Commissioning *on campus*

The smallest details can be root causes of large issues on commissioning cases. The author presents four case studies that analyze commissioning issues on campus chilled or condensed water systems.

BY DAVID SELLERS, PE, *Senior Engineer, Facility Dynamics Engineering, Portland, Ore.*

When practitioners in the buildings industry think of campuses—college universities, resorts, industrial complexes, etc., they envision large, expansive systems that perform exotic HVAC processes to support cutting edge research and systems that provide a comfortable working environment for the leading thinkers of the day, all served by central plants with big pipes, big conduits, and big machinery. And, while that picture generally is correct, the trick to making these systems perform ideally and achieve their best efficiency often lies in the smallest of details. Below, several mini case studies analyze small details that were root causes behind commissioning issues on campus chilled or condenser water systems. While the stories are framed in the context of several different large campus systems, most of the lessons learned apply across the entire spectrum of the building stock. After all, physics is physics.

Cooling tower piping symmetry

Central plants with water cooled chillers are common in campus facilities and the words "water cooled" typically are synonymous with a cooling tower. On the surface, cooling towers appear to be fairly simple machines exploiting evaporation. However, there are some fairly complex phenomenon occurring in cooling towers[1]. Consider the following example from a project at the University of California, Berkeley. The towers on this project are part of the central plant serving the Doe library, which houses rare collections, including the Tebtunis Papyri and Mark Twain's papers. Cooling and the related dehumidification processes are critical for the long-term care of these artifacts—so the central plant is the focus of scrutiny in the commissioning process to ensure that the design intent is realized.

During a construction observation visit before much piping was in place, the commissioning team noticed clues that indicated the field configuration for the piping might end up being different from the design configuration. Specifically, the drawings showed a symmetric piping arrangement (see Figure 1), but it appeared as though the mechanical contractor was about to install a non-symmetric piping arrangement.

The symmetric piping arrangement depicted on the design documents would be preferable because it ensures uniform flow distribution through both tower cells under all operating modes. This in turn:

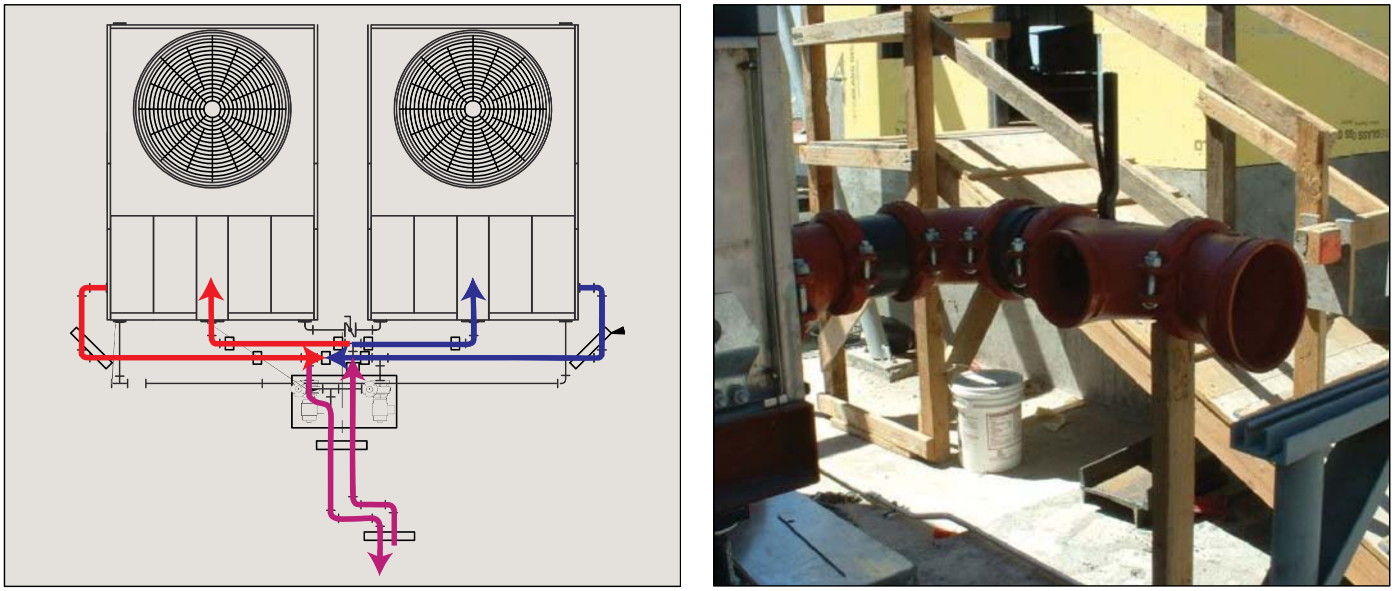

Figure 1: The cooling tower as depicted on the contract documents cooling tower piping (left) contrasted with the installed cooling tower piping (right) and also showed that the installation might not match the design intent. Note the symmetrical arrangement proposed by the design versus the non-symmetrical arrangement implied by the tee in the installed piping.

Source: Based on design plans prepared by Taylor Engineering. Photo: David Sellers

- Ensures uniform flow distribution to each tower cell. If flow is distributed uniformly to each cell, then the cells will perform predictably.
- Minimizes the potential for problems with level control. Maintaining tower basin levels can be deceptively difficult—discover why later in this article.

The critical detail is the configuration of the tee in the installed piping that splits the flow between the cooling towers. The loss through the tee and the branches it serves will be related to the flow through them. In the limit, if there is no flow through a branch, then there is no loss. If the tee is applied so the water comes in the branch and exits through the run in both directions—or comes into the run from both directions and exits via the branch—then the loss through either branch will be the same and can be more than six times the loss of one of the other configurations (see Figure 2).

In this particular situation, the higher loss is actually an advantage because it is equally difficult for the water to split in either direction—the flow will equalize between the two branches if the same difference in pressure is applied across them. It is important to recognize that in this situation, the constraints of physics will dictate that the pressure difference across both branches of the tee will the same. On one end, both branches are exposed to atmospheric pressure while at the other end, they are connected to the same pipe by virtue of the tee.

What will happen if the tee is applied where it is easier for water to flow in one direction and the pressure difference to drive flow is the same in either direction? The flow in the constrained direction will drop off, as will the associated loss due to flow. At the same time, the flow in the less constrained direction will increase until everything balances with the pressure drop, due to flow in the less constrained

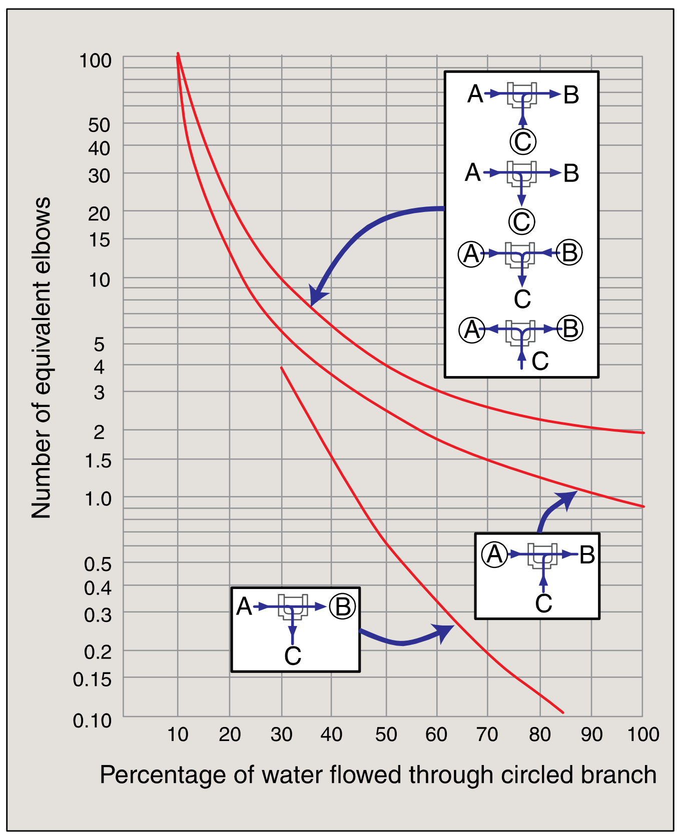

Figure 2: ASHRAE tee pressure drops in various configurations. Note that there is a factor of 6.7 difference between the highest loss and lowest loss configuration with a 50/50 flow split.

Source: ASHRAE Handbook of Fundamentals, 2001, Figure 4, page 35.7


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Location	Return (water back from chiller)		Supply (water to chiller)	
Critical issue	Water distribution to tower cells		Basin level control	
Pressure drop for each branch if flow was equal (ft/water column)	Run of tee	Branch of tee	Run of tee	Branch of tee
Design flow—246 gpm per branch	0.11	0.20	0.22	0.41
Limiting condition (max flow for line size) — 825 gpm per branch	1.15	2.18	2.43	4.57
Potential difference in flow for each branch	37	144	37	144
Potential difference in level, inches (feet converted to inches)			2.21	Design
			25.61	limiting condition

Table 1: Losses through the piping network on the library project with the project's design flow and at the limiting flow rate for the line size[2]. *Source: David Sellers*

branch, which is equal to the pressure drop due to flow in the constrained direction. Two questions remain:

- How much of a difference in flow will it take for things to come into balance?
- Will this difference in flow result in operational or performance issues with the tower?

For the cooling tower under discussion, the answer to the "how much of a difference in flow" question is related to the line size and the flow in the line. Specifically, if the flow rate in the line is at the low end of its application range, the losses will be lower and the issues created by the non-symmetrical arrangement will be minimal. On the other hand, if the flow is at the upper limit of the application range for the line, the problems can be significant.

The answer to the possibility of "operational or performance issues" question concerns location. If the non-symmetrical piping is on the return line—the water coming back from the chillers to the tower—then it will impact the uniformity of flow distribution to the hot basins in the cooling tower cells. This in turn will directly impact tower performance and indirectly impact the level in the cold basin. In contrast, if the non-symmetric piping is on the supply line—the water leaving the towers to go to the chillers—then it will impact the level in the basins.

The flow/loss relationship is not linear—rather the losses generally vary with the square of the flow. In other words, doubling the flow in a piping network with unequal pressure drops through the various branches, which are causing a 1-in. difference in cooling tower cold-water-basin level at the original flow rate, has the potential to create a 4-in. difference in level, all other things being equal. If the piping branches serving the tower basins were identical from a pressure drop standpoint, then there would be no difference in flow through them and thus no potential for generating a level difference.

On the return side, the non-symmetry is likely a non-issue for the library project (see Table 1). This is good because, as often is the case with new construction, the speed of the field staff exceeded the speed of the paper chain that transmitted my observations to the designer.

Figure 3: The piping for the Doe library project.
Source: David Sellers

By the time my concerns reached the design team, the non-symmetric piping arrangement (see Figure 3) had been installed. Thus, we decided to take a "wait and see" attitude. In accordance with a maxim often stated of Jay Santos, PE, as part of his training courses, our field engineers verified that "nature doesn't lie" during the early phases of the commissioning project when their functional testing showed that the flow distribution in the hot water basins was not significantly impacted by the piping arrangement under any operating conditions.

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On the supply side, my calculations indicated that the numbers had the potential to be a bit more significant: The seemingly minor difference in pressure drop of 0.19-ft water column between the piping associated with the two cooling tower cells translates to a potential level difference of 2.25-in. water column in a cooling tower basin where the difference between the operating level and beginning to overflow is 3 in. We will take a closer look at this in the next section.

Cooling tower level control

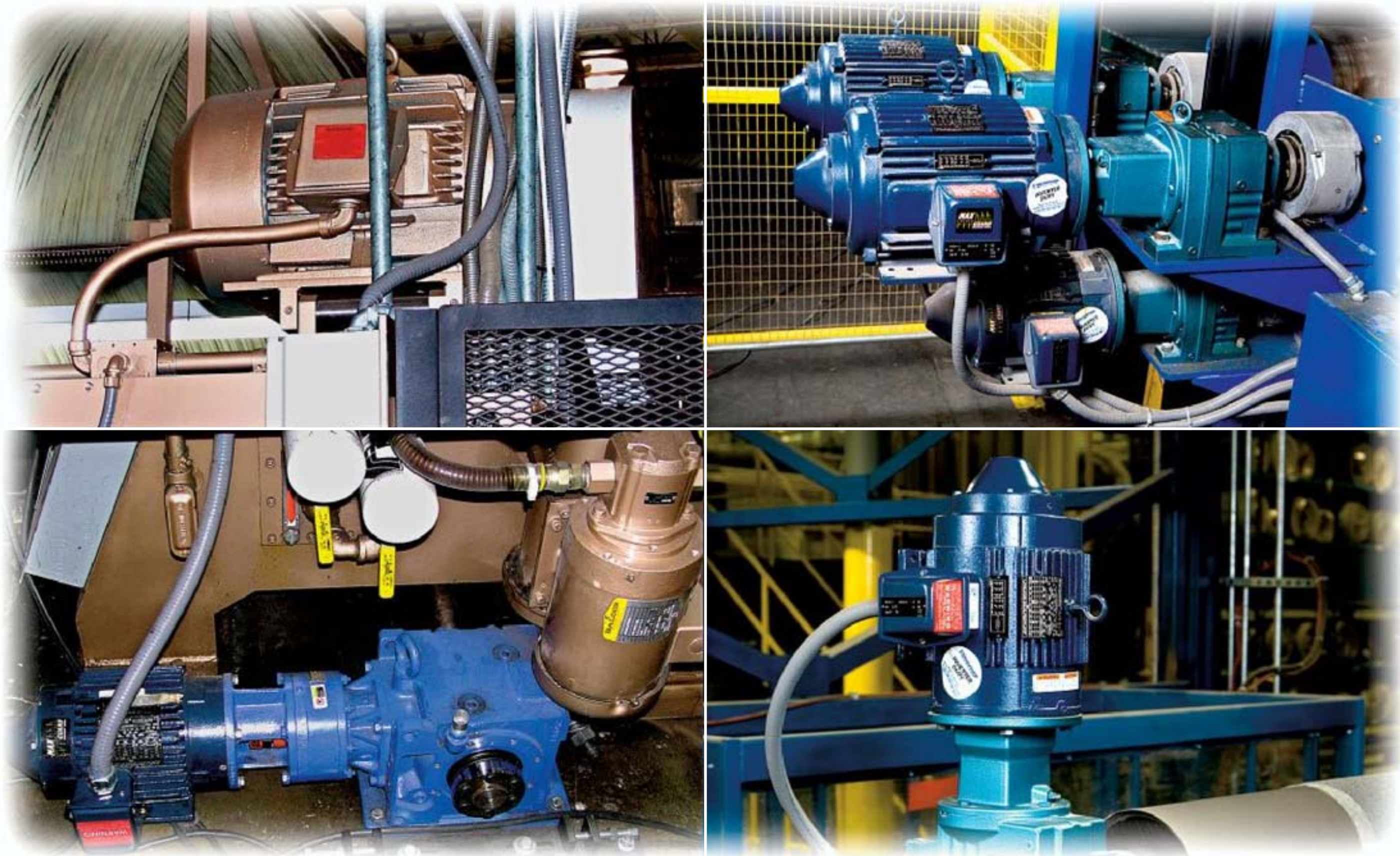
Level control issues due to imbalanced supply piping configurations in multiple cell cooling towers are not news to the design community. Multiple cell cooling towers frequently are equipped with equalizer lines that interconnect the basins. These lines provide a path between basins so the water that piles up in the basin with the longer piping run can simply move to the other basin and equalize the levels. But, because the equalizer is a real pipe with real water flowing through it, there will be a pressure drop due to the flow that occurs through it and, as a result, there still is the potential for a level difference between basins. The cooling towers on the Doe library were provided with a 6-in. equalizer line. During my calculations, I discovered that the equalizer as furnished and installed should be able to accommodate any potential level differences that might be generated by the piping differences on the supply side. I did the math because when the towers were started up, there were level control problems. Specifically:

- The makeup valve in one cell tended to be open—making up water—while the other cell was losing water through its overflow connection.
- On start-up, the pumps pulled the tower level down to the point where both makeup valves opened. But, when the pumps shut down, the basins overflowed.

These operating issues translated to unnecessary water and water treatment chemical consumption. Because the provided equalizer was smaller than what was contractually specified for the tower blame was pointed at it and the contractor who supplied the tower.

Having eliminated the equalizer line as the potential culprit, the commissioning team was still faced resolving the level control problem. It turns out that there are a lot of issues that could come into play and impact the operating level in the tower basins.

1. The obvious place to start is with the adjustment of makeup valves. For the Doe library towers, the difference between the



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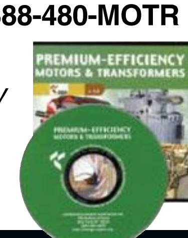

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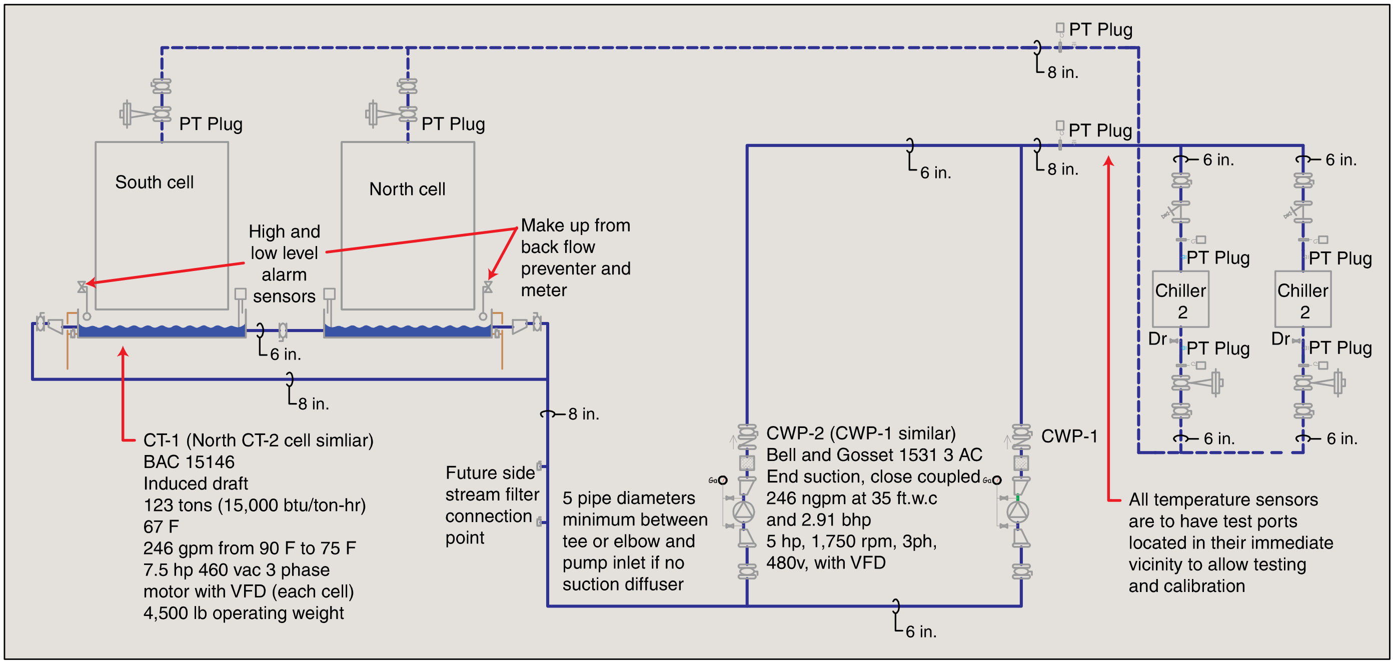

Figure 4: The system diagram for the library cooling towers

Source: David Sellers

manufacturers' recommended operating level and the bottom of the overflow connection was 3 in. Given that a float valve is a proportional control, there will need to be a change in level from the set point to fully open the valve. For the valves on the library project, the water level needed to change by more than an inch (32% of the difference between the desired level and an overflow condition) to completely open the makeup valve.

If the tower makeup valves were not adjusted properly and coordinated with each other, the overflow connection, the high and low alarm settings, and the operation of the pumps, including the impact of a pump starting (and associated draw down of the basin to fill drained piping) and stopping (and the associated drainage of piping that is filled when a pump starts).

2. If a check valve was not holding on one of the parallel pumps serving the towers (see Figure 4), then that could cause a basin overflow problem because discharge water from the operating pump would tend to recirculate through the inactive pump and pressurize the line leaving the cold basin. In addition, when the pumps both shut down, water that would normally be trapped in the piping above the basin level would drain back into the basin through the leaking check valve, causing it to overflow.

3. If there were obstructions in the piping to the hot distribution basins, then that could set up the problem the team was observing. This would tend to be more pronounced at the flow rate associated with two chillers. The obstruction could have several forms:

• Isolation valves that were not fully open even though they were commanded to be fully open.

• A valve disc on an isolation or service valve that had came loose from the shaft so it appeared open based on shaft position, but wasn't

• Debris hung up on the valve discs in the manual valve or the control valve serving a basin.

Even though the piping had been flushed at one point, it probably is worth checking one last time. Strange and unexpected obstructions to flow can be found in the piping on new construction projects including cans, welding gloves, chunks of wood, and deceased animals.

4. If the hot basin screens were obstructed, flow balance problems would arise, leading to basin level control problems.

5. In theory, the hot basin distribution nozzles should be clean if the hot basin screens are clean. But, if construction debris or manufacturing debris moved into the hot basin at some point, the nozzles could be obstructed even though the strainers were clean, causing problems with water distribution and basin level control.

6. Flow may not equally distributed to the hot basins. This is hard to assess, but it can be done by comparing the water levels in the basins. If the towers are identical and the nozzles are clean and free of obstructions, then the water level in the distribution basins should run at about the same depth on all cells if they are receiving the same amount of water. If one cell is deeper than the others, it's receiving more water. Solve this problem by throttling flow to the basis with more flow. But getting it right at one flow condition does not ensure it will be right under other conditions if the towers are not piped symmetrically.

7. If the pumps are not balanced yet and have more capacity than necessary, they could be running out their curves and moving more water than required, causing level control problems and making the issues set up by the non-symmetrical piping worse then they would be under design flow rates.

8. Another issue is if there is something blocking the cold basin screens or obstructing the lines leaving the cold basins. The potential obstructions are similar to those discussed for the hot basin.

9. If the equalization line was plugged or the valve disc on the service valve was not open even though the handle/operator indicated it was, that certainly could be an issue.

When the commissioning team dug into the problem at the library, they discovered that there where two root causes. One was that the

pumps were moving more water than required because the head required by the installed system was significantly below what was anticipated by the designer. The other was that the adjustment of the level control valves needed to be fine tuned. After these issues were addressed the level control problems disappeared and the team moved on to their next challenge.

Chiller tube bundle pressure drop

It is good practice to provide a pressure gauge or gauges on the condenser and evaporator tube bundles of the chillers, and this is quite common on the chillers installed on most campus systems, such as during a commissioning project at South East Missouri State University. Because flow and pressure drop through the tube bundles are related to each other and cataloged by the manufacturer, the information provided by the gauges often is used by the chiller's factory start-up technician and the test and balance team to set up and/or verify flow. The gauges also allow the operating team to monitor the tube bundle pressure drop and compare it to the original setup. A change may indicate an emerging problem in the form of a change in flow through the evaporator or fouling of the tubes or both.

Contract documents frequently indicate the requirement for pressure gauges or some means of measuring tube bundle pressure drop via a schematic detail (see Figure 5). On the plus side the detail clearly shows that a means of measuring pressure is required on each side of the tube bundle. Negatively, the detail is subject to interpretation in the field because the piping connection to the mains frequently requires elbows and other components not indicated on the schematic (see Figure 6).

Most field personnel have seen chillers with gauges installed at all of the locations illustrated in Figure 6—although they are seldom installed at all of these locations on the same project. Most manufacturers catalog the pressure drop for their tube bundles based on gauges installed in the piping immediately ahead of the water box— illustrated in location C1 and C2 in Figure 6. Thus, if the shop drawing for the chiller indicated that at design flow, the evaporator pressure drop should be 17 ft water column, the start-up technician would adjust the system until the reading at C1 and C2 matched the requirements. This is the base case documented in Table 2, associated with Figure 6.

Notice how measuring the pressure difference with one or more elbows between the gauge and the location used by the manufacturer to catalog the chillers performance can result in overestimating the system flow rate, even though the loss through the elbow would be considered relatively minor and would be difficult to actually measure using the gauges provided in the field.

Also note that gauges installed directly on the vent and drain connections on the waterbox (points D1 and D2 on Figure 6) will indicate a different pressure from the gauges on the piping only inches away. This is because there are losses associated with the change in velocity when the water exits the pipe into the water box and then re-enters the pipe from the water box. I learned this the hard way on a project at the Anheuser-Busch campus where we had installed gauges directly on the waterbox because taps had not been provided in the piping and were frantically trying to figure out why we were short of flow.

When in desperation, I called an older gentleman I knew who had been a representative of the chiller manufacturer for years, he

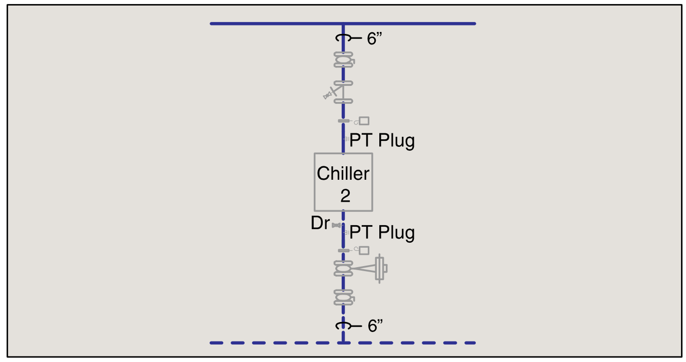

Figure 5: A typical schematic drawing showing pressure measurement provisions in the form of PT plugs.

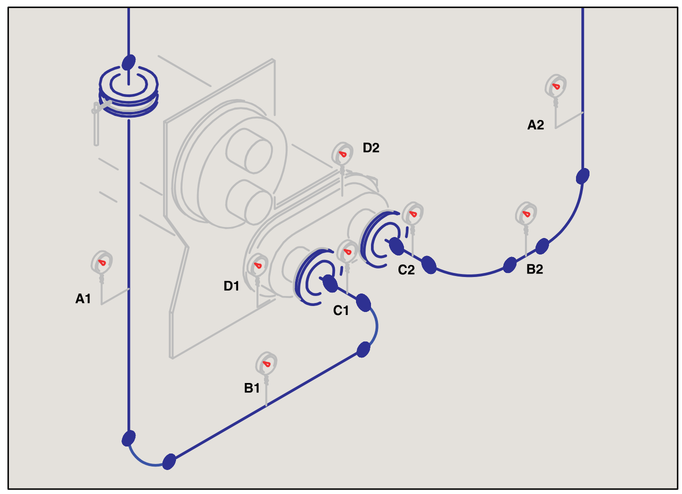

Figure 6: Pressure readings and associated flow rates based on the pressure readings taken at different points in an evaporator piping circuit.

Flow based on differential pressure			
Location	Pressure difference (ft/water column)	Flow based on pressure difference	
		gpm	%
D1-D2	14.48	1,363	85%
C1-C2	17.00	1,600	100%
B1-B2	18.26	1,718	107%
A1-A2	19.78	1,862	16%

Table 2: Note that the manufacturer's performance is based on the pressure reading taken at C1 and C2. A the flow condition under consideration, the pressure drop through the elbows serving the chiller is about 0.52 ft water column or 0.23 psi.

Source: David Sellers

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Input #**221** at csemag.com/quickResponse asked “Where are you measuring pressure?” When I told him, he explained the exit and entry losses and suggested that moving the gauges or using a pump test to set the flow might provide a better result. When we crosschecked the flow via a pump test of the dedicated evaporator pump, we discovered that its results indicated that the flow was at design. Doing the math on the loss from the pipe into and out of the water box at design flow and then adding those losses to the reading on our gauges verified the result; i.e., the measured pressure drop based on the waterbox gauges plus the entry and exit losses resulted in a number that was in the same ballpark as the manufacturer’s specified pressure drop at design and cross-checked with the pump test.

Leveraging details for ongoing improvements

Appreciating and understanding the implications of the piping details in campus chilled water systems during construction and start-up is only the beginning. Paying attention to details and learning from the experience can lead to ongoing improvements in the operation and efficiency of your chiller plant, as illustrated by the results of ongoing commissioning efforts at the San Diego Marriott Hotel and Marina (see Figure 7).

The bottom line is that even in the largest of systems, the smallest of details can matter. And the reality is that because the physical principles behind the details apply irrespective of system size, the lessons learned by the big boys on their campus systems can have merit on any system were fluid flows through a conduit, including yours.

Additional reading

1. Cooling Tower Fundamentals, http://spxcooling.com/pdf/Cooling-Tower-Fundamentals.pdf.

2. David Seller’s blog, “A field guide for engineers,” www.csemag.com

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Sellers is a member of CSE’s editorial advisory board. His background includes more than 30 years of experience with commissioning, design engineering, facilities engineering, mechanical and control system contracting, and project engineering in a wide array of facilities. Sellers also provides technical training and develops technical guidelines on retrocommissioning and commissioning field techniques and engineering fundamentals in a number of venues. This article was developed in collaboration with the Building Commissioning Assoc.

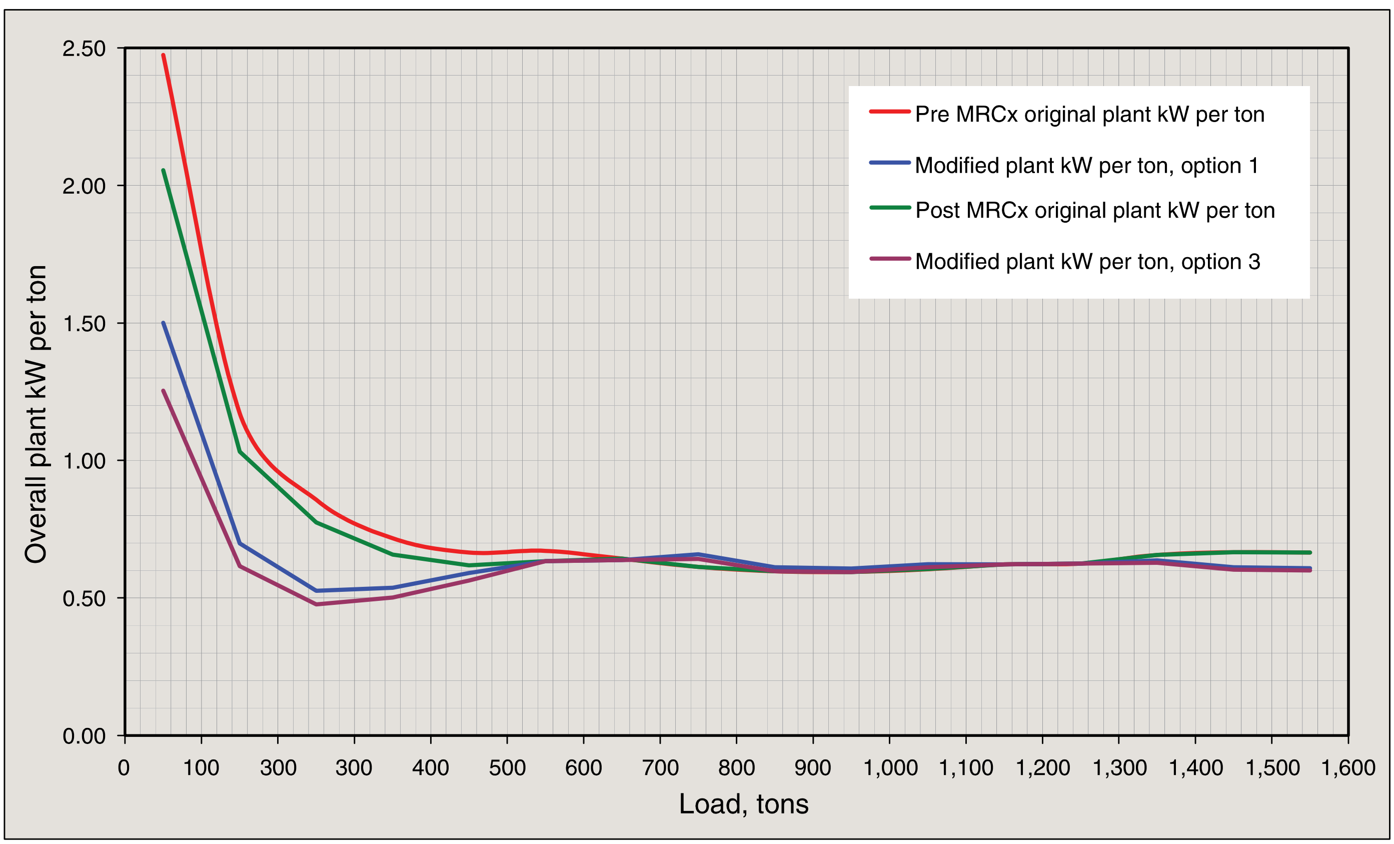

Figure 7: This graph illustrates the kW per ton profile (excluding tower fans) for the central chilled water plant serving the San Diego Marriott Hotel and Marina building complex. The red line illustrates where the plant started and the purple line is where the plant will be when completed. The operating team got from one point to the other by paying attention to the details. Source: David Sellers