Hydraulic Modeling of Large District Cooling Systems for Master Planning Purposes

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ABSTRACT

District Cooling Systems (DCS) have been widely applied in large institutions such as universities, government facilities, commercial districts, airports etc. The hydraulic system of a large DCS can be very complicated. They often stem from an original design that has had extensive additions and deletions over time. Expanding or retrofitting such a system involves large capital investment. Consideration of future expansion is often required. Therefore, a thorough study of the whole system at the planning phase is crucial. An effective hydraulic model for the existing DCS will become a powerful analysis tool for this purpose. Engineers can use the model to explore various alternatives of system configuration to find an optimal way of accommodating the DCS hydraulic system to the planned future.

This paper presents the first complete procedure for the use of commercial simulation software to construct the hydraulic model for a large District Cooling System (DCS). A model for one of the largest DCS hydraulic systems in the United States has been developed based on this procedure and has been successfully utilized to assist the decision makings for its master planning purpose.

INTRODUCTION

In the United States, District Cooling Systems (DCSs) have been widely applied in large institutions such as universities, government facilities, commercial districts, airports etc. The largest DCS in universities can have 44,000 tons of cooling capacity and the total linear pipe length (supply and return) can approach 17 miles in length [4]. Normally a DCS already means a large centralized cooling system that covers multi-buildings of various loads by a central plant. The work “large” specifically mentioned here is intended to focus on those DCSs that covers more than 3 ~ 5 million ft^2 and have more than 10,000 tons of cooling capacity as their hydraulic systems are more complicated and worth the attention to study.

The hydraulic systems of large DCSs often stem from an original design that has had extensive additions and deletions over time. A DCS is usually continuously expanding as the campus grows. When new buildings are to be built on campus, chilled water piping will be added to connect them with the existing DCS. The existing DCS hydraulic system may need to be modified to accommodate the new buildings. Accordingly, the total cooling capacity may need to be enlarged by installing new chillers in the existing central plant or possibly new satellite plants will need to be built or enlarged. Expanding or retrofitting such a system involves large capital investment [1]. On the other hand, once the piping infrastructure is built underground, it will stay there and serve for many years to come. Consideration of future expansion is often required. Therefore, a thorough study of the whole system at the planning phase is crucial. An effective hydraulic model for the existing DCS will become a powerful analysis tool for this purpose [3] [12]. With the DCS hydraulic system model, engineers can explore various alternatives of system configuration to find an optimal way of accommodating the DCS hydraulic system to the planned future. The DCS hydraulic system model can be used to answer important decision-making questions regarding to planning purposes. Also, the model can serve as an analysis tool for the Continuous Commissioning® (CC®)[1] of the DCS system. Eventually, the DCS hydraulic model can be seen as an asset to the facility owner and needs to be continuously maintained and updated

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so that it can help people make master planning decisions to guide system operation in an efficient way.

However, currently there are basically no papers to provide a complete study of DCS hydraulic modeling. This paper presents the first complete procedure for the use of commercial simulation software to construct the hydraulic model for a large District Cooling System (DCS).

CHARACTERISTICS OF LARGE DCS HYDRAULIC SYSTEMS

To better understand the modeling process, the characteristics of a large DCS hydraulic system are briefly summarized as:

1. DCS hydraulic systems are re-circulating systems, in which a fixed amount of water continuously circulates within the system.
2. DCS hydraulic systems belong to closed water systems, which are defined as having no more than one point of interface with a compressible gas or surface [1].
3. Parallel piping networks are the most commonly used in large DCS hydraulic systems as they provide the same chilled water temperature to all consumers.
4. Large DCS hydraulic systems are mostly variable flow systems, as they can reduce energy use and expand the capacity of the distribution system piping by using diversity.
5. From the pumping point of view, DCS hydraulic systems can be categorized into three major pumping configurations: (1) source distributed pumping, where source system pumping provides the total system pumping. (2) Distributed pumping, in contrast, uses local pumps, i.e. building pumps to provide all pumping for the DCS. (3) Combination of configurations 1 and 2. Configuration 3 is the most commonly applied pumping configuration for large DCS hydraulic systems.
6. Large DCS hydraulic systems consist of three sub-systems: (1) the source system, i.e. the utilities plants where the chilled water is generated; (2) the distribution system, i.e. pipe networks that distribute the chilled water to individual buildings; (3) the load system, i.e. the in-building chilled water systems at end users (see Figure 2). Basically the heat flows into the DCS from the consumer systems, then is transported via the distribution network and finally is rejected to the atmosphere at the source system.
7. According to building pumping mechanism, in-building chilled water systems can be categorized into constant flow system and variable flow system. In constant flow in-building systems, the chilled water flow does not vary much whereas the differential temperature varies while the building cooling load varies. In variable flow systems, the building flow varies and follows the changes of the building cooling load.

GENERAL MODELING PROCESS

The pipe network hydraulic theory has been developed [10]. Many commercial simulation software packages are available on the market today to solve pipe network problems. Standard modeling methodologies and procedures have been developed primarily for domestic water systems (DWSs) [1]. However, there are no previously published studies of complete DCS hydraulic modeling. Various publications related to DWS modeling technology, characteristics of large DCSs, DCS building cooling energy consumption modeling, and characteristics of building chilled water systems have been reviewed. The characteristics of a large DCS hydraulic system have been studied and compared with that of a DWS. It was found that although DWS and DCS hydraulic systems are same in nature as both of them belong to pipe networks, significant differences still exists between the two. It was found that although the DWS modeling methodology can be generally applied to DCS hydraulic systems, the differences between the two types of systems require unique solutions in order to develop a suitable hydraulic system model for a large DCS.

Taken the well adapted DWS modeling procedure as a reference [12], based on the study of characteristics of large DCS hydraulic systems, and summarized from actual modeling experience with one of the largest DCSs in the United States, a generalized DCS hydraulic systems modeling process has been developed. As shown in Figure 1, the DCS hydraulic modeling process follows three major steps: (1) Information collection, (2) Physical model and demand model construction, and (3) Model verification and calibration.

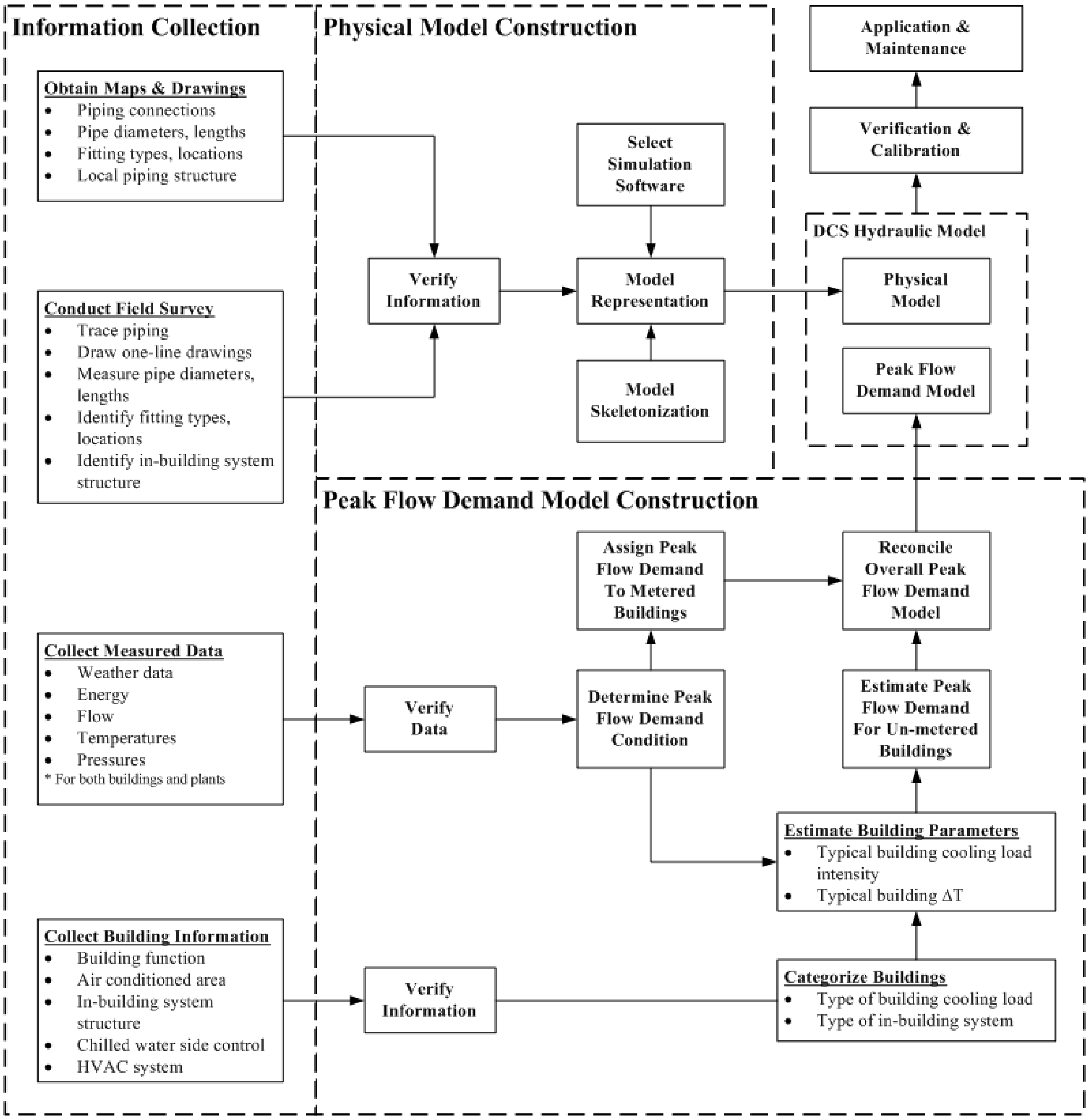

Figure 1 Generalized DCS Hydraulic System Modeling Procedure

In the first step, a tremendous amount of information and data are to be collected. Drawings and maps are to be collected. During this step, multiple departments will be involved to provide the requested information and data and coordinate field work.

In the second step, after being verified and cross checked, the collected information and data will be organized and analyzed to construct the physical and the flow demand models. The physical model is the part of the DCS hydraulic model that represents the physical structure of the real system, such as the piping infrastructure, pumps, valves, etc. A commercial pipe network simulation software package will be used to construct the physical model. The flow demand model is the part of the DCS hydraulic model that reflects the water usage at end consumers under certain conditions. The peak flow demand model is the flow demand model under peak flow conditions. Basically it is a set of flow numbers assigned to the modeled nodes that represent the end consumer i.e. buildings in the physical model. The modeling of the physical model and the flow demand model can be processed in parallel.

The third step is to verify and calibrate the DCS hydraulic model after the physical model and peak flow demand model are constructed. The hydraulic model can be verified with actual measured data.

Calibration is then conducted to match the simulated results to the measured results.

The entire modeling effort is an iterative process. At any moment, the modeler may go back to request new information, refine the model, and/or conduct additional field investigation, until the calibrated model is ready to use. Detailed modeling procedures will be discussed in the following sections.

INFORMATION COLLECTION

Modeling of a large DCS hydraulic system requires a tremendous amount of information be collected. The information needed to generate the physical model of a DCS hydraulic system includes:

(1) System physical information including:

  a. Pipe alignment, connectivity, material, size, length, etc.

  b. Locations and types of other system components, such as valves, tees/wyes, bends, area changes, heat exchangers, pumps, and storage tanks, etc.

  c. Elevations of junctions (optional).

(2) Building information including:

  a. Gross Square Footage (GSF) or air-conditioned area if available.

  b. Design cooling load, chilled water flow and differential temperature.

  c. HVAC systems water side control.

(3) Data records including:

  a. Weather data (ambient dry-bulb and wet-bulb temperatures).

  b. Plant chilled water production (total chilled water flow rate, supply/return temperatures and pressures). Pressures should be metered at the plant secondary system side.

  c. Building chilled water consumption (the chilled water flow rate, and supply/return temperatures and pressures if available). All the parameters should be measured at the building's primary system, i.e. at the building entrance.

The system physical information and building information can be collected from utility maps, as-built drawings, previous records, and even field survey. With modern computer technologies, data records can be retrieved from the building metering system or in the plant metering system. To reflect the current system conditions, the metered data should cover at least the most recent cooling season. When the metered data are not available, the historical data for previous cooling seasons, if available, is also desirable because if the most recent data is not available, it can at least indicate the system's past performance. Data records also can be obtained from the paper format of operation records or even field measurement records taken during the field investigation.

From the modeling experience of actual DCS hydraulic systems, it is realized that besides collecting maps, records, and trended data, the field survey and measurement are necessary. The field survey usually involves the following actions: (1) trace the piping; (2) draw one line drawings for the piping infrastructure; (3) measure the size and length of pipe sections; (4) identify the locations and types of fittings such as valves, area changes, tees/wyes, etc.; (5) conduct field measurement on plant secondary side and building primary side (selected buildings) including flow rate, supply/return pressures and temperatures.

PHYSICAL MODEL

The procedure of constructing the physical model of a large DCS hydraulic system is similar to that of a DWS. The collected physical information of the system will be crosschecked with the field investigation results to ensure an updated and accurate physical model. The piping structure of the entire DCS hydraulic system will be "skeletonized" so that only the parts of the hydraulic network that have a significant impact on the system for the master planning purposes will be included in the physical model. Then the skeletonized system will be input into a selected pipe network simulation software package. Typical DCS hydraulic system elements such as pipe, tee/wye, bend, valve, pump, etc will be represented in the physical model by using the pre-encapsulated model components in the simulation software. Although the general procedure of the physical model construction is similar between a DWS and a large DCS hydraulic system, unique considerations should be considered to large DCS hydraulic systems.

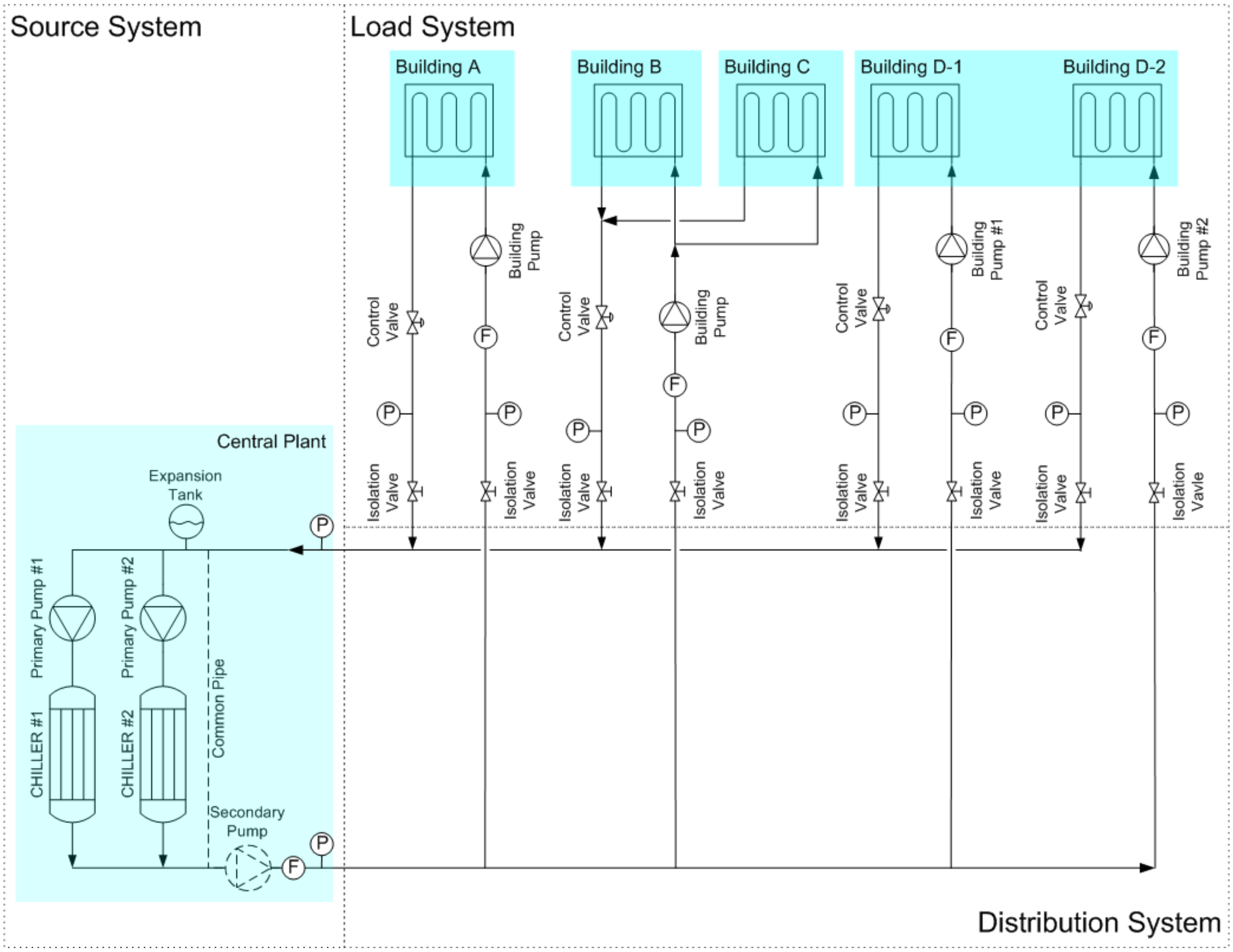

Figure 2 Typical System Structure of a Large DCS Hydraulic System

Skeletonization

A large DCS hydraulic system consists of three major sub-systems: the source system, the distribution system, and the load system, i.e. in-building systems. Figure 2 illustrates a typical system structure for large DCS hydraulic systems. The heat flows into the DCS from the consumer systems, then is transported via the distribution network and finally is rejected to the atmosphere at the source system. Each of the sub-systems itself is already a very complicated piping system. Having a complete DCS hydraulic model with every detail of each of these sub-systems is ideal. It could be easily realized for a small DCS with several buildings and a simple plant. However, for a large DCS with hundreds of buildings and multiple thermal utilities plants, trying to include each individual pipe, valve, pump, and every other component of a large system in a model could be a huge work load and make no significant impact on the model results. Capturing every feature of a system would also involve tremendous amounts of data, which would make the model error-prone [12].

The physical model should be built to certain extent of skeletonization which depends on the intended use of the model [12]. However, skeletonization does not mean omission of data. The portions of the system that are not included in the model during the skeletonization process are not discarded. Their effects are taken into account within the parts of the system that are included in the model. The objective of the large DCS hydraulic system model used for master planning is to predict the impact of newly planned buildings on the existing system. From the planning point of view, the distribution of predicted differential pressures or flows at the buildings and plant entrances is the key result needed from the model. Detailed hydraulic behavior within the plant (source system) and in-building systems (load system) is not the focus of master planning. Therefore, if the hydraulic parameters at the plant and building entrances are known, the plant and in-building systems can be simplified as nodal components without sacrificing the model accuracy.

For Figure 2 as an example, usually the chilled water flow, and supply/return pressures and temperatures are measured at plant entrances and building entrances (An "F" in a circle means flow meter and a "P" in a circle means pressure meter). As shown in Figure 2, a flow meter and two pressure meters are installed at the plant entrances. There are four buildings: building A, B, C and D. Building A is connected to the distribution system through one set of supply/return piping. The flow meter (shown as "F" in a circle) is installed at the building entrance. Buildings B and C are connected to the distribution system through one set of supply/return piping, i.e. share one pump room. And the flow meter measures the total flow of buildings B and C. Building D is connected to the distribution system through two sets of supply and return piping, i.e. two pumps rooms, with each set serving one portion of the building (D-1 and D-2).

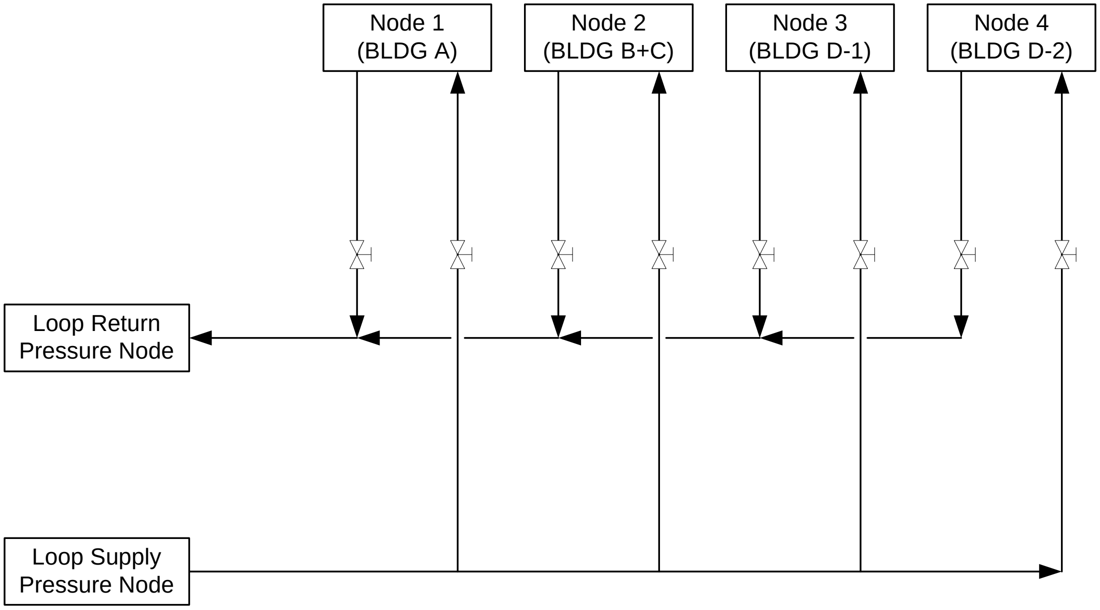

Figure 3 Skeletonized Representation of a Large DCS Hydraulic System

On the source system side, the entire plant can be simplified into two pressure nodes or one flow node with metered pressures or flow. On the load system side, the entire in-building chilled water piping can be simplified into one flow node with metered flow. Figure 3 is the skeletonized system layout of Figure 2. Buildings B and C are represented by one flow node, at which the flow demand is the measured total flow for these two buildings. Building D is represented as two flow nodes (D-1 and D-2), at which the flow demands are measured by each flow meter.

There are many situations where multiple buildings are tied into a branch and that branch is connected to the loop. Whether or not to aggregate them into one flow node is determined by evaluating the purpose of the model. When adding new buildings to a system, the total flow demand of the system will be increased. Consequently, the system pressure drop will be increased. Ensuring adequate differential pressure at the buildings that are the farthest from the plant is essential when adding new buildings. These buildings are usually located at the end of a branch. Therefore, the most remote buildings must be included in the physical model. In addition, even a very large DCS can only cover a few hundred of buildings, a small fraction of those included on a DWS. Therefore, it is preferred that every building on the DCS be included in the model.

Finally, as an example, Figure A - 1 is the physical layout of the TAMU main campus DCS hydraulic system model through a commercial pipe network simulations software interface. This model covers 117 buildings (shown as numbers flow nodes in Figure A - 1) supplied by the central utilities plant (shown as a pair of pressure nodes) and the south satellite plant (shown as a pair of flow nods).

PEAK FLOW DEMAND MODEL

The major difference between a DCS and a DWS lies in their water consumption behavior. A

DWS is a mass consumption system where water is consumed at the end user's point of delivery and based on the occupant's activity. For example, a typical trend is for people to take showers in the morning and with higher kitchen work activity in the evening. A DCS is an energy consumption system where the chilled water carries the cooling energy produced in the source system, i.e. the plant, through the distribution system to the end user's buildings. Buildings consume the cooling energy and circulate the chilled water back to the source system with higher return temperature.

To determine the flow demands at buildings of a DCS, two parameters, building cooling energy consumption and chilled water differential temperature, will be involved. And these two parameters are affected by many factors. For example, building cooling energy consumption relates to weather conditions, building construction, occupancy level, etc. Building chilled water differential temperature is affected by the piping configuration, pumping control, and HVAC system conditions.

Trying to predict the cooling load for above one hundred buildings on a large DCS by using a forward modeling method that involves detailed building information would be time consuming and cost prohibitive compared to the end results. In contrast, inverse modeling method [5][6][8][9] is a convenient way to estimate the cooling load for a large number of buildings as long as there are measured data available for these buildings. However, most large DCSs do not have complete metering that covers all of their buildings.

For master planning purposes, the key is to develop a flow demand model under the maximum flow condition. If under the peak flow demand condition, the planned system expansion/demolition could satisfy the pressure requirements of buildings, it should work for partial demand conditions as well. Due to the diversity effect, the chilled water flow rate of individual buildings does not peak at the same time. Simply adding up design values of individual buildings is likely to overestimate the overall system peak. This paper presents a method to model the building peak flow demands by using actual measured data and building categorization. Detailed processes are discussed in the following sub-sections.

Peak Flow Demand Conditions

The first step is to determine the peak flow demand conditions. The peak flow demand conditions should represent a moment when the overall system flow peaks. The actual metered data of the plant chilled water production are used to determine the peak flow demand conditions as it naturally takes the diversity effect into account.

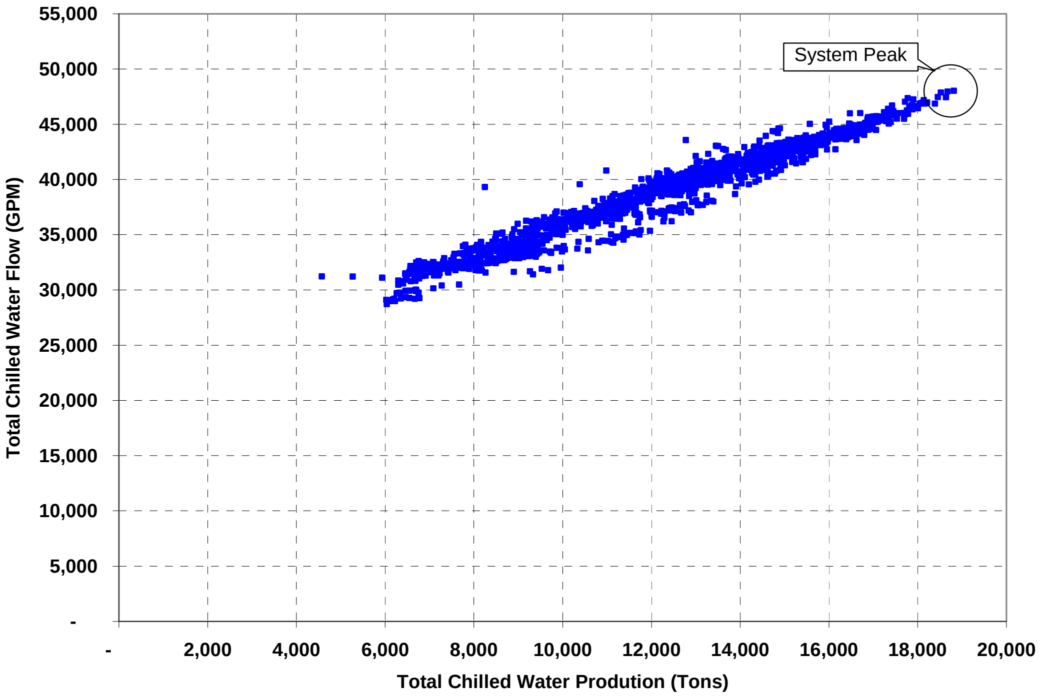

Figure 4 Relationship between Chilled Water Energy Production and Flow of a Large DCS

Large DCS hydraulic systems are usually variable flow systems. The total chilled water flow rate generally tracks the total cooling load. Therefore, the peak flow demand conditions usually coincide with peak cooling load conditions. For example, Figure 4 illustrates the relationship between the Texas A&M University (TAMU) main campus chilled water production and the chilled water flow rate. It clearly shows the linear relationship between these two factors, especially at high cooling loads.

To determine the peak load conditions, weather conditions are important factors. Generally speaking, the system cooling load is proportional to the ambient air enthalpy. Figure A - 2 is a scatter plot of the TAMU main campus chilled water production and flow over ambient air enthalpy. It visibly shows the system cooling load is proportional to the air enthalpy. However, ambient air enthalpies are usually not metered directly. Under this circumstance, the ambient wet-bulb temperature can be used to determine the peak flow demand condition.

Besides weather conditions, occupancy and the corresponding variation in gains from electricity is the other factor that affects the peak cooling load conditions. Especially, for university campuses, during summer break, even if the weather conditions reaches peak temperatures, the total cooling load on the campus may not reach peak load because of lower occupancy and internal heat gain of the buildings. For a normal working schedule of a university campus, the peak cooling load usually appears between 13:00 to 17:00 of a working day. As an example, Figure 6 illustrates the TAMU main campus DCS cooling load profile versus the hour of day. The small circles are actual measured hourly data, and the large dots are the average cooling loads for the corresponding hours.

Table 1 Example of Determine Peak Flow Demand Conditions

Time	TDB (°F)	TWB (°F)	Enthalpy (Btu/lb)	Energy (Tons)	Flow (GPM)	Note
9/15 16:00	99.7	78.1	41.4	18,096	46,937	Wet-bulb temperatures did not reach the highest values on these days hence the cooling load and the flow did not reach the peak.
9/15 17:00	99.8	78.5	41.9	18,137	47,178	
9/17 15:00	98.6	77.2	40.6	16,373	44,130	
9/17 16:00	100.6	77.0	40.3	16,385	43,911	
9/17 17:00	100.9	77.0	40.4	16,276	43,688	
9/18 16:00	100.1	77.1	40.5	15,962	43,681	
9/18 17:00	98.7	77.0	40.4	16,132	43,953	
9/19 16:00	99.4	76.5	39.9	16,924	44,840	
9/22 14:00	98.8	75.7	39.1	16,430	44,612	
9/22 15:00	100.2	76.7	40.0	16,816	45,116	
9/22 16:00	100.9	75.7	39.0	16,487	44,594	
9/25 14:00	100.4	76.1	39.5	14,455	40,769	Week end; although dry bulb temperatures reached peak values for the year, the campus load did not reach the peak.
9/25 15:00	103.0	76.9	40.2	14,722	41,593	
9/25 16:00	105.5	77.6	40.9	14,935	41,794	
9/25 17:00	105.0	77.1	40.4	14,956	41,790	
9/25 18:00	101.8	76.4	39.7	14,980	41,862	
9/25 19:00	98.3	75.5	38.9	14,834	41,560	
9/26 13:00	98.7	75.7	39.1	16,968	45,490	Wet-bulb temperatures did not peak.
9/26 14:00	101.7	75.5	38.9	17,035	45,620	
9/26 15:00	104.3	76.1	39.4	17,082	45,442	
9/26 16:00	106.3	76.2	39.5	17,072	45,735	
9/26 17:00	106.2	76.1	39.3	16,962	45,293	
9/27 14:00	100.2	78.8	42.2	17,868	46,740	Wet-bulb temperature was high but slightly lower than that of 9/28/2005.
9/27 15:00	101.2	78.9	42.3	18,162	46,870	
9/27 16:00	101.8	78.9	42.3	18,214	46,975	
9/27 17:00	101.5	78.7	42.0	18,008	46,452	
9/27 18:00	98.5	76.7	40.0	17,233	45,469	
9/28 13:00	98.0	80.3	43.8	18,638	47,451	Final candidates correspond to the highest day of wet bulb temperatures.
9/28 14:00	99.4	79.3	42.7	18,815	48,033	
9/28 15:00	102.3	79.6	43.1	18,673	47,970	
9/28 16:00	102.9	78.8	42.2	18,452	47,457	
9/28 17:00	102.0	79.1	42.5	18,524	47,875	
9/28 18:00	99.2	77.2	40.5	17,714	47,042	

Table 1 demonstrates an example of determining the peak flow demand conditions. The metered data of ambient dry-bulb temperature (TDB), wet-bulb temperature (TWB), the plant total cooling energy production, and the total chilled water flow rate were filtered out when the TDB and TWB are higher or equal than the climate design criteria for this site.

Second, the factors that affect the peak flow conditions discussed in the previous section are considered to further determine the peak flow demand conditions among those candidates. As shown in Table 1, from 9/15/2005 to 9/26/2005, the ambient air enthalpies were lower than the rest of the candidate periods. Therefore the data shows lower cooling loads and flow and these data are eliminated from the candidates. Also, it is noted that the cooling load of 9/25/2005 is significantly lower than the rest of the candidates. This is because that day was Sunday with less occupancy on campus. The ambient air enthalpy, system cooling load and flow of 9/27/2005 were lower than those of 9/28/2005. Finally, the time period between 13:00 and 17:00 of 9/28/2005 is when the peak flow demand condition occurs. It is also noted that the peak flow demand condition deviated very little during the four hours, of which the total chilled water flow varied only 582 GPM (only 1% of the maximum flow of 48,033 GPM). The long time period of these peak flow demand conditions also provided all the buildings on campus enough time to establish a stable peak flow condition. Lastly, due to the data availability, the final peak flow demand moment is then determined at 9/28/2005 17:00.

After the peak flow demand is determined, system parameters, if metered at this moment, are used to develop the peak flow demand model. The system parameters should include the boundary pressure conditions, i.e. the plant supply and return pressures, system overall ΔT, system main trunk flows, buildings' chilled water flow, ΔT, and ΔP (if metered).

Mass Balance

Regardless of how the peak flow demand is assigned to individual buildings, the chilled water flow out of the source system must be equal to the total flow through the load system plus the flow leaking out of the system. In equation form, this can be stated as:

$$Q_{source} - \sum Q_i - Q_{makeup} = 0 \qquad (1)$$

In equation (1), Q_{source} is the total chilled water flow out of the source system, such as chiller plants and storage tanks. Q_i is the chilled water flow for building i of the load system. Q_{makeup} is the make up water flow at the plant expansion tank. For a well maintained chilled water system the make up rate is negligible. For example, the metered data shows the makeup rate for the TAMU main campus chilled water system is less than 0.1%.

DCS buildings can be divided into metered buildings and un-metered buildings. Equation (1) is rewritten as:

$$Q_{source} = \sum Q_{mi} + \sum Q_{uj} \qquad (2)$$

Where:

Q_{mi} = flow demand for metered building i.

Q_{ui} = flow demand for un-metered building j.

If the building chilled water consumption is monitored, the metered chilled water flow at the peak demand flow moment can be assigned as its peak demand flow. However, before assigning the metered flow to the building, it must be ensured that: (1) the measured flow corresponds to the locations to which it is assigned; (2) the flow is metered at the building entrance; and (3) the flow meter is properly calibrated. Also, the metered data should be verified and crosschecked before it is assigned to the model. The flow estimations for un-metered buildings will be discussed below.

Categorizing Building Demands

Under the same weather condition, buildings serving similar functions tend to require similar cooling energy on a unit area basis, i.e. they tend to have similar cooling load intensity. Buildings on a large university campus can be student dorms, classrooms, offices, laboratories, libraries, sports facilities, auditoriums, dining halls, and any combinations of the above uses. Different types of buildings will have different levels of cooling requirements. For example, chemistry labs with 100% outside air intake require more cooling energy than a normal office. Buildings with lot of experimental equipment or computers require more cooling energy. If some chilled water consumption data for certain types of buildings is available, it can be used to estimate cooling requirements of other un-metered buildings of this type.

The average cooling load intensity for buildings of type j can be expressed as:

$$\bar{I}_j = \frac{\sum_{i=1}^{n_{mj}} q_{mij}}{\sum_{i=1}^{n_{mj}} A_{mij}} \qquad (3)$$

where:

$\bar{I}_j$ = Average cooling load intensity for buildings of type j (Btu/hr-ft^2).

q_{mij} = Metered cooling load of building *i* of type *j* (Btu/hr).

A_{mij} = Air conditioned area of metered building *i* of type *j* (ft^2).

Then the cooling load for an un-metered building of the same type can be estimated as:

$$\hat{q}_{uij} = \bar{I}_j \cdot A_{uij} \tag{4}$$

where:

$\hat{q}_{uij}$ = Estimated cooling load of the un-metered building *i* of type *j* (Btu/hr).

A_{uij} = Air conditioned area of the un-metered building *i* of type *j* (ft2).

For example, the DCS buildings on the TAMU main campus were categorized into four types: (1) student dorms; (2) general offices, classrooms; (3) laboratory buildings with 100% out side air requirement, such as chemistry labs; (4) mixed use buildings with offices, laboratories, classrooms, etc.

Table 2 summarizes the cooling intensities for each type of building based on the metered data under the peak load condition.

Table 2 Estimated Peak Cooling Load Intensity for Different Types of Buildings

Type	Number of Buildings	Number of Metered Buildings	Total AC Area (ft^2)	Metered AC Area (ft^2)	Avg. Peak Cooling Intensity (Btu/hr-ft^2)	Standard Deviation (Btu/hr-ft^2)
1	34	25	1,823,140	1,331,189	21	3.6
2	33	14	2,635,789	1,555,184	16	3.9
3	4	1	538,900	204,972	60	N/A
4	46	21	3,737,232	2,021,370	31	7.9
Overall	117	61	8,735,061	5,112,715	25	9.8

Finally, the chilled water flow for the un-metered building *i* can be estimated as:

$$\hat{Q}_{ui} = \frac{\hat{q}_{ui}}{500 \cdot \Delta\hat{T}_{ui}} \tag{5}$$

where:

$\hat{q}_{ui}$ = Estimated cooling load of un-metered building *i* (Btu/hr).

$\hat{Q}_{ui}$ = Estimated chilled water flow rate for un-metered building *i* (GPM).

$\Delta\hat{T}_{ui}$ = Estimated chilled water differential temperature for un-metered building *i* (°F).

To estimate the $\Delta\hat{T}_{ui}$, the average differential temperature at the plant entrance is a good starting point, as it represents the overall campus chilled water differential temperature. The in-building chilled water systems can be categorized into variable flow systems, and constant flow systems. The intention of varying the chilled water flow through the building is to increase the ΔT under partial load conditions and save pumping energy. For constant flow in-building systems, the chilled water flow is relatively constant and the ΔT fluctuates with the cooling load. The ΔT of a constant flow in-building system tends to be smaller than that of a variable flow in-building system. Therefore, the average building ΔT for metered buildings with a certain type of in-building system should be closer to the actual ΔT than the campus average and will be used to estimate the building ΔT for those un-metered buildings with the same type of in-building system. This can be expressed as:

$$\Delta\hat{T}_{k,ui} = \Delta\bar{T}_k = \frac{\sum \Delta T_{k,mi}}{n_{k,m}} \tag{6}$$

where:

$\Delta\hat{T}_{K,ui}$ = Estimated differential temperature for un-metered building *i* with type *K* of in-building system.

$\Delta\bar{T}_K$ = Average differential temperature of type *K* in-building systems.

$\Delta T_{K,mi}$ = Metered differential temperature for metered building *i* with type *K* in-building system.

$n_{K,m}$ = Number of metered buildings with type *K* in-building system.

Table 3 Estimated Building ΔT for Variable Flow and Constant Flow Types of In-building Systems

BLDG Type	Constant Flow			Variable Flow		
	# Metered / # Total	Average ΔT (°F)	Standard Deviation (°F)	# Metered / # Total	Average ΔT (°F)	Standard Deviation (°F)
1	13/18	7.0	2.3	16/16	9.1	3.3
2	8/19	7.3	1.9	10/15	10.1	3.1
3	0/0	0.0	0.0	1/4	15.1	1.4
4	8/21	7.3	1.9	17/24	11.8	4.5
Overall	**29/58**	**7.2**	**3.2**	**44/59**	**10.5**	**5.7**

Model Reconciliation

With the metered total peak flow demand, the metered demands, and the justified initial estimation of un-metered demands, the overall peak flow model can be reconciled based on mass balance:

$$\hat{Q}_{ui,R} = (Q_{source} - \sum_{i=1}^{n_m} Q_{mi}) \cdot \frac{\hat{Q}_{ui}}{\sum_{i=1}^{n_u} \hat{Q}_{ui}} \tag{7}$$

where:

$\hat{Q}_{ui,R}$ = Reconciled estimate of the peak flow demand for un-metered building *i*.

MODEL VERIFICATION AND CALIBRATION

Simulation software just solves the hydraulic equations by using the supplied data. Therefore, the accuracy of the simulation results heavily relies on the quality of the inputs including the physical model and demand model. The accuracy of the hydraulic model depends on how well it has been calibrated, so a calibration analysis should always be performed before a model is used for decision-making purposes.

A large DCS hydraulic system with hundreds of buildings is usually very complicated. Variations can stem from the cumulative effects of errors, approximations, and simplifications in the way the system is modeled; site-specific reasons such as outdated system maps, local piping resistance, partially open valves, and more difficult-to-quantify causes like the inherent variability of building flow demands. Therefore, it is imperative the verification and calibration must be processed systematically to avoid cumulative errors.

(1) Verify initial simulation results with measured values through the following three measures:

    a. Compare simulated main trunk flows and plant ΔPs with measured values.

    b. Overlap simulated and measured building ΔPs on a system map.

    c. Generally speaking, building ΔPs is lower when they are farther from the plant (see Figure A - 4). Draw simulated and measured building ΔPs by aligning the buildings from the one closest to the plant to the one farthest to the plant. Also, if the predicted distribution line ΔP is higher than the measured value, the overall model under estimates the system resistance. Conversely, if the predicted distribution line ΔP is lower than the measured value, the overall model over estimates the system resistance.

(2) Develop hypothetical explanations of the errors. Possible calibration factors should be identified. Normally, from the system point of view, the calibration factors include: flow and ΔP at plant entrance, overall system resistance factor, and building flow demand allocation.

(3) Conduct sensitivity studies on the calibration factors by varying one factor while keeping other factors fixed. The sensitivity study of the TAMU main campus DCS hydraulic system model shows that:

    a. Increase the ΔP at plant entrance will cause the ΔP distribution line moving upwards and vise versa. The slope of the ΔP distribution line will not change.

b. Increase the overall system resistance factor will increase the slope of the ΔP distribution line and vise versa.

c. Increase the flow demand of a building will increase the pressure drop through that building. Also, allocate more flow demand to down-stream buildings will increase the slope of the ΔP distribution line.

(4) Rough-tune the model by modifying the overall system calibration factors base on the sensitivity study to match major system parameters.

(5) Fine-tune of the model. This step involves adjustments of individual model components such as the roughness coefficient of a section of pipe. The collected information and data may need to be further verified and cross checked. Field investigation may be required. Even the metered calibration data should be verified. For a hydraulic system model that covers hundreds of buildings on a large DCS, the final step of calibration can be time consuming. The iteration process of the entire calibration procedure can further complicate the fine-tuning stage.

The level of effort required calibrating a hydraulic network model, and the desired level of the calibration's accuracy will depend upon the intended use of the model [2] [7] [12]. There are no hard numbers to define whether the calibration accuracy is acceptable or not. A range of values is given for most of the guidelines to reflect the differences among water systems and the needs of model users. A general guideline for master planning purposes of a small DWS system (24 inch pipe or smaller) has been established [12]. According to this criteria, the model should accurately predict hydraulic grade line (HGL, defined as the summation of elevation head and pressure head) to within 5 – 10feet (2.2 – 4.3psi). The high end of the range corresponds to large, more complicated systems, while the lower end of the range is more relevant for smaller, simpler systems.

Because the diameter of the main pipes for a small DWS (24 inches or smaller) is similar to that of a large DCS hydraulic system (e.g. the main pipe diameter of TAMU main campus DCS is 24 inches), the overall water delivering capacity for the two types of systems should be similar. On the other hand, the ΔP distribution line of a DCS hydraulic system presents the same concept of the HGL of a DWS except the elevation effect is cancelled out in the DCS hydraulic system. Therefore, this criterion can be used as a reference for the calibration of a large DCS hydraulic system model for master planning purposes.

Since each application of a DCS hydraulic simulation model is unique and has its specific situations, it is impossible to derive a single set of guidelines to evaluate calibration. Although the above guidelines provide some numerical guidelines for calibration accuracy, they are in no way meant to be definitive even for their own purpose i.e. DWS model calibration [12].

CONCLUSIONS

A practical procedure has been developed for modeling large DCS hydraulic systems for master planning purposes. It was found that although the DWS modeling methodology can be generally applied to DCS hydraulic systems, significant differences exist which require unique solutions in order to develop a suitable hydraulic system model for a large DCS. The major difference between the DCS hydraulic modeling procedure and the DWS modeling procedure lies in their demand modeling processes. Instead of dealing with one parameter i.e. flow in DWS demand modeling, the DCS demand modeling involves two parameters i.e. energy and temperature.

Specific considerations relating to the physical model construction have been discussed. The level of "skeletonization" suitable for master planning purposes of large DCS hydraulic system has been discussed and a method to model the peak flow demand has been developed. This method uses actual metered data and a variety of information and data to categorize the building energies and differential temperatures and then determine the building peak flow demands based on mass conservation. The effectiveness of this method depends on the data availability and reliability.

The methodology can be applied for broader purposes, such as operation optimization and system continuous commissioning®. This creates the opportunity for future study to expand on the current research.

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APPENDICS

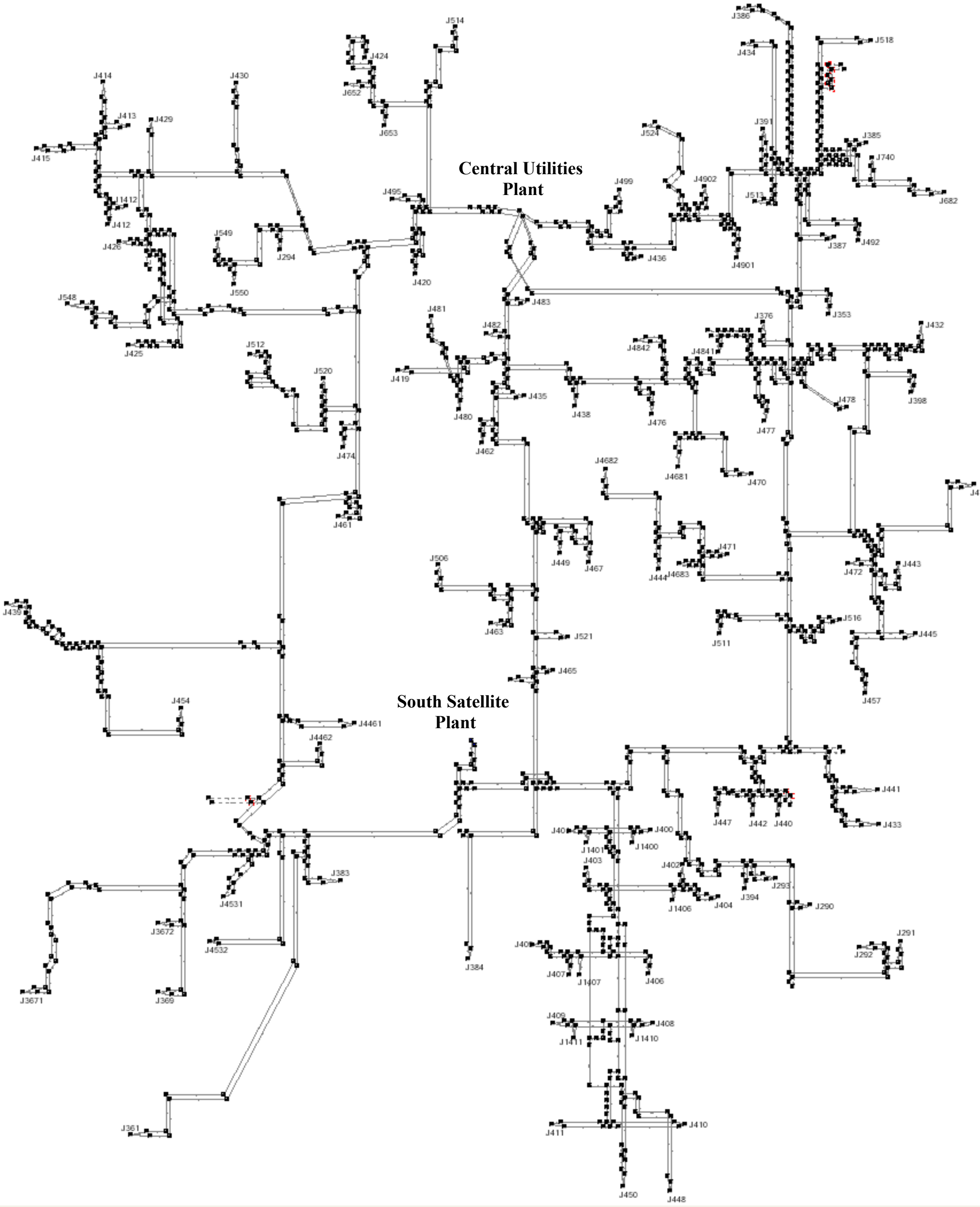

Figure A - 1 Physical Layout of the TAMU Main Campus DCS Hydraulic System Model

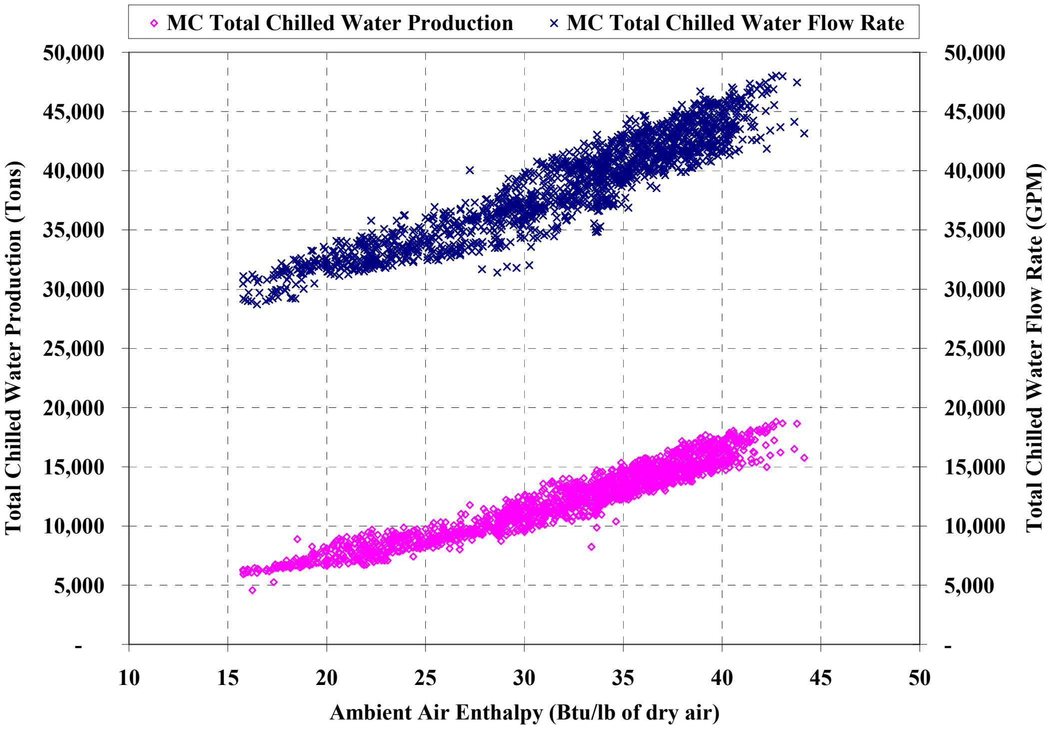

Figure A - 2 TAMU Main Campus CHW Production and Flow vs. Ambient Air Enthalpy

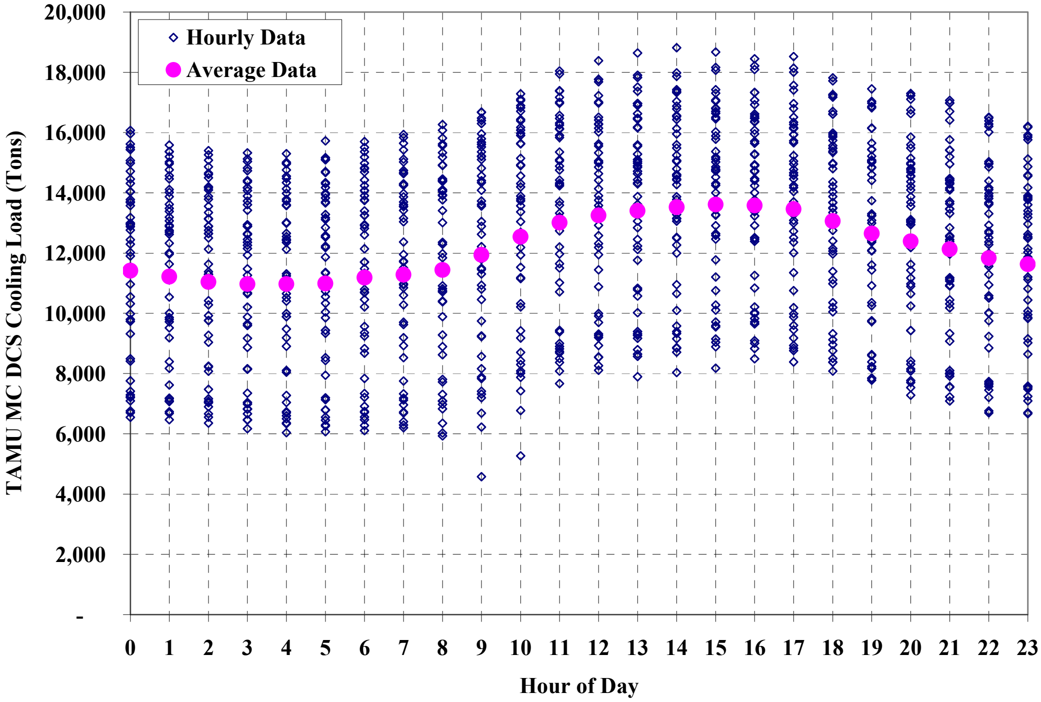

Figure A - 3 TAMU MC DCS Cooling Load vs. Hour of Day

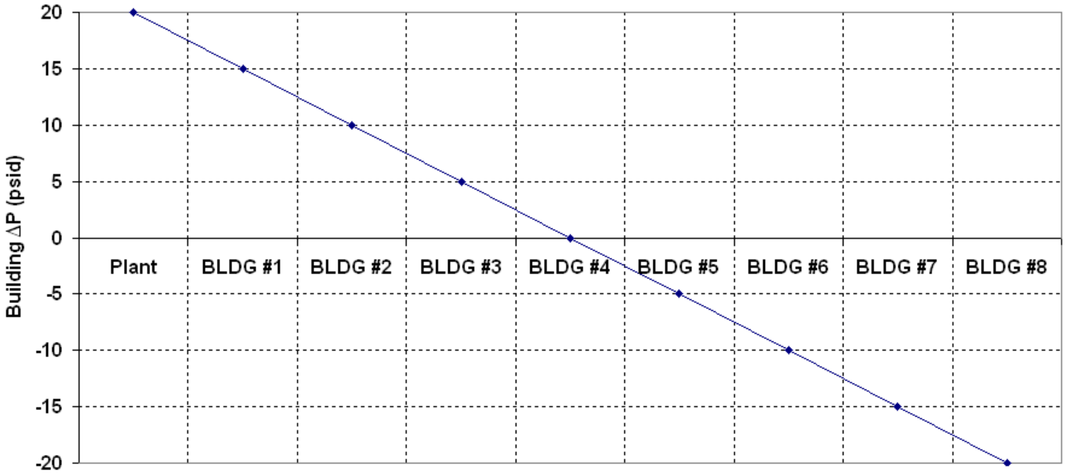

Figure A - 4 Typical Building ∆P Distribution Line