HYDRAULIC MODELING OF LARGE DISTRICT ENERGY SYSTEMS FOR PLANNING PURPOSES

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ABSTRACT

District Energy Systems (DES), e.g. District Cooling Systems (DCS) and District Heating Systems (DHS), have been widely applied in large institutions in the United States, such as universities, government facilities, commercial districts, airports etc. The hydraulic system of a large DES 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 DHS 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 DES hydraulic system to the planned future.

A complete procedure has been developed to construct the hydraulic model for a large DES by using commercial simulation software for planning purposes. This paper will first introduce the overall modeling procedure. Then real hydraulic models for one DCS and one DHS, which are among the largest DES in the United States, will be introduced, as well as its successful applications in assisting decision makings.

KEYWORDS

Pipe Network, District Cooling System, District Heating System, Central Chilled Water System, Central Heating Hot Water System, Hydraulic Simulation

INTRODUCTION

In the United States, DESs have been widely applied in large institutions such as universities, government facilities, commercial districts, airports etc. For example, the largest DCS in universities can have 154,742 kW of cooling capacity and the total linear pipe length (supply and return) can approach 27 km in length (IDEA 2002). Normally a DES already means a large centralized cooling and/or heating system that covers multi-buildings of various loads by a central plant. The word "large" specifically mentioned here is intended to focus on those DESs that covers more than 300,000 ~ 500,000 m^2 of building space and have more than 40,000 kW of cooling capacity as their hydraulic systems are more complicated and worth the attention to study.

The hydraulic systems of large DESs often stem from an original design that has had extensive additions and deletions over time. A DES is usually continuously expanding as the campus grows. When new buildings are to be built, they will typically be connected to the distribution systems of a DES, i.e. the central Chilled Water (ChW) and Heating Hot Water (HHW) systems. The existing distribution systems may need to be modified to accommodate the new buildings. Accordingly, the total thermal capacity may need to be enlarged by installing new equipments in the existing central plant or possibly new satellite plants will need to be built or expanded. Expanding or retrofitting such a system involves large capital investment (ASHRAE 2000). On the other hand, once the piping infrastructure is built underground, it will stay there and serve for many years to come. Meanwhile, 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 DES distribution systems will become a powerful analytical tool for this purpose (Chen et al. 2002, Walski et al. 2001). With the DES hydraulic system model, engineers can virtually explore various alternatives of system configuration to find an optimal solution of accommodating the existing system to the planned future. So that, the hydraulic model can be used to answer important decision-making questions regarding to planning purposes. Furthermore, the model can serve as an powerful tool for the Continuous Commissioning®[1] (CC®) of the DES distribution systems, e.g. identifying potential problems of the ChW and HHW systems and providing optimized the operation and control guidelines. Eventually, the DES hydraulic model can be seen as an asset to the facility owner and needs to be continuously maintained and updated.

Based on the research on several large DES systems, including one of the largest systems in the United States, a comprehensive hydraulic simulation

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procedure has been developed (Xu et al. 2006). This paper will first briefly introduce the simulation procedure and then introduce two successful projects accomplished based on this procedure.

SIMULATION PROCEDURE

Typical Large DESs

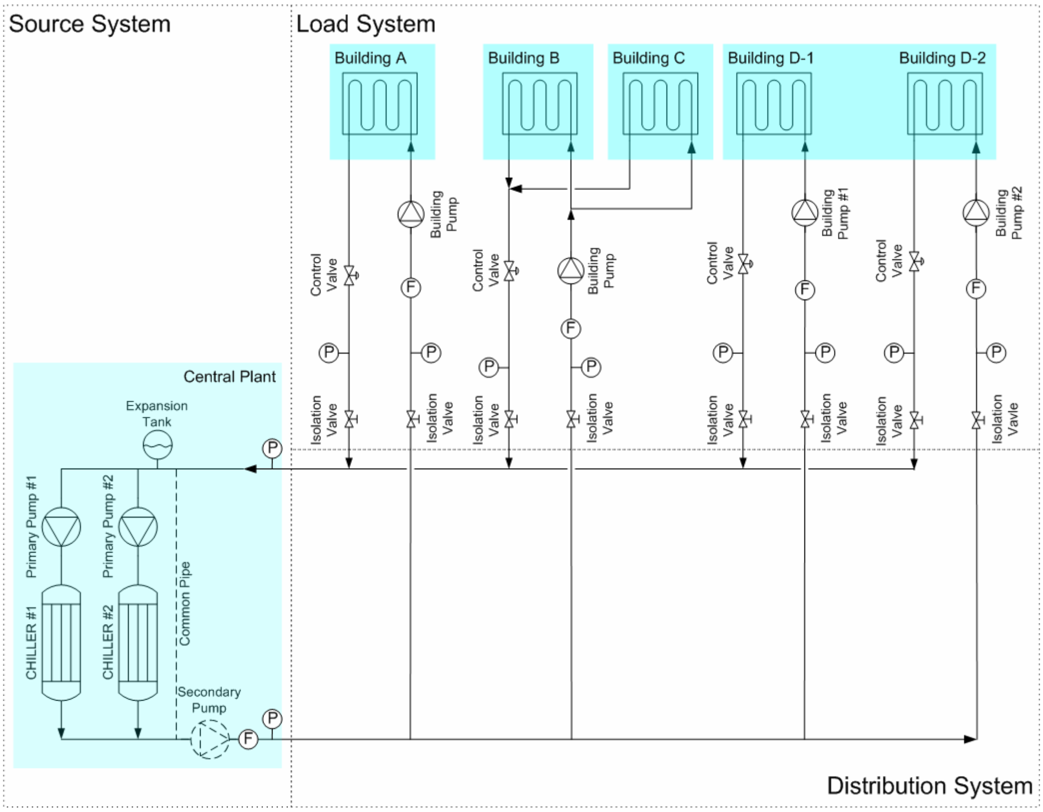

Figure 1 Schematic Layout of a Typical Large DCS

From the hydraulic stand point, a typical large DES system have the following characteristics:

- DES systems are usually closed loop re-circulating systems.
- Parallel piping networks are the most commonly used in large DES hydraulic systems as they provide the same chilled water temperature to all end users.
- The distribution systems of a large DES are mostly variable flow systems, as they can reduce energy use and expand the capacity of the distribution system piping by using diversity.
- Large DES distribution systems often employ the combination of distributed pumping and source distributed pumping (DOE 2004).
- Large DESs consist of three sub-systems: (1) the source system, i.e. the energy plants; (2) the distribution piping networks; (3) the load system, i.e. the in-building ChW and HHW systems, either constant or variable flow systems. As an example, Figure 1 demostrates a schematic layout of a typical large DCS.

Modeling Procedure

The methodology for solving pipe network problems have been developed (Walski 1984). Nowadays, many commercial simulation software packages are available on market. Standard modeling procedures have been developed primarily for Domestic Water Systems (DWSs) (Walski 2001). It was found that although both DWSs and DES hydraulic systems belong to pipe networks, significant differences still exists between the two. For example: (1) DWSs are open loop systems whereas DES hydraulic systems are closed loop systems. (2) DWSs are mass consumption systems whereas DESs are energy consumptions systems involving both mass flow and temperatures. It was found that although the DWS modeling procedure can be generally applied to DES hydraulic systems, differences between the two types of systems require unique solutions in order to develop a suitable hydraulic system model for a large DCS.

Figure 2 illustrates the general modeling procedure, which includes three major steps: (1) Information collection, (2) Physical model and demand model construction, and (3) Model verification and calibration.

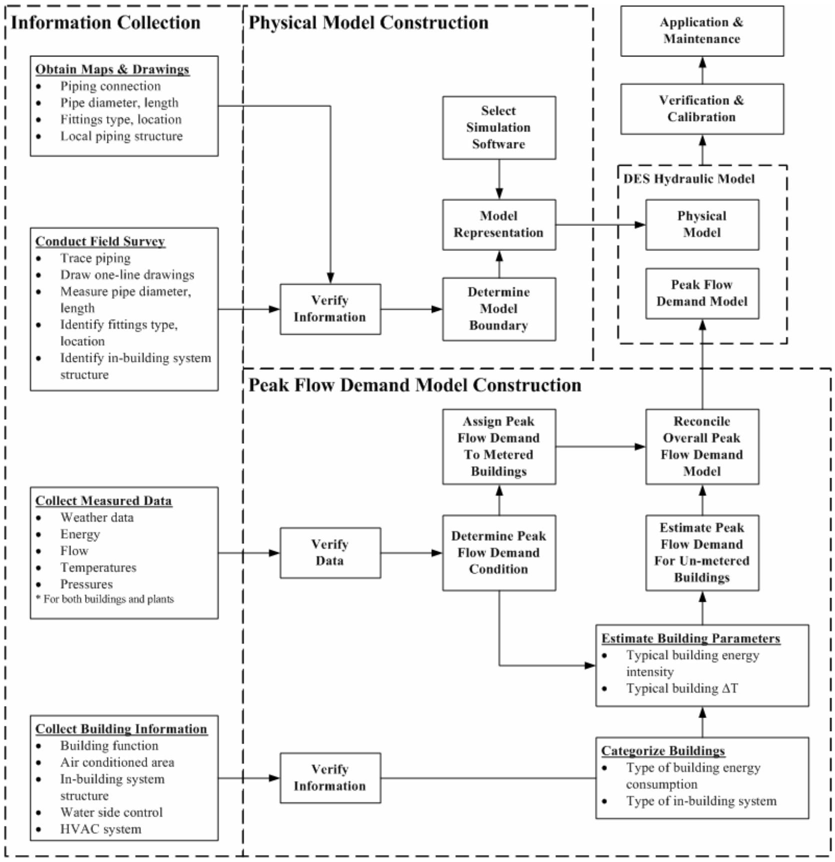

Figure 2 Generalized DCS Hydraulic System Modeling Procedure

In the first step, tremendous amount of information and data are to be collected. Multiple departments will be involved to provide the requested information and data and be coordinated with field work. It was found that beside collecting maps and drawings, field investigation is very necessary to obtain the up-to-date system parameters. The physical model represents the physical structure of the real system, such as the piping infrastructure, pumps, valves, etc. A commercial pipe network simulation software package is often used to construct the physical model. The flow demand model 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 values assigned to each building represented as a modeled node in the physical model. Before using the hydraulic model, it will 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.

Physical Model

The procedure of constructing the physical model is similar to that of a DWS. For a large DES, each of the sub-systems itself can be very complicated. Having a complete DES hydraulic model with every detail of each of these sub-systems is ideal, but could involve huge amout of work load, and make no significant impact on the results if this model is used for certain purposes. Capturing every feature of a system would also involve tremendous amounts of data, which would make the model error-prone. Therefore, the physical model should be built to certain extent of skeletonization which depends on the intended use of the model (Walsk 2001). However, skeletonization does not mean omission of data. The portions of the system that are not included in the model are not discarded. Their effects are taken into account in the physical model.

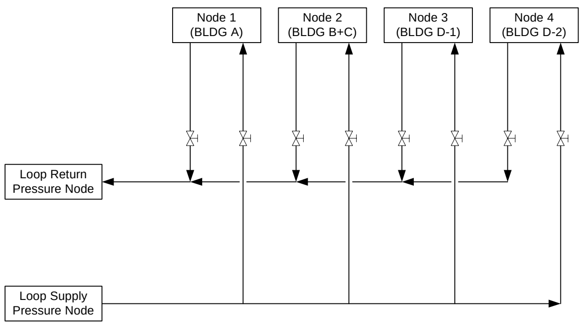

Figure 3 The Skeletonized Model Layout of Figure 1

The large DES hydraulic model is used for planning purposes. It's objective 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 entrances of buildings and plants are 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. Therefore, the plant and in-building systems can be simplified as flow or pressure nodal components without sacrificing the model accuracy. For example, Figure 3 is the skeletonized system layout of Figure 1 introduced above.

Peak Flow Demand Model

As mentioned above, building energy consumption and water differential temperature, are involved with the flow demand model. These two parameters are affected by many factors. For example, building energy consumption relates to weather conditions, building construction, occupancy level, etc. The differential temperature is affected by the physical condition of the in-building system and its operation and control.

Trying to predict the energy consumption and water flow rate for above one hundred buildings on a large DES by using a forward modeling method that involves detailed building information would be time consuming and cost prohibitive. A practical approach of developing the flow demand model is to use general building information and actural measured data.

Determine Peak Flow Demand Conditions

For 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 buildings, it should work under partial flow 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. So 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 ChW or HHW production can be used to determine the peak flow demand conditions as it naturally takes the diversity effect into account. Large DES hydraulic systems are usually variable flow systems. The total water flow rate is generally proportional to total thermal load. To determine the peak load conditions, weather conditions are important factors. Besides weather conditions, occupancy and the corresponding variation in gains from electricity is other factors that affect the peak load conditions.

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 flow out of the source system. Q_i is the 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 system the make up rate is negligible. It is seldom that all the buildings of a large DES are fully metered. Even if all the buildings are metered, metering inconsistency may occur. Therefore, 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.

The metered flow at the peak demand flow moment can be assigned to the model. 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.

Categorizing Building Demands

Under the same weather condition, buildings serving similar functions tend to require similar energy on a unit area basis. If some energy consumption data for certain types of buildings is available, it can be used to estimate the energy consumpton for un-metered buildings of the same type. The average cooling load intensity for buildings of type j can be expressed as:

$$\bar{I}_j = \frac{1000 \times \sum_{i=1}^{n_{mj}} q_{mij}}{\sum_{i=1}^{n_{mj}} A_{mij}} \qquad (3)$$

where:

$\bar{I}_j$ = Average cooling load intensity for buildings of type j (W/m^2).

q_{mij} = Metered cooling load of building i of type j (kW).

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

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

$$\hat{q}_{uij} = \frac{\bar{I}_j \cdot A_{uij}}{1000} \quad (4)$$

where:

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

A_{uij} = Air conditioned area of the un-metered building *i* of type *j* (m^2).

Finally, the flow rate of an un-metered building *i* can be estimated as:

$$\hat{Q}_{ui} = \frac{\hat{q}_{ui}}{4180 \times \Delta\hat{T}_{ui}} \quad (5)$$

Where:

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

$\hat{Q}_{ui}$ = Estimated flow rate for un-metered building *i* (m^3/sec).

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

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 system. The in-building 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 flow is relatively stable and the ΔT fluctuates with the load variation. The ΔT of a constant flow in-building system tends to be smaller than that of a variable flow in-building system. This can be expressed as:

$$\Delta\hat{T}_{k,ui} = \Delta\overline{T}_k = \frac{\sum \Delta T_{k,mi}}{n_{k,m}} \quad (6)$$

where:

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

$\Delta\overline{T}_K$ = 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.

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:

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

where:

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

Model Verification and Calibration

A large DES 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. 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.

(3) Conduct sensitivity studies on the calibration factors by varying one factor while keeping other factors fixed.

(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. The final step of calibration can be time consuming. The iteration process of the entire calibration procedure can further complicate the fine-tuning stage.

CASE STUDY

This section uses two sucessful real projects to demonstrate how the hydraulic model can help decision makings.

Case 1: A ChW Expansion Project of a Large University

Site Description

This univeristy has a 21 km^2 campus, among the largest in the United States. It main campus has an extensive and sophisticated ChW system. The current ChW system has more than 26 km of piping and reaches out to 117 buildings with a total of more than 83,6130 m^2 of conditioned space. The 117 buildings are composed of offices, classrooms, laboratories, dormitories, dining facilities, sports facilities and combinations of these uses. These buildings vary in ages ranging from those built in late 19th century to some built in recent years.

All these buildings receive chilled water from two utilities plants: the Central Utilities Plant (CUP) and the South Satellite Plant (SS3). With installed cooling capacity of 75,261 kW, the CUP sends out ChW through four loops: West, East, South, and Central. All these loops are interconnected. The SS3 is a complementary plant with installed cooling capacity of 16,523 kW, connected to the South loop about 2/3 of the way from the CUP. Such a large campus is still expanding. According to the university's 30-year master plan, 548,130 square meters of new building space is planned and 83,613 square meters of building space is scheduled to be demolished.

Project Description

Six new buildings were planned to be built in the near future (see Table 1). Building #1 will serve multiple purposes such as offices, biological laboratories, auditoriums, etc. Buildings #2, #3, and #4 are typical engineering buildings including classrooms, offices, and laboratories. Buildings #5 and #6 are parking garages. Each garage will be wrapped on two sides with occupied space that is both subservient to and complementary of the Old System Administration Building.

Table 1 Information of Six Planned New Buildings

Bldg. #	**Area** (m^2)	**Load** (kW)	**Flow** (m^3/sec)
1	N/A	6,154	0.221
2	9,913	1,502	0.054
3	9,826	1,488	0.054
4	6,049	914	0.033
5	14,865	805	0.029
6	14,865	805	0.029

These new buildings require added cooling capacity, at either CUP or SS3 or at both of them. The appropriate place(s) to add new chillers needs to be determined. From the distribution point of view, the second question is whether the current piping infrastructure is capable of delivering the added chilled water to the campus. What are the possible piping modifications to accommodate the expansions becomes the third question. According to the above decision making questions, it was requested to evaluate the existing ChW system capability and future expansion possibilities.

Simulation

To reflect the planned new buildings, the hydraulic model for the existing system was modified to reflect the possible piping arrangement. Figure 4 is the system map. The six planned new buildings are shown as slash hatched blocks in red. Selected loop end buildings are cross hatched and colored in green. The impact of the new buildings on these loop end buildings will be studied. Numbers #1 through #6 are assigned to each of these planned buildings.

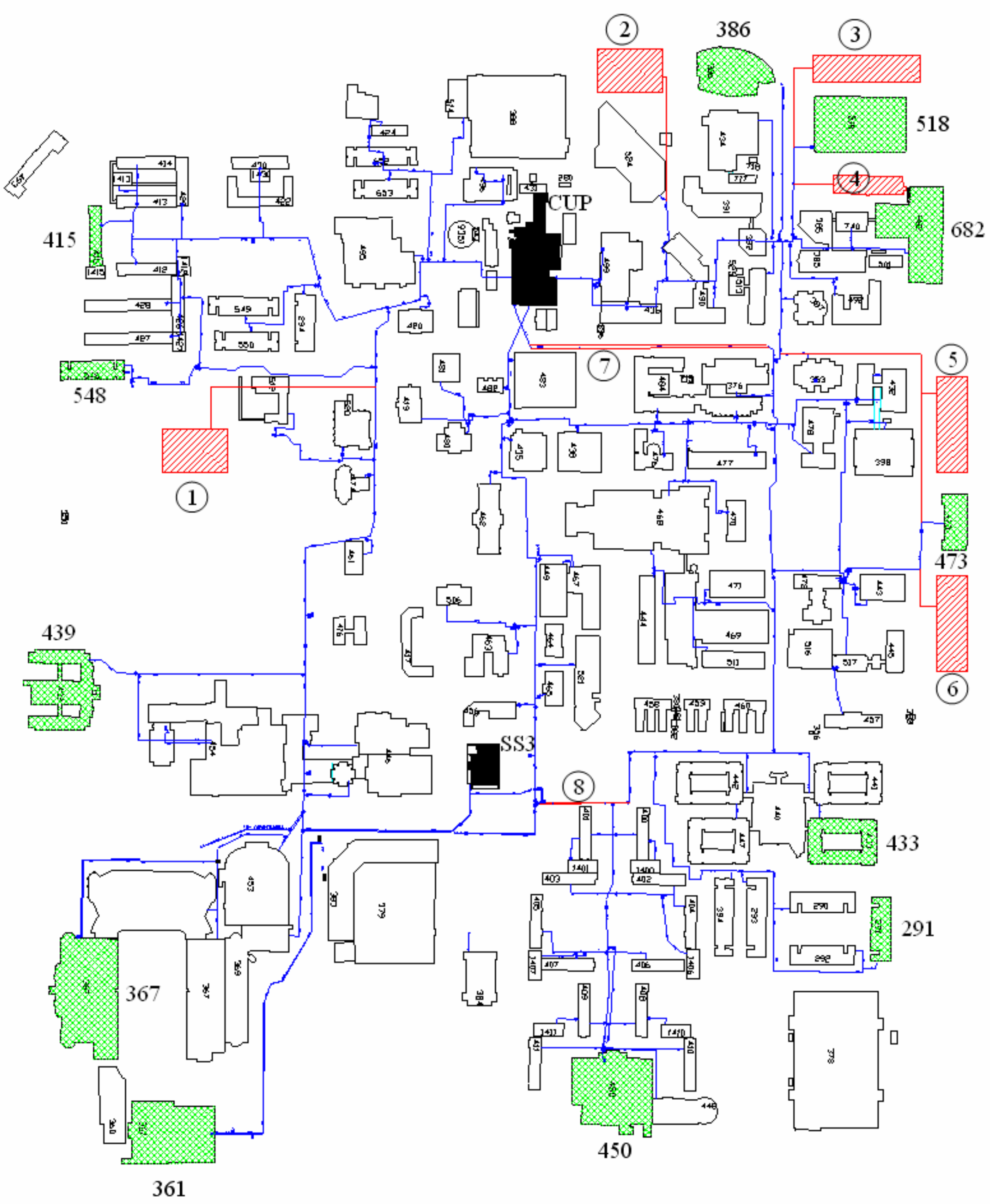

Figure 4 Planned New Buildings and Possible System Piping Expansion

To answer the above decision making questions, a series of scenarios of possible combinations of plant flow allocation and system piping modifications were simulated. The differential pressures for loop-end buildings were compared. Then the optimal way of accommodating the six new buildings to the existing system was selected. The simulated scenarios are:

(1) This is the base scenario, i.e. existing system without any new buildings.

(2) It is assumed that the new chillers will be installed in the CUP, so that the chilled water flow from CUP will be increased. Other system parameters have no change.

(3) This scenario considers replacing the 610 mm main pipe under Ross Street (number 7 in Figure 32) with a larger 762 mm pipe, with new chillers installed in the CUP, the same as scenario one.

(4) This scenario considers installing the new chillers in the SS3, which is easily expanded. The main pipe under Ross Street remains at 610 mm.

(5) Through the existing system model study, it was determined that a section of the main pipe on the east side of the SS3 (number 8 in Figure 32) is significantly undersized (356 mm). This scenario considers replacing it with 453 mm pipe. New chillers are installed in the

SS3, so that the SS3 chilled water flow increases from 0.757 m^3/sec to 1.009 m^3/sec.

(6) This scenario considers increasing both the 610 mm main pipe under Ross Street to 762 mm and the 356 mm. pipe on SS3 east loop to 457 mm. New chillers are considered to be installed in the SS3.

The system parameters for different scenarios are listed in Table 2.

Table 2 System Parameters for Different Scenarios

System Parameters	Scenarios					
	Base	1	2	3	4	5
CUP differential pressure (kpa)	110.3	110.3	110.3	110.3	110.3	110.3
Ross Street pipe (7) size (mm)	610	610	762	610	610	762
SS3 bottle neck pipe (8) size (mm)	356	356	356	356	457	457
CUP total flow (m^3/sec)	2.263	2.862	2.862	2.429	2.429	2.429
SS3 total flow (m^3/sec)	0.757	0.757	0.757	1.009	1.009	1.009
Main campus total flow (m^3/sec)	3.020	3.619	3.619	3.438	3.438	3.438

Simulation Results

Table 3 Simulated Building Differential Pressures (kPa) for Different Scenarios

#	Scenarios					
	Base	1	2	3	4	5
291	-172.4	-194.4	-154.4	-165.5	-138.6	-112.4
433	-29.0	-51.7	-9.7	-26.2	-9.7	24.8
450	-163.4	-185.5	-148.2	-148.9	-118.6	-91.0
361	60.0	29.6	48.3	116.5	77.9	96.5
367	43.4	12.4	31.7	98.6	60.7	79.3
439	-11.0	-51.0	-41.4	-15.9	-28.3	-22.1
548	52.4	16.5	21.4	36.5	28.3	32.4
415	-46.2	-75.8	-71.7	-59.3	-66.2	-62.7
386	-15.9	-40.7	0.7	-29.6	-22.8	9.0
518	21.4	-18.6	22.8	-7.6	0.0	30.3
682	-17.2	-44.1	-2.8	-33.1	-25.5	5.5
473	-30.3	-52.4	-4.1	-33.1	-21.4	15.9
6	N/A	-62.1	-13.8	-42.7	-31.0	6.2
5	N/A	-52.4	-4.1	-34.5	-22.8	14.5
1	N/A	-24.1	-17.9	0.7	-9.7	-4.8
4	N/A	-50.3	-9.0	-39.3	-31.7	-0.7
3	N/A	-71.0	-30.3	-60.0	-53.1	-22.1
2	N/A	-17.2	6.2	-11.0	-6.9	11.0

Table 3 lists the simulation results for the 6 different scenarios. Comparing the simulation results of the base scenario and scenario 1, all the building differential pressures are negatively affected. The result of scenario 2 indicates a significant building DP improvement by replacing the 610 mm main pipe under Ross Street with a 762 mm diameter pipe. The result of scenario 3 also demonstrates a good improvement on building ΔP, if new chillers are placed at SS3 and nothing else is changed. Furthermore, the result of scenario 3 shows that the building ΔPs on the south-end of the main campus show significant improvement over the base scenario and scenarios 1 and 2. The result becomes even better when applying scenario 4, which further increases the 356 mm pipe to 457 mm. The building ΔPs in the Corps of Cadets area (building #450 and its vicinity area) significantly improved. Finally, the overall campus building ΔPs are further improved when applying scenario 5. Further analysis from the pumping point of view shows that scenario 5 will require the lowest pumping power among the scenarios. It can be concluded that installing new chillers at the SS3 is a better choice. In addition, increasing pipe sizes will also help the water distribution. However, the installation cost becomes the key issue for the decision-makings.

This project has been sucessfully fnished. Currently, Construction of Building #1 (a $98 million project) has started.

Case 2: Preliminary Design of a ChW Expansion Project

In this project, it was requested to evaluate a previously designed ChW loop expansion plan for a univeristy campus at San Antonio, Texas, with approximately 139,355 square meters of gross building space. Because of the high initial construction cost, we were asked to give a another round of “look” before they build it. So we had a site visit, took measurments, traced all the piping, and made adetailed piping scketch. Then A hydraulic simulation model using commercial simulation software was constructed and verified with previous hydraulic data provided by another engineer. The model was modified to evaluate and analyze different plans including the original expansion plan and to recommend the best one.

Six different loop expansion scenarios were chosen in a way that one tie-in location is further upstream than another. The facility owner specified that the proposed preliminary design should be able to have positive building primary differential pressure for all buildings. The simulation results indicated that some of the buildings had negative building differential pressures for the first three scenarios, where the tie-in points of the loop expansion was located at the nearby area of the new buildings. After examining the calculation results, we found that it was because the pipe sizes of the existing ChW loop located immediately before the tie-in points were not large enough. Therefore, these expansion plans were not feasible and the loop should be expanded farther upstream.

The other three scenarios, which connect the new buildings to the ChW loop farther upstream, were all acceptable. Among these three designs, the original expansion plan was the most expensive one, because it had the longest piping length and requires digging up the parking lot to build. Further more detailed simulation was conducted to investigate where to place the pipes and fittings and where to connect them with the existing loop. Eventually we recommended a different piping arrangment. While still satisfiying pressure requiemrnts, this design required fewer steel pipes and avoided digging up parking lots by expanding the ChW loop through existing underground tunnels and building crawl spaces. Therefore it had much lower construction cost and minimal impact on university daily operation. This university expanded their chilled water loop in 2003 exactly as recommended. The actual construction cost was $1.8 million less than the original expansion plan.

CONSLUSIONS

This paper briefly introduced a comprehensive yet practical hydaulic modeling proecedure for large DESs planning purposes. Case studies are also provided to demonstrate how a hydraulic model can serve as a powerful analysis tool for assisting decision makings. With a effective hydraulic simulation model, engineer can virtually explore all possible scenarios and determine optimum preliminary designs. On the other hand, the hydraulic simulation model can be used to optimize the operation and controls of large DESs. Same technique is encouraged for other enginnerings because it is cost effective.

REFERENCES

ASHRAE. 2000. Handbook of Systems and Equipment. ASHRAE, Atlanta.

Chen, Q., Xu, C., Deng, S., Claridge, D.E., and Turner, W.D. 2002. Chilled Water System Hydraulic Study - The University of Texas at San Antonio. Energy System Lab Technical Report (ESL-TR-02/01-01).

DOE. 2002. Continuous Commissioning^{SM} Guide Book, Washington D.C.: U.S. Department of Energy.

IDEA 2002. Cooling, heating, and power in the nation's college & universities – census, survey, and lessons learned. Report. International district energy association, Westborough, MA.

Walski, T.M. 1984. Analysis of Water Distribution Systems.

Walski, T.M., Chase, D.V., and Savic, D.A. 2001. Water Distribution Modeling, 1st ed. Waterbury, CT.

Xu, C., Chen, Q., Claridge, D. E., Turner, W. D., and Deng, S. 2006. "Hydraulic Modeling of Large District Cooling Systems for master Planning Purposes," 15th Symposium on improving Building Systems in Hot and Humid Climates, Orlando, Florida.