCEM system. The optimization methodology should be applied to other types of systems to determine its applicability to cooling systems in general. Guidelines should be developed for the application of the optimization techniques to different system configurations or equipment types.

Finally, the optimization methodology was implemented on a system model, not on an actual HVAC system. A more realistic test of the optimization techniques studied here would involve implementing them on a real HVAC system.

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Appendix A

Chiller Subroutine

C-----
C THIS SUBROUTINE MODELS THE CHILLER. THE FIRST TIME THAT
C IT IS CALLED, IT CURVE FITS DATA FROM AN EXTERNAL DATA
C FILE INTO A CHILLER MODEL. ON SUBSEQUENT CALLS, IT USES
C THE CURVE TO GIVE CHILLER POWER. PORTIONS OF THIS
C SUBROUTINE WERE TAKEN FROM THE TRNSYS MODEL TYPE 53
C CHILLER MODEL. IT CALLS THE TRNSYS CURVE FIT
C SUBROUTINE DFIT
C-----

subroutine chiller (xin, out, itest, curve)
implicit none

C-----
C DESCRIPTION OF SUBROUTINES
C-----

C DFIT: TRNSYS LIBRARY SUBROUTINE THAT CURVE FITS DATA
C USING LEAST SQUARES TECHNIQUES.
C-----

C DESCRIPTION OF EXTERNAL FILES
C-----

C CHILLKW.DAT: THIS FILE CONTAINS CHILLER POWER DATA TO
C BE CURVE FIT INTO THE CHILLER MODEL. ITS FIRST LINE
C CONTAINS ONLY THE NUMBER OF LINES TO BE READ. EACH
C SUBSEQUENT LINE CONTAINS, IN ORDER, THE NUMBER OF
C OPERATING CONDENSER FANS, CHILLED WATER SET
C TEMPERATURE, OUTDOOR AIR TEMPERATURE, SYSTEM
C COOLING LOAD, AND THE CHILLER POWER.
C-----

C DESCRIPTION OF VARIABLES
C-----

C NDMAX: THIS PARAMETER DEFINES THE MAXIMUM NUMBER
C OF DATA SETS THAT CAN BE USED IN THE
C CURVE FIT
C ROUND: THIS FUNCTION ROUNDS OFF REAL NUMBERS TO THE
C NEAREST INTEGER
C COUNTER: THIS COUNTS THE NUMBER OF DATA POINTS AT
C EACH FAN SETTING
C ITEST: FLAGS THE FIRST TIME THE SUBROUTINE IS CALLED
C XDATA: OPERATING CONDITIONS TO BE CURVE FIT
C YDATA: CHILLER POWERS TO BE USED FOR CURVE FIT (KW)

```

C   F2:          COEFFICIENTS OF THE CURVE FIT FOR TWO FANS
C   F4:          COEFFICIENTS OF THE CURVE FIT FOR FOUR FANS
C   F6:          COEFFICIENTS OF THE CURVE FIT FOR SIX FANS
C   IFLAG:       ERROR FLAG FROM CURVE FIT SUBROUTINE
C   CPCHW:       SPECIFIC HEAT OF CHILLED WATER (KBTU/LB-F)
C   IPRT:        FLAG INDICATING WHETHER OR NOT CURVE FIT
C                   RESULTS SHOULD BE PRINTED
C   LU:          LOGICAL UNIT OF CHILLER DATA FILE
C   LUW:         LOGICAL UNIT TO WHICH ERROR MESSAGES OR
C                   RESULTS SHOULD BE PRINTED
C   NDATA:       ACTUAL NUMBER OF CHILLER DATA SETS TO BE
C                   CURVE FIT
C   NFANS:       NUMBER OF CONDENSER FANS
C   TCHW:        CHILLED WATER TEMPERATURE (F)
C   TAMB:        AMBIENT OUTDOOR AIR TEMPERATURE (F)
C   QH2O:        COOLING COIL LOAD (KBTU/HR)
C   PWR:         CHILLER POWER (KW)
C   Z:           HOLDING VARIABLE
C   N,IJ:        COUNTERS
C   CURVE:       STORAGE ARRAY FOR THE CHILLER CURVE FIT
C   TCHWIN:      INLET CHILLED WATER TEMPERATURE (F)
C   FLWCHW:      CHILLED WATER FLOW RATE (LBS/HR)
C   TCHWSET:     OUTLET CHILLED WATER TEMPERATURE
C                   SET POINT (F)
C   XIN:         ARRAY CONTAINING ALL INPUTS TO CHILLER MODEL
C       XIN(1):   INLET CHILLED WATER TEMPERATURE (F)
C       XIN(2):   CHILLED WATER FLOW RATE (LBS/HR)
C       XIN(3):   AMBIENT OUTDOOR TEMPERATURE (F)
C       XIN(4):   NUMBER OF OPERATING CONDENSER FANS
C       XIN(5):   OUTLET CHILLED WATER SET TEMPERATURE (F)
C   TCHWOUT:     OUTLET CHILLED WATER TEMPERATURE (F)
C   CLOAD:       CHILLER COOLING LOAD (KBTU/HR)
C-----

```

```

integer round, counter, itest,ndmax,iprt,luw,ndata,iflag
integer n,i,ij,nfans,lu
double precision xdata(7,ndmax), ydata(ndmax),f2(7),f4(7)
double precision f6(7),curve(50)
real z,pwr,qh2o,tamb,tchw,cpchw,tchwout,tchwset,flwchw
real xin(5),out(5),cload,tchwin
parameter (ndmax = 200)
common / lunit / luw

```

```

C-----
C   STATEMENT FUNCTION FOR ROUND-OFF OF REAL NUMBERS
C   TO NEAREST INTEGER
C-----

```

```

round(rnum) = rnum + sign(0.5,rnum)

```

```
C-----
C  SET UP PARAMETERS
C-----
```

```
cpchw = 1.0
iprt = 0
lu    = 3
```

```
C-----
C  DETERMINE NUMBER OF DATA SETS
C-----
```

```
if(itest.eq.1)then
  open(unit = lu, file = 'chillkw.dat',status='old')
  rewind lu
  read(lu,*)ndata
  iflag = 0
  if(ndata .gt. ndmax) then
    write(luw,1001) ndmax
    stop
  endif
  if(ndata .lt. 7) then
    write(luw,1007)
    stop
  endif
endif
```

```
C-----
C  IF DATA IS TO BE PRINTED OUT, PRINT HEADER
C-----
```

```
if(iprt.eq.1)then
  write(luw,1008)lu
endif
```

```
C-----
C  SORT AND STORE DATA FOR TWO FAN EXPERIMENTS, AND
C  PRINT DATA IF DESIRED
C-----
```

```
counter = 0
do 100 n = 1,ndata
  read(lu,*)nfans,tchw,tamb,qh2o,pwr
  if(iprt.eq.1)then
    write(luw,1009)n,tchw,tamb,qh2o,pwr
  endif
  if(nfans.eq.2)then
    counter = counter + 1
    xdata(1,counter) = 1.0
    xdata(2,counter) = tamb
  endif
enddo
```

```

        xdata(3,counter) = tamb**2
        xdata(4,counter) = tchw
        xdata(5,counter) = tchw**2
        xdata(6,counter) = qh2o
        xdata(7,counter) = qh2o**2
        ydata(counter) = pwr
    endif
100    continue

C-----
C    REWIND TAPE, AND SET UP FOR NEXT READING
C-----

        rewind(lu)
        read(lu,*)ndata

C-----
C    DOUBLE PRECISION CURVE-FIT OF POWER W/ 2 FANS
C-----

        if(counter.gt.7) then
            call dfit(7,ndmax,7,counter,xdata,ydata,f2,iflag)

C-----
C    IF CURVE FIT FAILS, PRINT ERROR MESSAGE
C-----

            if(iflag .ne. 0) then
                write(luw,1002)
            endif

C-----
C    COMPARE CURVE-FIT RESULTS WITH THOSE DETERMINED FROM
C    THE DATA, IF DESIRED
C-----

        if(iprt.eq.1) then
            write(luw,1012)
            do 150 n = 1,counter
                z = 0.
                do 125 i = 1,7
                    z = z + f2(i)*xdata(i,n)
125                continue
                    write(luw,1015) n, z, ydata(n)
150                continue
            endif
        else
            write(luw,1020)
        endif

```

```
C-----
C  SORT AND STORE DATA FOR FOUR FAN EXPERIMENTS
C-----
```

```

counter =0
do 200 n = 1,ndata
  read(lu,*)nfans,tchw,tamb,qh2o,pwr
  if(nfans.eq.4)then
    counter = counter + 1
    xdata(1,counter) = 1.0
    xdata(2,counter) = tamb
    xdata(3,counter) = tamb**2
    xdata(4,counter) = tchw
    xdata(5,counter) = tchw**2
    xdata(6,counter) = qh2o
    xdata(7,counter) = qh2o**2
    ydata(counter) = pwr
  endif
200  continue
```

```
C-----
C  REWIND TAPE, AND SET UP FOR NEXT READING
C-----
```

```

rewind(lu)
read(lu,*)ndata
```

```
C-----
C  DOUBLE PRECISION CURVE-FIT OF POWER W/ FOUR FANS
C-----
```

```

if(counter.gt.7)then
  call dfit(7,ndmax,7,counter,xdata,ydata,f4,iflag)
```

```
C-----
C  IF CURVE FIT FAILS, PRINT ERROR MESSAGE
C-----
```

```

if(iflag .ne. 0) then
  write(luw,1004)
endif
```

```
C-----
C  COMPARE CURVE-FIT RESULTS WITH THOSE DETERMINED FROM
C  THE DATA IF DESIRED
C-----
```

```

if(iprt.eq.1) then
  write(luw,1013)
  do 250 n = 1,counter
```

```

                z = 0.
                do 225 i = 1,7
                    z = z + f4(i)*xdata(i,n)
225                continue
                write(luw,1015) n, z, ydata(n)
250            continue
        endif
    else
        write(luw,1021)
    endif

```

```

C-----
C   SORT AND STORE DATA FOR SIX FAN EXPERIMENTS
C-----

```

```

        counter = 0.0
        do 300 n = 1,ndata
            read(lu,*)nfans,tchw,tamb,qh2o,pwr
            if(nfans.eq.6)then
                counter = counter + 1
                xdata(1,counter) = 1.0
                xdata(2,counter) = tamb
                xdata(3,counter) = tamb**2
                xdata(4,counter) = tchw
                xdata(5,counter) = tchw**2
                xdata(6,counter) = qh2o
                xdata(7,counter) = qh2o**2
                ydata(counter) = pwr
            endif
300        continue

```

```

C-----
C   REWIND TAPE, AND SET UP FOR NEXT READING
C-----

```

```

        rewind(lu)
        read(lu,*)ndata

```

```

C-----
C   DOUBLE PRECISION CURVE-FIT OF POWER W/ 6 FANS
C-----

```

```

        if(counter.gt.7)then
            call dfit(7,ndmax,7,counter,xdata,ydata,f6,iflag)

```

```

C-----
C   IF CURVE FIT FAILS, PRINT ERROR MESSAGE
C-----

```

```

    if(iflag .ne. 0) then
      write(luw,1006)
    endif

```

```

C-----
C  COMPARE CURVE-FIT RESULTS WITH THOSE DETERMINED FROM
C  THE DATA IF DESIRED
C-----

```

```

    if(iprt.eq.1) then
      write(luw,1014)
      do 350 n = 1,counter
        z = 0.
        do 325 i = 1,7
          z = z + f6(i)*xdata(i,n)
325         continue
          write(luw,1015) n, z, ydata(n)
350         continue
        continue
      endif
    else
      write(luw,1022)
    endif

```

```

C-----
C  STORE CURVE FITS IN ARRAY
C-----

```

```

    do 400 ij = 1,7
      curve(ij) = f2(ij)
      curve(ij+7) = f4(ij)
      curve(ij+14) = f6(ij)
400    continue
  endif

```

```

C-----
C  TAKE CURVE OUT OF STORAGE
C-----

```

```

    do 450 ij = 1,7
      f2(ij)=curve(ij)
      f4(ij)=curve(ij+7)
      f6(ij)=curve(ij+14)
450    continue

```

```

C-----
C  SET UP INPUTS INPUTS
C-----

```

```

tchwin = xin(1)
flwchw = xin(2)
tamb = xin(3)
nfans = round(xin(4))
tchwset = xin(5)

```

```

C-----
C IF THERE ARE CONDENSER FANS RUNNING AND CHILLED WATER
C FLOWING, CALCULATE THE CHILLER LOAD
C-----

```

```

if(nfans.gt.0. .and. flwchw.gt.0.) then
    tchwout = tchwset
    cload = flwchw*cpchw*(tchwin-tchwset)/1000.
    tchw = tchwout

```

```

C-----
C THEN PERFORM POWER CALCULATIONS
C-----

```

```

    if(nfans.eq.2)then
+       pwr=f2(1)+f2(2)*tamb+f2(3)*tamb**2+f2(6)*cload+f2(7)*cload**2
+       +f2(4)*tchw+f2(5)*tchw**2
    else
        if(nfans.eq.4)then
+           pwr=f4(1)+f4(2)*tamb+f4(3)*tamb**2+f4(6)*cload
+           +f4(7)*cload**2
+           +f4(4)*tchw+f4(5)*tchw**2
        else
            if(nfans.eq.6)then
+               pwr=f6(1)+f6(2)*tamb+f6(3)*tamb**2+f6(6)*cload
+               +f6(7)*cload**2
+               +f6(4)*tchw+f6(5)*tchw**2
            else
                write(luw,1110)nfans
            endif
        endif
    endif
else

```

```

C-----
C IF THE CHILLER ARE OFF, THERE IS NO FLOW, OR THE
C CONDENSER FANS ARE OFF, RETURN ZEROS
C-----

```

```

    cload = 0.0
    tchwout = tchwin
    pwr = 0.0

```

```

endif

```

```

C-----
C   SET UP OUTPUT
C-----

```

```

    out(1) = tchwout
    out(2) = flwchw
    out(3) = cload
    out(4) = pwr
    return

```

```

C-----
C   ALL WRITE FORMATS ARE HERE
C-----

```

```

1001 format(/2x,'***** error *****/4x,'only ',i3,
.         ' data points allowed in chiller curve fit!')
1002 format(/2x,'***** error ***** '
.         /4x,' unable to perform chiller curve fit for two fans')
1004 format(/2x,'***** error ***** '
.         /4x,' unable to perform chiller curve fit for four fans')
1006 format(/2x,'***** error *****'
.         /4x,' unable to perform chiller curve fit for six fans')
1007 format(/2x,'***** error *****/4x,'a minimum of 6 data'
.         ', points are required in chiller curve fit!')
1008 format(/2x,'***** chiller input data ***** '
.         ' logical unit ',i3//2x,'number chw temp',
.         ' amb temp   load       power ')
1009 format(3x,i3,3x,4(1x,1pe10.3))
1012 format(/2x,'***** curve-fit results for two fans *****/4x,
.         ' number      p(model)      p(data)      (p=chiller power)')
1013 format(/2x,'***** curve-fit results for four fans *****/4x,
.         ' number      p(model)      p(data)      (p=chiller power)')
1014 format(/2x,'***** curve-fit results for six fans *****/4x,
.         ' number      p(model)      p(data)      (p=chiller power)')
1015 format(6x,i3,1x,2(1x,1pe11.3))
1020 format(/2x,'***** warning *****'
.         /4x,' not enough data was supplied to curve fit 2 fans!')
1021 format(/2x,'***** warning ***** '
.         /4x,' not enough data was supplied to curve fit 4 fans!')
1022 format(/2x,'***** warning ***** '
.         /4x,' not enough data was supplied to curve fit 6 fans!')
1110 format(/2x,'*****error*****'
.         /4x,' number of fans = ',i4,'/number of fans',
.         ' must be 2, 4 or 6')

```

```

end

```

Appendix B

Main Model Program

C-----
C THIS PROGRAM COORDINATES THE VARIOUS COMPONENT
C MODELS INTO AN OVERALL SYSTEM MODEL
C-----

program model
implicit none

C-----
C DESCRIPTION OF SUBROUTINES
C-----

C FINDOPT: FINDS THE OPTIMUM CONTROL VARIABLE SETTINGS
C FOR A GIVEN SET OF OPERATING CONDITIONS.
C FINDFLOW: FINDS THE REQUIRED SUPPLY AIR FLOW FOR A
C GIVEN LOAD AND SENSIBLE HEAT RATIO.
C FINDHR: FINDS THE COOLING COIL INLET HUMIDITY
C RATIO FOR SENSIBLE HEAT RATIOS
C LESS THAN 1.
C FINDTEMP: FINDS THE COOLING COIL EXITING AIR
C TEMPERATURE FOR SENSIBLE HEAT
C RATIOS OF 1.
C CHILLER: FINDS CHILLER POWER FROM CURVE FIT
C BASED ON OPERATING CONDITIONS
C-----

C DESCRIPTION OF EXTERNAL FILES
C-----

C TEST.IN: INPUT FILE FOR SYSTEM OPERATING CONDITIONS.
C THE FIRST LINE CONTAINS ONLY THE NUMBER
C OF SETS OF OPERATING CONDITIONS TO BE
C READ. EACH SUBSEQUENT LINE MUST
C CONTAIN, IN ORDER, CHILLED WATER SET
C TEMPERATURE, SUPPLY AIR SET TEMPERATURE,
C NUMBER OF CONDENSER FANS, OUTDOOR AIR
C TEMPERATURE, SYSTEM COOLING LOAD, AND
C SENSIBLE HEAT RATIO. IF OPTIMIZATION IS TO
C BE DONE, THE FIRST 3 INPUTS MAY BE DUMMY
C NUMBERS.
C TEST.OUT: OUTPUT FILE OF OPERATING CONDITIONS AND
C SYSTEM POWER
C BAD.OUT: OPERATING CONDITIONS THAT RESULT IN AN ERROR
C ARE PRINTED TO THIS FILE.

DESCRIPTION OF VARIABLES	
XIN:	INPUT TO THE SUBROUTINES FINDHR AND FINDTEMP
XIN(1):	COOLING COIL INLET AIR TEMPERATURE (F)
XIN(2):	COOLING COIL INLET AIR HUMIDITY RATIO (LBS H ₂ O/ LBS DRY AIR)
XIN(3):	MASS FLOW RATE OF AIR (LBS/HR)
XIN(4):	CHILLED WATER SET TEMPERATURE (F)
XIN(5):	CHILLED WATER FLOW RATE (LBS/HR)
OUT:	OUTPUT FROM SUBROUTINES FINDHR AND FINDTEMP
OUT(1):	COOLING COIL OUTLET AIR TEMPERATURE (F)
OUT(2-3):	UNUSED
OUT(4):	COOLING COIL OUTLET CHILLED WATER TEMPERATURE (F)
OUT(5):	CHILLED WATER FLOW RATE (LBS/HR)
OUT(6-10):	UNUSED
XLOAD:	SYSTEM COOLING LOAD (KBTU/HR)
TCHWSET:	TEMPERATURE SET POINT FOR SUPPLY CHILLED WATER (F)
GPMA:	HIGHEST FEASIBLE CHILLED WATER FLOW (LBS/HR)
GPMB:	LOWEST FEASIBLE CHILLED WATER FLOW (LBS/HR)
GPMC:	CURRENT GUESS OF CHILLED WATER FLOW (LBS/HR)
RATIO:	USED TO CALCULATE NEXT GUESS VALUE FOR CHILLED WATER FLOW
SHR:	SENSIBLE HEAT RATIO
TAIN:	TEMPERATURE OF INLET AIR TO COOLING COIL (F)
TSET:	TEMPERATURE SETPOINT FOR SUPPLY AIR (F)
AIRFLO:	SUPPLY AIR MASS FLOW RATE (LBS/HR)
TOUTA:	OUTLET SUPPLY AIR TEMPERATURE AT HIGHEST FEASIBLE CHILLED WATER FLOW RATE (F)
TOUTB:	OUTLET SUPPLY AIR TEMPERATURE AT LOWEST FEASIBLE CHILLED WATER FLOW RATE (F)
TOUTC:	OUTLET SUPPLY AIR TEMPERATURE AT CURRENT GUESS OF CHILLED WATER FLOW RATE (F)
CIN:	INPUT TO CHILLER SUBROUTINE
CIN(1):	INLET CHILLED WATER TEMPERATURE (F)
CIN(2):	INLET CHILLED WATER FLOW RATE (LBS/HR)
CIN(3):	OUTSIDE AIR TEMPERATURE (F)
CIN(4):	NUMBER OF CONDENSER FANS
CIN(5):	OUTLET CHILLED WATER TEMPERATURE (F)
COU:	OUTPUT FROM CHILLER SUBROUTINE
COU(1-3):	UNUSED
COU(4):	CHILLER POWER (KW)
COU(5-10):	UNUSED
CHWFLO:	CHILLED WATER FLOW RATE (LBS/HR)
RATFLO:	FLOW RATE AS FRACTION OF MAXIMUM POSSIBLE FLOW RATE
SUM:	TOTAL SYSTEM POWER (KW)

C PWR: POWER OF INDIVIDUAL SYSTEM COMPONENTS (KW)
 C TAMB: OUTSIDE AIR TEMPERATURE (F)
 C FACTOR: LOAD, BELOW WHICH THE CONDENSER
 C FANS CYCLE (KBTU/HR)
 C CURVE: UNUSED, REQUIRED AS INPUT TO
 C CHILLER SUBROUTINE
 C LUW: LOGICAL UNIT TO WHICH ERROR MESSAGES
 C ARE WRITTEN
 C IFAIL: CONDITION FLAG FOR SUBROUTINES FINDHR
 C AND FINDTEMP IT INDICATES WHETHER
 C SUBROUTINE OUTPUT IS AN ACTUAL POINT,
 C OR AN ESTIMATE
 C I,K: COUNTERS
 C IFAILA: CONDITION FLAG AT HIGHEST FEASIBLE CHILLED
 C WATER FLOW
 C IFAILB: CONDITION FLAG AT LOWEST FEASIBLE CHILLED
 C WATER FLOW
 C IFAILC: CONDITION FLAG AT CURRENT GUESS OF CHILLED
 C WATER FLOW
 C NUMFANS: NUMBER OF OPERATING CONDENSER FANS
 C NDATA: NUMBER OF OPERATING CONDITIONS TO BE RUN
 C KCK: FLAG TO MARK THE FIRST CALL TO THE CHILLER
 C SUBROUTINE
 C FLAG2: FLAGS WHEN THE SUPPLY AIR TEMPERATURE IS
 C DECREASED TO MEET A CONSTRAINT
 C

 real xin(5),out(10),xload,tchwset,gpma,gpmb,gpmc,ratio
 real shr,tain,tset,airflo,touta,toutb,toutc
 real chwflo,ratflo,sum,pwr,tamb,cin(5),cout(10)
 real factor
 double precision curve(50)
 integer luw,ifail,i,ifaila,ifailb,ifailc,numfans,k
 integer ndata,kck,flag2
 common / lunit / luw

C-----
 C OPEN UP DATA FILES
 C TEST.IN: INPUT FILE
 C TEST.OUT: MAIN OUTPUT FILE
 C BAD.OUT: ANY OPERATING CONDITIONS THAT
 C GENERATE ERRORS ARE PRINTED TO BAD.OUT
 C-----

open(unit=1,file='test.out',status='new')
 open(unit=2,file='bad.out',status='new')
 open(unit=4,file='test.in',status = 'old')

```

C-----
C  SET UP DEFAULT UNIT TO WHICH TO WRITE ERROR
C  MESSAGES AS THE MAIN OUTPUT FILE, AND
C  WRITE COLUMN HEADERS
C-----

```

```

    luw = 1
    write(1,2001)
    write(2,2001)
    kck = 1

```

```

C-----
C  READ IN NUMBER OF DATA SETS, BEGIN TO LOOP
C  THROUGH ALL DATA SETS BY READING IN FIRST
C  SET OF OPERATING CONDITIONS
C-----

```

```

    read(4,*) ndata
    do 400 k = 1,ndata
        read(4,*)tchwset,tset,numfans,tamb,xload,shr
    
```

```

C-----
C  SET UP INITIAL CONSTANTS AND COUNTERS
C-----

```

```

    tain = 76.5
    i = 0
    flag2 = 0

```

```

C-----
C  IF AT A NO LOAD CONDITION, WRITE 0 FOR ALL VARIABLES
C  AND JUMP TO THE NEXT SET OF OPERATING CONDITIONS
C-----

```

```

    if(xload.eq.0)then
        write(1,2003)xload,shr,0.0,0.0,0,tamb,0.0
        goto 400
    endif

```

```

C-----
C  DETERMINE THE OPTIMAL CONTROL SETTINGS FOR
C  THE CURRENT SET OF OPERATING CONDITIONS
C-----

```

```

    call findopt(0,xload,shr,tamb,tset,tchwset,numfans)

```

```

C-----
C  FIND THE SUPPLY AIR FLOW RATE
C-----

```

```
100      call findflow(xload,shr,tain,tset,airflo)
```

```
C-----
C      IF THE SUPPLY AIR FLOW RATE IS TOO HIGH, ADJUST THE
C      SUPPLY AIR TEMPERATURE DOWN AND FLAG THAT IT
C      HAS BEEN DECREASED. THEN FIND A NEW AIR FLOW RATE
C-----
```

```
      if(airflo.gt.(12500*0.064*60))then
          tset = tset - 0.1
          flag2 = 1
          goto 100
      endif
```

```
C-----
C      SET UP INPUT VARIABLES FOR SUBROUTINES
C-----
```

```
      xin(1) = tain
      xin(3) = airflo
      xin(4) = tchwset
```

```
C-----
C      BEGIN SEARCH FOR OPERATING CONDITIONS BY SETTING THE
C      CHILLED WATER FLOW TO MAXIMUM
C-----
```

```
      gpma = 30000
      xin(5) = gpma
      ifail = 0
```

```
C-----
C      IF THERE IS ANY LATENT LOAD, USE SUBROUTINE FINDHR,
C      OTHERWISE, USE SUBROUTINE FINDTEMP
C-----
```

```
      if(shr.lt.1.0)then
          call findhr(xin,xload,out,ifail)
      else
          call findtemp(xin,tset,out,ifail)
      endif
```

```
C-----
C      USE THE RESULTANT OUTLET SUPPLY AIR TEMPERATURE AS ONE
C      SEARCH BOUNDARY. ALSO RETAIN THE CONDITIONS FLAG AT
C      THIS POINT.
C-----
```

```
      touta = out(1)
      ifaila = ifail
```

```

C-----
C IF, AT MAXIMUM CHILLED WATER FLOW, THE LOAD IS LESS THAN
C THE DESIRED LOAD, THEN THE LOAD CANNOT BE MET.
C PRINT MESSAGES INDICATING SITUATION AND GO TO
C THE NEXT SET OF OPERATING CONDITIONS
C-----

```

```

      if((ifail.eq.1).and.(shr.lt.1.0))then
        write(2,1000)
        write(1,1000)
        write(2,2004)xload,shr,tchwset,tset,numfans,tamb
        goto 400
      endif

```

```

C-----
C IF, AT MAXIMUM CHILLED WATER FLOW, THE OUTLET AIR TEMP. IS
C HIGHER THAN DESIRED, THE SUPPLY AIR TEMP. SETPOINT WILL
C NEVER BE MET. IF THE SUPPLY AIR TEMP. HAS NOT PREVIOUSLY
C BEEN REDUCED TO MEET OTHER CONSTRAINTS, INCREASE IT.
C ALSO, DECREASE THE CHILLED WATER TEMP. SETPOINT.
C THEN, RESTART THE CALCULATIONS WITH NEW SETPOINTS.
C-----

```

```

      if(touta.gt.tset)then
        if(flag2.eq.0)then
          tset = tset + 0.1
        endif
        tchwset = tchwset - 0.1
        flag2=0
        goto 100
      endif

```

```

C-----
C CHECK TO SEE IF SUPPLY AIR TEMPERATURE SETPOINT IS MET.
C IF SO, GO STRAIGHT TO THE POWER CALCULATIONS
C-----

```

```

      if((abs(touta-tset).le.0.1).and.(ifail.eq.0))then
        write(6,1001)i
        goto 300
      endif

```

```

C-----
C CONTINUE SEARCH FOR OPERATING CONDITIONS WITH THE
C MINIMUM CHILLED WATER FLOW RATE.
C-----

```

```

      gpmb = 7500
      xin(5) = gpmb
      ifail = 0

```

```

C-----
C   IF THERE IS ANY LATENT LOAD, USE THE SUBROUTINE FINDHR,
C   OTHERWISE USE FINDTEMP
C-----

```

```

      if(shr.lt.1.0)then
        call findhr(xin,xload,out,ifail)
      else
        call findtemp(xin,tset,out,ifail)
      endif

```

```

C-----
C   USE THE RESULTANT OUTLET SUPPLY AIR TEMPERATURE AS THE
C   SECOND SEARCH BOUNDARY. ALSO, RETAIN CONDITIONS FLAG
C   AT THIS POINT.
C-----

```

```

      toutb = out(1)
      ifailb = ifail

```

```

C-----
C   IF, AT MINIMUM CHILLED WATER FLOW, THE LOAD IS GREATER
C   THAN THE DESIRED LOAD, THEN THE LOAD CAN NOT BE MET.
C   PRINT MESSAGES AND GO TO THE NEXT SET OF OPERATING
C   CONDITIONS.
C-----

```

```

      if((ifail.eq.2).and.(shr.lt.1.0))then
        write(1,1002)
        write(2,1002)
        write(2,2004)xload,shr,tchwset,tset,numfans,tamb
        goto 400
      endif

```

```

C-----
C   IF, AT MINIMUM CHILLED WATER FLOW, THE OUTLET AIR
C   TEMPERATURE IS LOWER THAN DESIRED, THE SUPPLY AIR
C   TEMPERATURE SETPOINT WILL NEVER BE MET. PRINT
C   MESSAGES AND GO TO THE NEXT SET OF OPERATING CONDITIONS
C-----

```

```

      if(toutb.lt.tset)then
        write(2,1005)
        write(1,1005)
        write(2,2004)xload,shr,tchwset,tset,numfans,tamb
        goto 400
      endif

```

```

C-----
C CHECK TO SEE IF SUPPLY AIR TEMPERATURE IS MET. IF SO, GO
C STRAIGHT TO POWER CALCULATIONS.
C-----

```

```

      if((abs(toutb-tset).le.0.1).and.(ifail.eq.0))then
        goto 300
      endif

```

```

C-----
C ONCE TWO SETS OF OPERATING CONDITIONS HAVE BEEN FOUND
C THAT BOUND THE DESIRED LOAD AND SUPPLY AIR TEMPERATURE,
C ITERATIONS BEGIN UNTIL OPERATING CONDITIONS ARE FOUND
C THAT YIELD THE DESIRED LOAD AND SUPPLY AIR TEMPERATURE.
C-----

```

```

      do 200 i = 1,50

```

```

C-----
C IF EITHER OF THE SEARCH BOUNDARIES HAVE BEEN ESTIMATED,
C TRY THE MEDIAN CHILLED WATER FLOW. OTHERWISE, LINEARLY
C INTERPOLATE A GUESS FOR THE CHILLED WATER FLOW.
C-----

```

```

      if(((ifaila.eq.2).or.(ifailb.eq.1)).and.(shr.lt.1.))then
        ratio = 0.5
      else
        ratio = (toutb-tset)/(toutb-touta)
      endif
      gpmc = ratio*(gpma-gpmb)+gpmb
      xin(5) = gpmc
      ifail = 0

```

```

C-----
C SELECT THE APPROPRIATE SUBROUTINE BASED ON LATENT LOAD.
C-----

```

```

      if(shr.lt.1.0)then
        call findhr(xin,xload,out,ifail)
      else
        call findtemp(xin,tset,out,ifail)
      endif

```

```

C-----
C SAVE THE RESULTANT OUTLET SUPPLY AIR TEMPERATURE AND
C CONDITIONS FLAG.
C-----

```

```

      toutc = out(1)
      ifailc = ifail

```

```

C-----
C CHECK TO SEE IF NEW POINT IS THE SOLUTION
C-----

```

```

      if((abs(toutc-tset).le.0.1).and.(ifail.eq.0))then
        goto 300
      endif
      if((abs(toutc-tset).le.0.1).and.(shr.eq.1.0))then
        goto 300
      endif

```

```

C-----
C IF THE NEW POINT IS NOT THE SOLUTION, USE IT AS
C A NEW SEARCH BOUNDARY
C-----

```

```

      if(ifail.eq.0)then
        if(toutc.gt.tset)then
          gpmb = gpmc
          toutb = toutc
          ifailb = ifailc
        else
          gpma = gpmc
          touta = toutc
          ifaila = ifailc
        endif
      else
        if(ifail.eq.1)then
          gpmb = gpmc
          toutb = toutc
          ifailb = ifailc
        else
          gpma = gpmc
          touta = toutc
          ifaila = ifailc
        endif
      endif

```

```

200      continue

```

```

C-----
C IF NO SOLUTION IS FOUND AFTER 50 ITERATIONS, PRINT
C MESSAGE AND GO TO THE NEXT SET OF OPERATING CONDITIONS
C-----

```

```

      write(2,1003)
      write(1,1003)
      write(2,2004)xload,shr,tchwset,tset,numfans,tamb
      goto 400

```

C-----
 C IF A SOLUTION HAS BEEN FOUND, CALCULATE POWERS FOR ALL
 C COMPONENTS, BEGINNING WITH THE CHILLER
 C-----

```
300      cin(1) = out(4)
         cin(2) = out(5)
         chwflo = out(5)
         cin(3) = tamb
         cin(4) = real(numfans)
         cin(5) = tchwset
         call chiller(cin,cout,kck,curve)
         if(kck.eq.1) kck=2
         sum = cout(4)
```

C-----
 C FIRST PUMP POWER IS CONSTANT
 C-----

```
sum = sum + 1.25
```

C-----
 C SECOND PUMP POWER IS FOUND FROM CURVE FIT
 C-----

```
ratflo = chwflo/(30000.0)
pwr=(0.20058-0.60989*ratflo+1.3515*(ratflo**2))*2.0
sum = sum+pwr
```

C-----
 C SUPPLY FAN POWER IS FOUND FROM CURVE FIT
 C-----

```
ratflo = airflo/(12000.0*0.064*60.0)
pwr=(0.19381-0.72069*ratflo+1.4652*(ratflo**2))*9.0
sum = sum+pwr
```

C-----
 C RETURN FAN POWER IS FOUND FROM CURVE FIT
 C-----

```
pwr = (0.2828-0.92510*ratflo+1.6578*(ratflo**2))*3.0
sum = sum+pwr
```

C-----
 C AIR COOLED CONDENSER POWER IS FOUND FROM CURVE FIT,
 C AND THEN MAY BE REDUCED TO ACCOUNT FOR CHILLER
 C CYCLING.
 C-----

```

pwr = 0.057415 + 1.5224*numfans
if(numfans.eq.2)then
    factor = 180.0
endif
if(numfans.eq.4)then
    factor = 170.0
endif
if(numfans.eq.6)then
    factor = 145.0
endif

if(xload.lt.factor)then
    pwr = xload/factor*pwr
endif
sum = sum+pwr

```

```

C-----
C   WRITE RESULTS TO OUTPUT FILE AND GO TO NEXT SET
C   OF OPERATING CONDITIONS
C-----

```

```

400   write(1,2003)xload,shr,tchwset,tset,numfans,tamb,sum
      continue
      stop

```

```

C-----
C   ALL WRITE FORMATS ARE BELOW
C-----

```

```

1000  format(10x,' all loads < than desired load ',
.      ' even at max chilled h2o flow')
1001  format(10x,' solution found after ',i2,' iterations')
1002  format(10x,' all loads > desired load ',
.      ' even at min chilled h2o flow')
1003  format(10x,' after 50 iterations, no solution ')
1004  format(10x,'desired supply air temp too low ',
.      'even at max chilled h2o flow')
1005  format(10x,'desired supply air temp too high ',
.      ' even at min chilled h2o flow')
1006  format(10x,'required air flow rate is too high ')
2001  format(3x,' load',3x,' shr',3x,'chwt',3x,
.      ' sat',3x,'#f',3x,'tamb',3x,' pwr')
2002  format(3x,' load',3x,' shr',3x,'chwt',3x,
.      ' sat',3x,'#f',3x,'tamb')
2003  format(3x,f5.1,3x,f4.2,3x,f4.1,3x,f4.1,
.      3x,i2,3x,f4.1,3x,f4.1)
2004  format(3x,f5.1,3x,f4.2,3x,f4.1,3x,f4.1,
.      3x,i2,3x,f4.1)

      end

```

Appendix C

Subroutine to Find Supply Air Flow Rate

C-----
C THIS SUBROUTINE FINDS THE AIR FLOW THROUGH THE COOLING
C COIL, GIVEN INLET CONDITIONS, SET POINTS, AND
C AND DESIRED LOAD AND SENSIBLE HEAT RATIO
C-----

subroutine findflow(qtot,shr,tin,tset,airflo)
implicit none

C-----
C DESCRIPTION OF SUBROUTINES
C-----
C PSYCH: TRNSYS PSYCHROMETRICS SUBROUTINE, USED HERE TO
C FIND AIR ENTHAPLY AT A GIVEN TEMPERATURE AND
C HUMIDITY RATIO.
C-----

C DESCRIPTION OF VARIABLES
C-----
C PSYDAT: THESE ARE THE INPUTS TO THE TRNSYS SUBROUTINE
C PSYDAT(1): AMBIENT AIR PRESSURE (ATM)
C PSYDAT(2): AIR TEMPERATURE (F)
C PSYDAT(3-5): UNUSED
C PSYDAT(6): HUMIDITY RATIO (LBS WATER/LB DRY AIR)
C PSYDAT(7): AIR ENTHALPY (BTU/LB)
C HROUT: HUMIDITY RATIO OF AIR EXITING COOLING COIL (F)
C QTOT: TOTAL COOLING LOAD (KBTU/HR)
C SHR: SENSIBLE HEAT RATIO
C TIN: AIR TEMPERATURE ENTERING THE COOLING COIL (F)
C TSET: TEMPERATURE SET POINT OF AIR EXITING THE
C COOLING COIL (F)
C ENTHOUT: ENTHAPLY OF AIR EXITING THE COOLING
C COIL (BTU/LB)
C SENS: AIR ENTHALPY CHANGE DUE TO SENSIBLE
C LOAD (BTU/LB)
C ENTHMID: ENTHALPY OF AIR IF ONLY LATENT COOLING
C WAS DONE (BTU/LB)
C TOTAL: TOTAL AIR ENTHAPLY CHANGE ACROSS COOLING
C COIL (BTU/LB)
C AIRFLO: MASS FLOW RATE OF AIR (LBS/HR)
C STAT: UNUSED, BUT NECESSARY INPUT TO
C PSYCHROMETRICS SUBROUTINE

```

C   LUW:          LOGICAL UNIT TO WHICH ERROR MESSAGES
C                   SHOULD BE PRINTED
C-----

```

```

real psydat(9),hrout,qtot,shr,tin,tset
real enthout,sens,enthmid,total,airflo
integer stat
common / lunit / luw

```

```

C-----
C   AN OUTLET HUMIDITY RATIO IS GUESSED
C-----

```

```

hrout = 0.004
psydat(1) = 0.82

```

```

C-----
C   ENTHALPY EXITING THE COOLING COIL IS FOUND
C-----

```

```

psydat(2) = tset
psydat(6) = hrout
call psych(2,4,0,psydat,stat)
enthout = psydat(7)

```

```

C-----
C   FIND THE INLET ENTHALPY IF ONLY SENSIBLE COOLING IS DONE
C-----

```

```

psydat(2) = tin
psydat(6) = hrout
call psych(2,4,0,psydat,stat)
enthmid = psydat(7)

```

```

C-----
C   FIND ENTHALPY CHANGE DUE TO SENSIBLE LOAD, AND TOTAL
C   ENTHALPY CHANGE
C-----

```

```

sens = enthmid - enthout
total = sens/shr

```

```

C-----
C   USE TOTAL ENTHALPY CHANGE TO FIND AIRFLOW
C-----

```

```

airflo = qtot/total*1000.0

```

```

return
end

```

Appendix D

Subroutine to Find Supply Air Temperature

C-----
C THIS SUBROUTINE DETERMINES THE OUTLET COIL SUPPLY
C AIR TEMPERATURE FOR A GIVEN SET OF OPERATING
C CONDITIONS AT A SENSIBLE HEAT RATIO OF 1.0.
C THE INLET HUMIDITY RATIO IS NOT FOUND, IT IS
C ASSUMED TO BE VERY LOW TO FORCE THE SENSIBLE
C HEAT RATIO TO BE 1.0
C-----

subroutine findtemp(xin,tset,out,ifail)
implicit none

C-----
C DESCRIPTION OF SUBROUTINES
C-----

C COIL: TRNSYS TYPE 52 COOLING COIL SUBROUTINE. THE
C SUBROUTINE WAS MODIFIED SLIGHTLY TO MORE
C ACCURATELY MODEL THE ACTUAL SYSTEM COOLING
C COIL.
C-----

C DESCRIPTION OF VARIABLES
C-----

C XIN: THESE ARE THE INPUTS REQUIRED FOR THE TRNSYS
C TYPE 52 COOLING COIL SUBROUTINE.
C XIN(1): COOLING COIL INLET AIR TEMPERATURE (F)
C XIN(2): COOLING COIL INLET AIR HUMIDITY RATIO
C (LBS WATER/LBS DRY AIR)
C XIN(3): MASS FLOW RATE OF AIR (LBS/HR)
C XIN(4): CHILLED WATER SET TEMPERATURE (F)
C XIN(5): CHILLED WATER FLOW RATE (LBS/HR)
C OUT: THESE ARE THE OUTPUTS FROM THE TRNSYS
C TYPE 52 COOLING COIL SUBROUTINE
C OUT(1): EXITING SUPPLY AIR TEMPERATURE (F)
C OUT(2-3): UNUSED
C OUT(4): EXITING CHILLED WATER TEMPERATURE (F)
C OUT(5-10): UNUSED
C TSET: THE OUTLET SUPPLY AIR TEMPERATURE SET
C POINT (F)
C HR: INLET AIR HUMIDITY RATIO
C (LBS WATER/LBS DRY AIR)
C TOUT: OUTLET SUPPLY AIR TEMPERATURE (F)

```

C   IFAIL:      VARIABLE TO DESCRIBE THE OUTLET
C               AIR CONDITIONS
C               =1;  OUTLET SUPPLY AIR TEMPERATURE IS GREATER
C                   THAN ITS SET POINT
C               =2;  OUTLET SUPPLY AIR TEMPERATURE IS LESS
C                   THAN ITS SET POINT
C   LUW:        LOGICAL UNIT TO WHICH ERROR MESSAGES
C               ARE PRINTED
C-----

```

```

real xin(5),out(10),tset,hr,tout
integer ifail,luw
common / lunit / luw

```

```

C-----
C   FIND THE LOAD AND OUTLET AIR TEMPERATURE AT A LOW INLET
C   HUMIDITY RATIO, WHERE THE SHR WILL CERTAINLY BE 1.0
C-----

```

```

hr = 0.004
xin(2) = hr
call coil(xin,out)
tout = out(1)

```

```

C-----
C   SET CONDITIONS FLAG TO APPROPRIATE VALUE
C-----

```

```

if(tout.lt.tset)then
  ifail = 2
  return
endif

if(tout.gt.tset)then
  ifail = 1
  return
endif

return

end

```

Appendix E

Subroutine to Find Inlet Air Humidity Ratio

C-----
C THIS SUBROUTINE WILL ITERATE TO FIND THE INLET COOLING
C COIL HUMIDITY RATIO NECESSARY FOR A PARTICULAR
C COOLING COIL LOAD.
C-----

```
subroutine findhr(xin,xload,out,ifail)
implicit none
```

C-----
C DESCRIPTION OF SUBROUTINES
C-----

C COIL: TRNSYS TYPE 52 COOLING COIL SUBROUTINE. THE
C SUBROUTINE WAS MODIFIED SLIGHTLY TO MORE
C ACCURATELY MODEL THE ACTUAL SYSTEM COOLING
C COIL.
C-----

C DESCRIPTION OF VARIABLES
C-----

C XIN: THESE ARE THE INPUTS REQUIRED FOR THE TRNSYS
C TYPE 52 COOLING COIL
C XIN(1): COOLING COIL INLET AIR TEMPERATURE (F)
C XIN(2): COOLING COIL INLET AIR HUMIDITY (F)
C XIN(3): MASS FLOW RATE OF AIR (LBS/HR)
C XIN(4): CHILLED WATER SET TEMPERATURE (F)
C XIN(5): CHILLED WATER FLOW RATE (LBS/HR)
C OUT: THESE ARE THE OUTPUTS FROM THE COOLING COIL
C MODEL
C OUT(1-5): UNUSED
C OUT(6): COIL LOAD (KBTU/HR)
C OUT(7-10): UNUSED
C XLOAD: DESIRED COOLING LOAD (KBTU/HR)
C ALOAD: COIL LOAD AT LOW INLET HUMIDITY
C RATIO (KBTU/HR)
C BLOAD: COIL LOAD AT HIGH INLET HUMIDITY
C RATIO (KBTU/HR)
C CLOAD: COIL LOAD AT CURRENT GUESS OF
C HUMIDITY RATIO (KBTU/HR)
C HRA: HIGH END BOUNDARY FOR INLET HUMIDITY RATIO
C (LBS WATER/LBS DRY AIR)
C HRB: LOW END BOUNDARY FOR INLET HUMIDITY RATIO

```

C          (LBS WATER/LBS DRY AIR)
C HRC:     CURRENT GUESS VALUE FOR INLET HUMIDITY RATIO
C          (LBS WATER/LBS DRY AIR)
C RATIO:   USED TO CALCULATE NEXT GUESS VALUE OF INLET
C          HUMIDITY RATIO
C I:       COUNTER
C LUW:     LOGICAL UNIT TO WHICH ERROR MESSAGES
C          ARE WRITTEN
C IFAIL:   FLAG TO DESCRIBE OUTLET CONDITIONS
C          =0;  OUTLET NUMBERS ARE EXACT
C          =1;  OUTLET NUMBERS ARE ESTIMATED BECAUSE
C          ALL LOADS ARE LESS THAN DESIRED LOAD
C          =2;  OUTLET NUMBERS ARE ESTIMATED BECAUSE
C          ALL LOADS ARE GREATER THAN DESIRED LOAD
C-----

```

```

real xin(5),out(10),xload,aload,bload,cload,hra
real hrb,hrc,ratio
integer i,luw,ifail
common / lunit / luw

```

```

C-----
C BEGIN BY GUESSING A LOW INLET AIR HUMIDITY RATIO AND
C FINDING THE RESULTANT LOAD
C-----

```

```

hra = 0.004
xin(2) = hra
call coil(xin,out)
aload = out(6)

```

```

C-----
C NEXT, GUESS A HIGH INLET HUMIDITY RATIO AND FIND THE
C RESULTANT LOAD
C-----

```

```

hrb = 0.017
xin(2) = hrb
call coil(xin,out)
bload = out(6)

```

```

C-----
C IF THIS RANGE OF INLET HUMIDITY RATIOS DOES NOT CONTAIN
C THE DESIRED LOAD, THEN SET FLAGS
C-----

```

```

if(sign(1.0,(xload-aload)).eq.sign(1.0,(xload-bload)))then

```

```

C-----
C IF DESIRED LOAD IS TOO LOW, RETURN THE LOWEST LOAD FOUND
C AND SET IFAIL TO 2.
C-----

```

```

    if(aload.gt.xload)then
      ifail = 2
      xin(2) = hra
      call coil(xin,out)
      return

```

```

C-----
C IF DESIRED LOAD IS TOO HIGH, RETURN HIGHEST LOAD FOUND
C AND SET IFAIL TO 1.
C-----

```

```

      else
        ifail = 1
        xin(2) = hrb
        call coil(xin,out)
        return
      endif
    endif

```

```

C-----
C IF THE RANGE DOES INCLUDE THE DESIRED LOAD,
C BEGIN ITERATIVE SEARCH FOR CORRECT HUMIDITY RATIO
C-----

```

```

do 100 i = 1,50

```

```

C-----
C ESTIMATE BETTER ENTERING HUMIDITY RATIO BY LINEARLY
C INTERPOLATING BETWEEN THE TWO BOUNDARY POINTS
C-----

```

```

      ratio = (xload-aload)/(bload-aload)
      hrc = ratio*(hrb-hra) + hra

```

```

C-----
C FIND THE LOAD AT THE NEW HUMIDITY RATIO
C-----

```

```

      xin(2) = hrc
      call coil(xin,out)
      cload = out(6)

```

```

C-----
C IF THE COIL IS AT DESIRED LOAD, RETURN VALUES
C-----

```

```

if(abs(xload-cload).lt.(0.01*xload))then
  return
else

```

```

C-----
C  IF GUESS IS NOT THE DESIRED VALUE, USE IT AS A NEW BOUNDARY
C-----

```

```

      if(cload.gt.xload)then
        hrb = hrc
        blood = cload
      else
        hra = hrc
        aload = cload
      endif
    endif

```

```

100  continue

```

```

C-----
C  IF, AFTER 50 ITERATIONS, AN APPROPRIATE HUMIDITY RATIO
C  HAS NOT BEEN FOUND, WRITE MESSAGE
C-----

```

```

write(luw,1002)xin(3),xin(5)

```

```

stop

```

```

1002 format(/10x,' *** error *** '/5x,' at an air flow of',
.         e12.3,' and a water flow of ',e12.3/5x,' the load remains',
.         ' unfound after 50 iterations.')

```

```

end

```

Appendix F

Optimization Subroutine

C-----
C THIS SUBROUTINE FINDS THE OPTIMAL CONTROL SETTINGS
C BASED ON EXISTING SYSTEM CURVES
C-----

```
subroutine findopt(iflag,xload,shr,tamb,sat1,chwt1,nfans)
implicit none
```

C-----
C DESCRIPTION OF EXTERNAL FILES
C-----

C CURVE.OUT: THIS FILE CONTAINS 3 SYSTEM CURVES, ONE FOR
C EACH FAN SETTING. EACH LINE CONTAINS THE COEFFICIENT
C NUMBER, 1 THRU 17, FOLLOWED BY THE COEFFICIENT VALUE.
C THE CURVE IS DEFINED AS FOLLOWS:
C

```
power = c(1) + c(2)*xload + c(3)*xload**2 + c(4)*shr
      + c(5)*shr**2 + c(6)*sat + c(7)*sat**2
      + c(8)*tamb + c(9)*tamb**2 + c(10)*chwt
      + c(11)*chwt**2 + c(12)*xload*sat
      + c(13)*xload*chwt + c(14)*shr*sat
      + c(15)*shr*chwt + c(16)*chwt*sat
      + c(17)*tamb*chwt
```

C WHERE power IS THE TOTAL SYSTEM POWER,
C xload IS THE SYSTEM LOAD
C shr IS THE SENSIBLE HEAT RATIO
C sat IS THE SUPPLY AIR TEMPERATURE
C tamb IS THE OUTDOOR AMBIENT TEMPERATURE
C chwt IS THE CHILLED WATER SET TEMPERATURE
C-----

C DESCRIPTION OF VARIABLES
C-----

C	C(17):	COEFFICIENTS FOR THE SYSTEM CURVE
C	XLOAD:	SYSTEM COOLING LOAD (KW)
C	SHR:	SENSIBLE HEAT RATIO
C	TAMB:	AMBIENT OUTDOOR TEMPERATURE (F)
C	DELTA:	DIFFERENCE BETWEEN THE RECOMMENDED SUPPLY
C		AIR AND CHILLED WATER
C		TEMPERATURES (F)
C	DELTEST:	MINIMUM POSSIBLE DIFFERENCE BETWEEN THE

```

C          SUPPLY AIR AND CHILLED WATER
C          TEMPERATURES (F)
C      K(4):  HOLDING VARIABLE FOR SUPPLY AIR TEMPERATURE
C            TERMS
C      CHWT(3): OPTIMUM CHILLED WATER TEMPERATURE FOR
C            EACH OF THE THREE CONDENSER
C            FAN SETTINGS (F)
C      SAT(3):  OPTIMUM SUPPLY AIR TEMPERATURE FOR
C            EACH OF THE THREE CONDENSER
C            FAN SETTINGS (F)
C      POWER(3): OPTIMUM SYSTEM POWER FOR EACH OF THREE FAN
C            SETTINGS (F)
C      SAT1:    FINAL OPTIMUM SUPPLY AIR TEMPERATURE (F)
C      CHWT1:   FINAL OPTIMUM CHILLED WATER TEMPERATURE
C            SETTING (F)
C      PWR1:    FINAL OPTIMUM SYSTEM POWER (KW)
C      PWR:     HOLDING VARIABLE FOR SYSTEM POWER TERMS
C      HOLD:    HOLDING VARIABLE
C      B(2):    COEFFICIENTS OF CURVE DEFINING MINIMUM
C            DIFFERENCE BETWEEN CHILLED WATER AND
C            SUPPLY AIR TEMPERATURES
C      JUNK:    NULL DATA THAT MUST BE READ IN
C      NFANS:   NUMBER OF CONDENSER FANS OPERATING
C      I,J:     COUNTERS
C      IFLAG:   VARIABLE TO DETERMINE ANALYSIS TYPE
C            = 0; FIND OVERALL SYSTEM OPTIMUM
C            = 1; ONLY FIND OPTIMUM AT 2 FANS
C            = 2; ONLY FIND OPTIMUM AT 4 FANS
C            = 3; ONLY FIND OPTIMUM AT 6 FANS
C      LUW:     LOGICAL UNIT TO WHICH ERROR MESSAGES
C            SHOULD BE WRITTEN
C-----

```

```

real c(17),xload,shr,tamb,delta,deltest
real k(4),chwt(3),sat1,chwt1,b(2)
real sat(3),pwr,power(3),pwr1,hold
integer junk,nfans,i,j,iflag,luw
common / lunit / luw

```

```

C-----
C      OPEN THE FILE CONTAINING THE SYSTEM CURVE FIT
C-----

```

```

open(unit=6,file='curve.out',status='old')
rewind(6)

```

```

C-----
C      DEFINE CURVE OF MINIMUM SAT/CHWT DIFFERENCE CONSTRAINT
C-----

```

```

b(1) = 7.9413
b(2) = 0.044808
b(3) = -10.2753

```

```

C-----
C BEGIN LOOP FOR EACH FAN SETTING
C-----

```

```

do 200 j=1,3

```

```

C-----
C READ COEFFICIENTS INTO ARRAY
C-----

```

```

do 100 i=1,17
  read(6,*)junk,c(i)
100 continue

```

```

C-----
C SET UP VARIABLES PERTAINING TO CURVE PARTIAL DIFFERENTIAL
C-----

```

```

k(1)=-c(6)-c(12)*xload-c(14)*shr)/2.0/c(7)
k(2)=-c(16)/2.0/c(7)
k(3)=-c(10)-c(13)*xload-c(15)*shr-c(17)*tamb
k(3) = k(3)/2.0/c(11)
k(4) = -c(16)/2.0/c(11)

```

```

C-----
C OPTIMIZE FOR SAT
C-----

```

```

sat(j) = (k(1)+k(2)*k(3))/(1.0-k(2)*k(4))

```

```

C-----
C IF SUPPLY AIR TEMPERATURE IS UNREASONABLY HIGH, SET IT
C TO ITS MAXIMUM VALUE
C-----

```

```

if(sat(j).gt.60.0)then
  sat(j) = 60.0
endif

```

```

C-----
C OPTIMIZE FOR CHWT
C-----

```

```

chwt(j) = k(3)+k(4)*sat(j)

```

```

C-----
C IF CURVE RETURNS CHILLED WATER TEMP AT A LOCAL MAXIMUM,
C RATHER THAN AT A MINIMUM, PRINT A MESSAGE
C-----

```

```

    if(c(11).lt.0.0)then
      write(luw,*)'chwt is at a MAXIMA'
    endif

```

```

C-----
C IF CURVE RETURNS SUPPLY AIR TEMPERATURE AT A LOCAL
C MAXIMUM, RATHER THAN AT A MINIMUM, PRINT A MESSAGE.
C-----

```

```

    if(c(7).lt.0.0)then
      write(luw,*)'the sat is at a MAXIMA'
    endif

```

```

C-----
C FIND ACTUAL AND CONSTRAINT SUPPLY AIR / CHILLED WATER
C TEMPERATURE DIFFERENCE
C-----

```

```

    delta = sat(j)-chwt(j)
    deltest = b(1) + b(2)*xload + b(3)*shr

```

```

C-----
C IF THE ACTUAL TEMPERATURE DIFFERENCE DOES NOT MEET
C THE CONSTRAINT, USE THE REVISED CURVE TO
C DETERMINE NEW CHILLED WATER TEMPERATURE
C-----

```

```

    if(delta.lt.deltest)then
      hold = c(6)+2.0*c(7)*deltest+c(10)+c(17)*tamb
      hold=hold+(c(12)+c(13))*xload+(c(14)+c(15))*shr
      hold = hold+c(16)*deltest
      hold=-hold/2.0/(c(7)+c(11)+c(16))

      chwt(j) = hold
    endif

```

```

C-----
C IF THE CHILLED WATER TEMPERATURE IS TOO LOW, SET
C IT TO MINIMUM
C-----

```

```

    if(chwt(j).lt.39.0)then
      chwt(j) = 39.0
    endif

```

```

C-----
C  RECALCULATE OPTIMAL SUPPLY AIR TEMPERATURE
C-----

```

```

    sat(j) = chwt(j) + deltest
endif

```

```

C-----
C  USE THE SYSTEM CURVE TO ESTIMATE THE SYSTEM POWER
C-----

```

```

    pwr=c(1)+c(2)*xload+c(3)*xload**2+c(4)*shr
    pwr=pwr+c(5)*shr**2+c(6)*sat(j)+c(7)*sat(j)**2
    pwr=pwr+c(8)*tamb+c(9)*tamb**2+c(10)*chwt(j)
    pwr=pwr+c(11)*chwt(j)**2+c(12)*xload*sat(j)
    pwr=pwr+c(13)*xload*chwt(j)+c(14)*shr*sat(j)
    pwr=pwr+c(15)*shr*chwt(j)+c(16)*chwt(j)*sat(j)
    pwr=pwr+c(17)*tamb*chwt(j)

```

```

    power(j) = pwr

```

```

200  continue

```

```

C-----
C  DETERMINE WHETHER THE MINIMUM OVERALL POWER SETTING IS
C  DESIRED, OR IF ONLY ONE PARTICULAR FAN SETTING IS NEEDED
C-----

```

```

if(iflag.eq.0)then
    pwr = min(power(1),power(2),power(3))
else
    pwr = power(iflag)
endif

```

```

C-----
C  SET THE OUTPUT VARIABLES TO THE APPROPRIATE OPTIMUM
C  SETTINGS
C-----

```

```

if(pwr.eq.power(1)) then
    sat1 = sat(1)
    chwt1 = chwt(1)
    nfans = 2
endif
if(pwr.eq.power(2)) then
    sat1 = sat(2)
    chwt1 = chwt(2)
    nfans = 4

```

```
endif
if(pwr.eq.power(3)) then
    sat1 = sat(3)
    chwt1 = chwt(3)
    nfans = 6
endif

return
end
```

Appendix G

Summary of Raw JCEM Data

This is a summarized listing of the test data from the Joint Center of Energy Management. The readings listed here are averages, and were used to create the fan and pump performance curves. The chiller model used individual data points rather than averages. The first table lists the operating conditions recorded for each test. Power output for each component is listed in the second table.

Operating Conditions Used In JCEM Tests

Test #	Chilled Water Temp (F)	Supply Air Temp (F)	# of Cond. Fans	Outside Air Temp (F)	System Cooling Load (KBtu)	Sensible Heat Ratio
1	39.8	56.2	6	89.3	308.6	0.90
2	40.0	53.2	6	91.4	287.4	0.88
3	40.0	50.4	6	88.8	227.0	0.80
4	40.1	52.9	4	87.6	207.9	0.85
5	40.0	52.9	4	88.1	210.8	0.87
6	40.0	54.2	6	87.4	297.0	0.90
7	40.1	53.1	4	85.9	171.3	0.85
8	44.6	52.3	6	84.6	176.3	0.85
9	45.6	53.2	6	84.9	177.2	0.89
10	45.1	58.0	4	87.2	237.0	0.70
11	45.1	56.5	2	87.1	246.0	0.70
12	44.8	55.4	2	85.1	228.0	0.69
13	44.5	52.9	2	73.0	175.0	0.79
14	45.6	53.8	2	74.6	178.1	0.79
15	49.1	53.8	4	74.7	112.6	0.70
16	44.3	58.9	2	75.8	131.4	0.70
17	49.5	58.9	2	78.2	119.6	0.80
18	44.0	53.7	4	73.6	106.0	0.76
19	43.9	53.6	4	79.5	115.8	0.74
20	40.1	52.7	4	81.5	261.2	0.78
21	45.0	57.8	6	81.3	262.0	0.80
22	49.9	59.7	6	48.3	203.4	1.00
23	45.0	54.5	6	50.5	196.1	0.84
24	43.8	52.3	2	40.6	178.9	0.97
25	45.0	56.2	2	50.0	185.0	0.91
26	44.8	54.8	4	50.4	204.6	0.84
27	44.9	56.5	2	58.2	166.7	0.85
28	44.0	54.5	4	60.7	212.5	0.87
29	43.6	54.0	6	56.7	208.9	0.86
30	42.0	56.5	2	55.6	168.8	0.85

Component Powers from JCEM Tests

Test #	Chilled Water Pump 1 (KW)	Chilled Water Pump 2 (KW)	Supply Fan. (KW)	Return Fan (KW)	Condenser Fans (KW)	Chiller (KW)
1	1.25	2.06	8.43	3.01	9.01	33.67
2	1.25	1.92	8.23	3.00	9.01	32.09
3	1.25	1.92	3.20	1.17	9.10	28.00
4	1.25	0.62	3.28	1.20	6.11	28.10
5	1.25	0.66	3.37	1.23	6.06	28.50
6	1.25	1.90	8.41	3.00	9.05	32.10
7	1.26	0.36	2.57	0.97	6.10	22.68
8	1.25	1.91	2.44	0.93	9.19	22.37
9	1.25	1.91	2.75	1.04	8.38	20.88
10	1.25	1.02	5.16	1.86	6.06	29.34
11	1.25	1.89	4.55	1.66	2.97	37.20
12	1.26	1.91	3.68	1.35	3.03	34.80
13	1.27	1.50	2.31	0.88	2.96	24.14
14	1.27	1.76	2.66	0.98	3.13	27.36
15	1.26	1.01	1.02	0.45	3.35	12.97
16	1.25	0.26	1.49	0.63	2.39	18.50
17	1.26	0.35	1.71	0.70	2.07	16.80
18	1.27	0.31	0.97	0.44	4.19	14.90
19	1.26	0.42	1.26	0.53	3.93	15.70
20	1.24	1.90	5.72	2.03	6.04	31.28
21	1.24	1.89	8.22	3.00	9.06	28.65
22	1.24	1.85	8.34	3.34	7.97	16.08
23	1.25	1.87	3.51	2.04	8.92	17.39
24	1.27	1.92	3.01	1.82	2.73	17.88
25	1.25	0.75	4.19	2.33	2.68	18.91
26	1.25	1.87	3.82	2.14	5.79	18.05
27	1.25	0.60	2.55	1.60	2.68	18.88
28	1.25	1.85	3.82	2.20	6.31	21.75
29	1.25	1.84	3.44	2.01	9.53	19.68
30	1.25	0.45	2.51	1.59	2.69	19.65

Chiller Performance Data

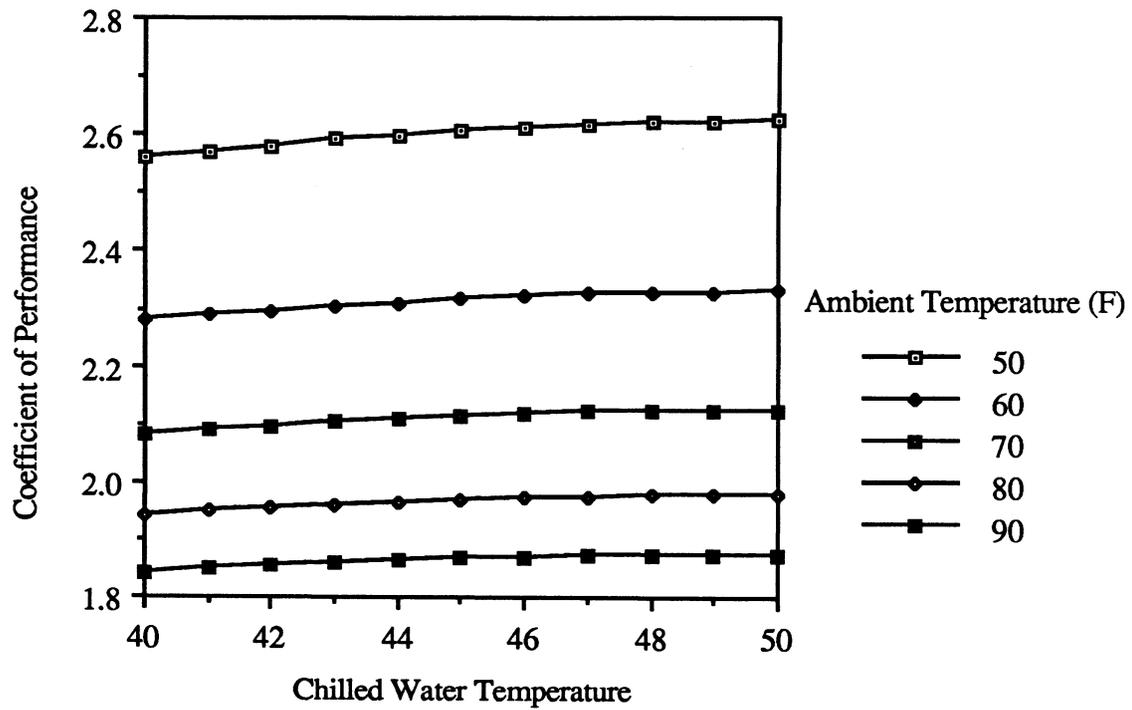
First, the general form of the chiller curve is presented, followed by the coefficients used for each fan setting. A graph of each curve, at a load of 200 KBtu/hr, is also presented. The coefficient of performance is calculated as the chiller load divided by the chiller power.

Ordinarily, chiller operating curves are presented at full load conditions. However, the chiller at the JCEM is oversized, and can not be operated at full load. The results presented here are at a load of 200 KBtu/hr, which is one-third of the chiller capacity. The intent of these chiller curves is to provide a chiller model that calculates chiller power based on operating conditions at JCEM. The chiller curves used for this research do not produce valid operating curves over the full range of chiller operating conditions, only near the operating conditions for which test data was taken.

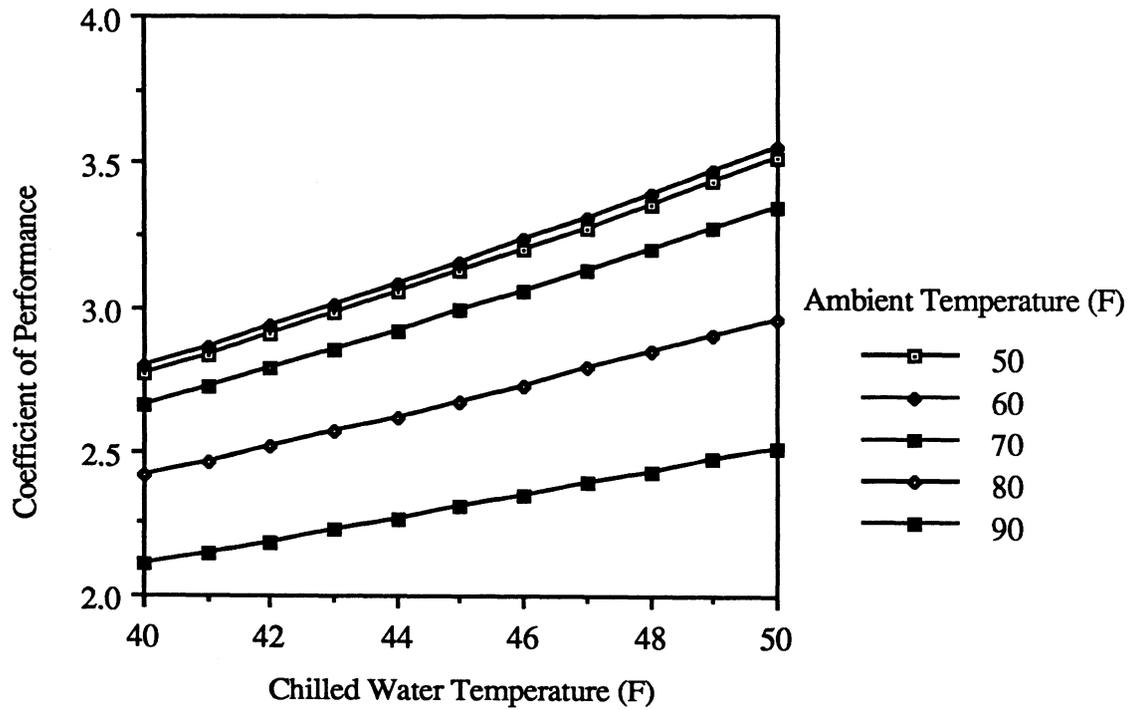
$$\text{Power} = C_0 + C_1 (T_{\text{amb}}) + C_2 (T_{\text{amb}})^2 + C_3 (T_{\text{chw}}) + C_4 (T_{\text{chw}})^2 + C_5 (\text{Load}) + C_6 (\text{Load})^2$$

Eqn Term	Number of Fans		
	2	4	6
1.0	-21.54	64.14	33.46
T_{amb}	0.50	-0.70	0.70
$(T_{\text{amb}})^2$	-1.98e-3	6.17e-3	-3.64e-3
T_{chwt}	-0.53	-0.96	-2.46
$(T_{\text{chwt}})^2$	5.32e-3	5.75e-2	2.57e-2
Load	0.24	-3.80e-2	9.18e-2
$(\text{Load})^2$	-2.60e-4	3.34e-4	-5.05e-5

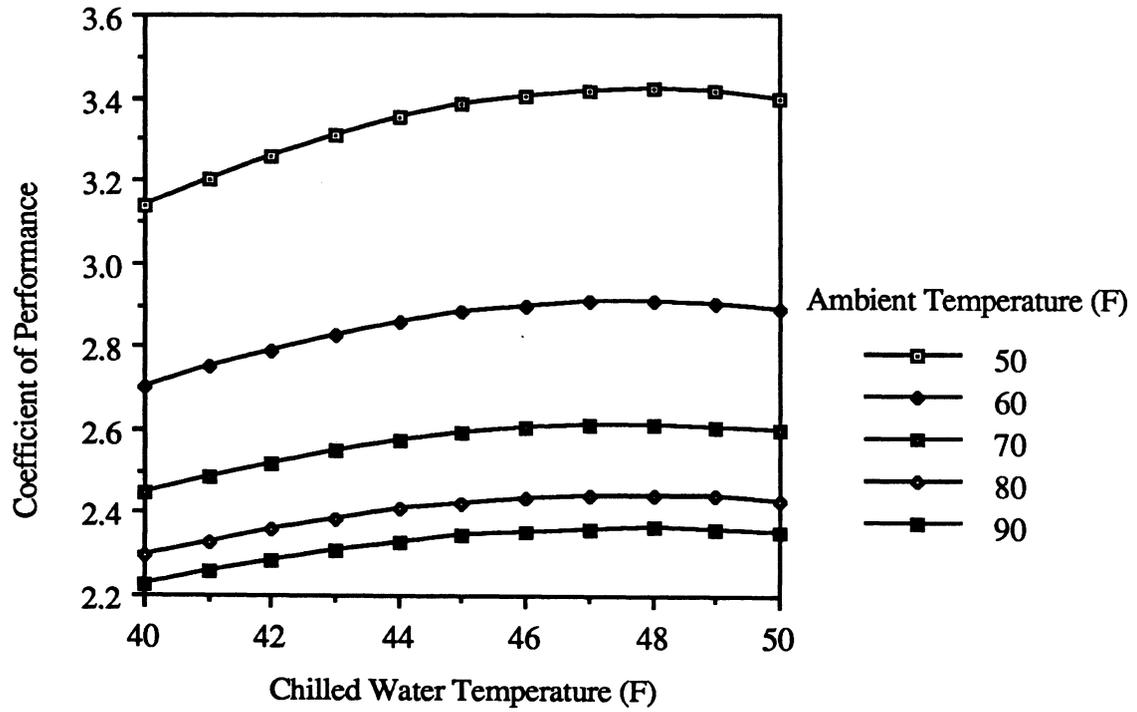
List of Coefficients for Each Fan Setting



**Model of Chiller Performance Curve with Two Fans and
with a Total System Load of 200 KBtu/hr.**



Model of Chiller Performance Curve with Four Fans and with a Total System Load of 200 KBtu/hr.



**Model of Chiller Performance Curve with Six Fans and
with a Total System Load of 200 KBtu/hr.**