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Would you Just Answer my Question!?

By: Walter Bright, PE, PEM

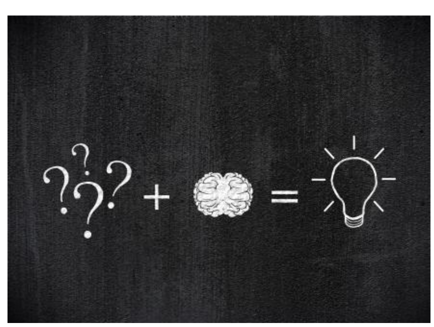
As I begin to write my first "technical" article for IEP, it made me think about other things I have written and read in the past. While I've read many an article, only a select few are ones I have saved and go to again and again to brush-up and relearn. I hope that you will find the articles within our newsletters, past, present, and future to be ones you will save and go back to as well.

While the authors of my go-to articles are not personal friends, I imagine they possess the same qualities of my best technical mentors. While each of them is unique in their expertise, delivery, and other traits, I think they all shared (at a minimum) one quality: they didn't answer my questions.

Maybe take a second and read that again. This may be counter-intuitive initially. Do we not read articles to learn? Do we not ask our mentors for guidance/explanation when we are lost? Definitely. However, in my case my best mentors did not answer my questions. They instead bolstered my understanding at a fundamental level, which ultimately allowed me to answer my own questions. In addition, it also "answered" the question for tomorrow, the day after, and the multiple other questions because I had a better set of basics. …maybe my mentors were only trying to keep me out of their office so much… Unlikely, but either way it worked.

As I write articles, or do any of our PEM classes for that matter, I like to enforce the fundamentals as a result of my own experiences with my mentors. It results in, admittedly, sometimes a "drug out" discussion for a relatively simple point. The intent is not to "bore you with the details" or "get in the weeds," but rather to help develop your own fundamental knowledge.

So, in the future, when you read an article in our IEP newsletter, know that if we are "beating a dead horse" (I think I've used all the clichés now), we are headed somewhere. While it might take a little longer than you'd like, maybe we will keep you from asking another question (joking of course! We love questions). More importantly, I hope it strengthens your fundamental knowledge to help you in answering those complex energy calculations and recommendations.



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Hydronic Systems, an Energy Perspective, Part 1

By: Walter Bright, PE, PEM

In our previous newsletter, we presented a case study on the Belimo Energy Valve. While the savings are compelling, sometimes why "Low Delta-T" develops and how you fix it, are difficult to understand. To fully explain low delta T, we need to go back to the basics first. In Part 1 of our series, we look at how a hydronic system is created, designed, and balanced. In future newsletters, we will look at how this can cause problems resulting in low delta T and ultimately how to correct it. In each part of our Hydronic Systems article series, we will draw some conclusions that might be problems you have at your facility now, and how to address them.

Let's create a simple and traditional chilled water (CHW) system for a school that we can do some analysis on. The CHW system below is for a school and is composed of three air handling units (AHUs) with CHW coils. Coil 1 is for the gymnasium (basketball court), coil 2 is for classroom wing and coil 3 is for the library. Figure 1 is a simple schematic of our system. This is a basic schematic of a primary/secondary CHW system, but is applicable to many hydronic systems, including heating hot water. As such, we will simplify and only show the secondary side of this sample system, or the "load-side" of the system. This system does not include a bypass or three-way valve which may be required in certain systems, but this will help simplify our schematic for analysis.

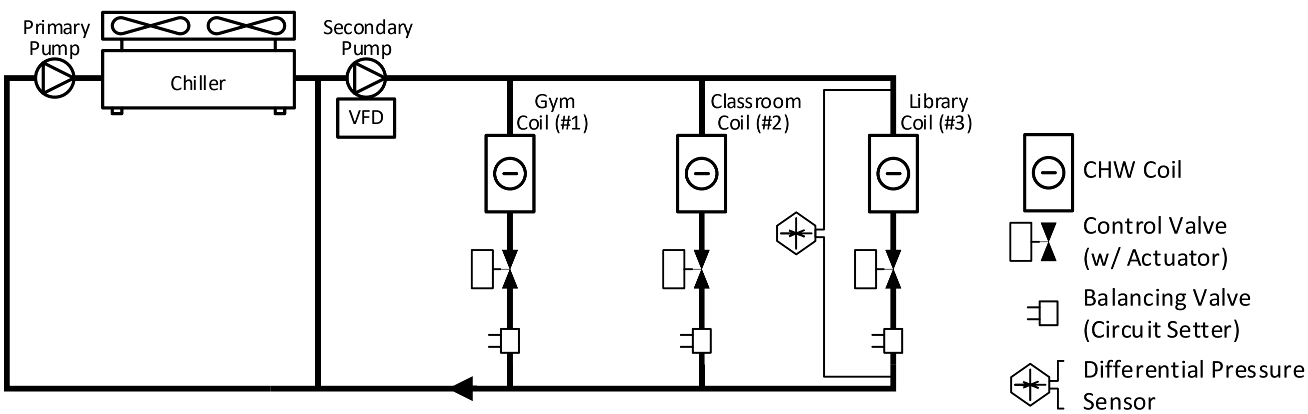

Figure 1 – Sample CHW System

In a typical system like this, each coil would be equipped with a control valve on the return side, which will modulate in some form or fashion as the load the coil needs to deliver changes. For example, as the outside air temperature drops and the load on the building decreases, the control valve would close to deliver less gpm through the coil. Each coil would also be equipped with a balance valve to help "balance" the system. In Figure 1, we have chosen to use circuit setters, which is the most basic type of balance valve. Later, we will look at other means of balancing as well. Circuit setters are simply valves (pressure-dependent flow control device) which can be opened and closed to a specific position and fastened at that point. Using the markings on the valve, the measured pressure drop across it, and the corresponding chart, one can determine what the flow through the circuit setter is. More importantly, the flow through the circuit setter would also be the flow through the CHW coil.

In our system above, the coil, control valve and balance valve piped together would be known as the "branch." The piping which leaves the pump and provides CHW to each coil (and returns the CHW back to the pump) would be known as the "mains." The schematic has been drawn such that the mains are the horizontal pipes (supply main on top and return main on bottom) and the branches are the vertical pipes. The branch would start and end at the "tee" off and back into the main.

Circuit Setter, courtesy of B&G

During design of our school, the engineer will run a load calculation on our building to determine how much CHW we need for each AHU. For simplicity, let's pretend that all 3 coils need 100 gpm, shown in orange on Figure 2. (Note that I am using imperial units, but the math and discussion works for metric units as well, if you ignore the units shown). To deliver that 300 gpm, we need a pump that can create sufficient pressure to "push" the water through each coil. The longer the pipe, the more elbows, and the smaller the pipe will all result in the pump needing more pressure to deliver 100 gpm to each coil. With the system drawn out on paper, using the length and size of pipe, the engineer can determine the pressure drop across each piece of pipe. The engineer can also determine the pressure drop across each component of the system, such as a CHW coil. Those pressure drops are shown in Figure 2 in red and are simply some typical numbers you might see in a real system; in other words, they are made up and have not been calculated. Note that pressure drop shown for the control valve and the circuit setter for coil 3 would be in the fully open position.

The engineer's next step will be to select a pump that is appropriate for our system. The pump needs to be selected for gpm, which is the sum of each CHW coil, for a total of 300 gpm. It also needs to be selected for pressure. To determine this, the engineer will add up the pressure drop across each path and component. They start at the pump, go around each path, and end back at the pump. The path with the most pressure drop will be the selection for the pump.

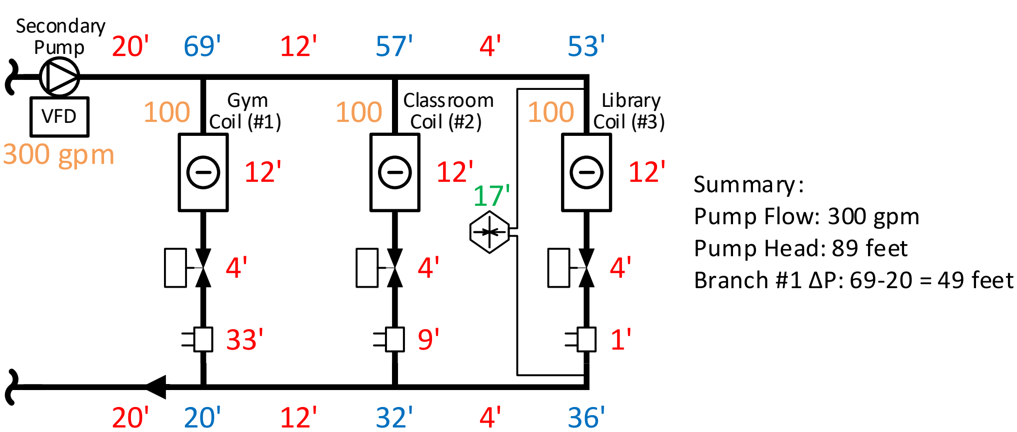

Figure 2 – Balanced CHW System (at Full Load)

In a simple system like this, one can quickly realize that the farthest coil will have the highest pressure drop. In more complex systems, note that this is not always intuitively obvious. By adding up each number in red, we can determine that the pump will need to be selected to deliver 89 feet of pressure, or more commonly referred to as “head” in the engineering world. For those of you not familiar with the term feet, it is synonymous with PSI and abbreviated with a single quotation mark. For those of you who have selected pumps, you know that you’d select one with more than 89 feet as a safety factor but let’s ignore that for now for keeping the math simple later. With the pressure leaving the pump known (89 feet), we can determine the relative pressure at each unique point in the system. As an example, leaving the pump at 89 feet, we arrive at the first pipe run with a pressure drop of 20 feet. Therefore, at the takeoff from the CHW main for coil 1, it would be 89-20=69 feet. This math can be continued around the critical path and each point is shown in blue in Figure 2.

With the pump selected, the system would be installed. While our imaginary contractors are building our imaginary system, let’s take a break and discuss the relationship between pressure and flow. For a fixed geometry (aka a piece of pipe, a CHW coil, a circuit setter or a control valve not moving), they are related by the following formula:

$$\left(\frac{Q_2}{Q_1}\right)^2 = \left(\frac{H_2}{H_1}\right)$$

Where Q equals the flow in gpm and H equals the pressure drop in feet. Note these formulas work for other units as well. This formula is one from a set of formulas known as the affinity laws. As a sidebar, these formulas are extremely powerful and can quickly help determine the relationship between pump speed, flow, pressure, and horsepower. However, there are assumptions built into these formulas (one of which is the fixed geometry requirement as stated above). The affinity laws are often misused, albeit mostly by accident, to justify energy savings for pumps. This will be a subject for a future article.

With the system built, the next step is the test and balance (TAB) process. Without balancing, you can see how the pressure drop across each branch (vertical pipes and components) is different. Branch 1 is 69-20=49 feet while branch 3 is 53-36=17 feet. If the circuit setters are not adjusted, coil 1 would have more flow than coil 2, and coil 2 would have more flow than coil 3. This is because water takes the path of least resistance, and we must make it go where we want it to go. To do that, we close the circuit setters on coil 1 and 2 until we force more water to coil 3, with the goal of trying to achieve 100 gpm through each coil. In the real world this is a trial and error process. However, in our system, we can calculate how much pressure drop we need across each circuit setter to get the correct flow. For example, branch 1 has a pressure drop of 49 feet (previously calculated above). The coil and control valve pressure drop at 100 gpm is specified to be 12 and 4 feet, respectively. Therefore, to get the correct flow, the circuit setter pressure drop must be 49-12-4=33 feet. Note that even with the circuit setter on branch 3 set at 100% open, there will still be a minor amount of pressure drop across it, estimated here to be 1 foot.

In a modern hydronic system, a variable frequency drive (VFD) will be installed on the secondary pump, which will modulate to maintain a fixed differential pressure (DP) in the system. Most commonly, this DP sensor is chosen to be placed on the critical branch. The theory is as the valves on the coils begin to open, the VFD will speed up to match the increasing demand in the system, and vice versa. This setpoint is determined at the end of the TAB process by measuring the DP across the critical branch, which in our example is 17 feet (12+4+1=17 feet). This is shown in green in Figure 2.

So, in our example, it works like this. When coil #3 has a decrease in demand and begins to close from 100%, the pressure drop across the control valve will increase incrementally, let's say from 4 to 6 feet. This means that the pressure sensor would now read 19 feet (12+6+1=19 feet). This would signal to the building automation system (BAS) to slow down the pump in an effort to get back to 17 feet. In the real world, the pressure changes very slowly and the BAS can respond extremely fast, so you never see the pressure change much from 17 feet, but in essence this is what is happening. The more the control valve closes the higher the pressure drop climbs, until the control valve is completely closed, and no flow goes through the coil (infinite pressure drop means no flow).

Figure 3 shows our system if the three control valves close to get 50 gpm (50% load) across each coil.

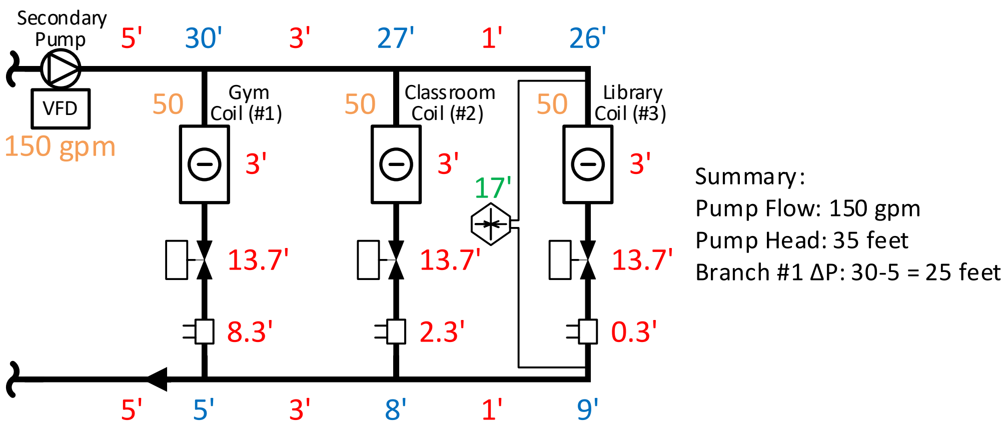

Figure 3 – Balanced CHW System (at 50% Load)

Notice what has happened to the values in red and blue – they have dropped as well. This is because of the formula presented earlier. Recall that at full load (Figure 2), the piece of pipe between the pump and the first branch was a pressure drop of 20 feet. This was with a flow of 300 gpm. Now that the flow has dropped to 150 gpm (3 coils at 50 gpm), we can calculate the pressure drop for the reduced flow as follows:

$$\left(\frac{150\ gpm}{300\ gpm}\right)^2 = \left(\frac{H_2}{20\ feet}\right), H_2 = 5\ feet$$

So, for a 50% reduction in flow, the pressure drop falls 75%. We can do this for all the pressure drops in red from Figure 2…except the control valve. Remember the control valve is closing, which means that its geometry is changing. As such, the formula above is not valid. The good news is we can still calculate its pressure drop. Remember that our DP setpoint is 17 feet. That will be the same no matter what. So, if our CHW coil pressure drop fell from 12 to 3 feet, and our circuit setter pressure drop fell from 1 to 0.25 (rounded up to 0.3) feet, then our control valve pressure drop must be 17-3-0.3=13.7 feet. Also, since we know the branch pressure drop, we can do the same for branch 1 and 2. Interestingly the control valve pressure drop is the same for all three branches (do the math and prove that to yourself).

At 50% load, the gpm has dropped, but so has the pump head: from 89 to 35 feet. How does that impact energy consumption? To keep it simple for now, just know that pump energy consumption is a function of gpm and head. If we decrease either we save energy. Since we have done that comparing full load to 50% load, we have reduced the energy consumption of the pump.

Let's add another level of complexity. In the real world, not all our coils are going to have the same demand. They are going to vary depending on envelope load, internal loads, etc. Let's talk about a situation where there is a hot, daytime Saturday basketball game. School would be out of session, so the classrooms and library would be at part-load since no one was in them. The gym would be at full load since it has full occupancy and it's a hot day. The resulting system is presented in Figure 4.

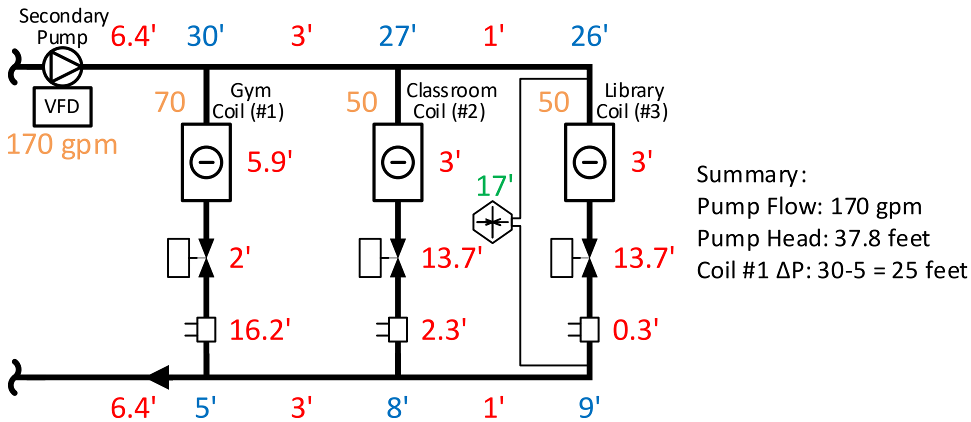

Figure 4 – Balance CHW System (Saturday Basketball Game)

Let's assume that the load on the classroom and library coil is 50%. Our DP setpoint is still 17 feet. Look back at Figure 2 and Figure 3, and in the summary section look at the branch 1 pressure drops. You'll see that at 100% load, the branch pressure drop is 49 feet whereas at 50% load its 25 feet. If the gym needs 100 gpm, which it probably does at the load condition we have described, there is no way we can get 100 gpm in this operation. We simply do not have a high enough pressure drop across branch 1 to "push" 100 gpm of water through it. Since the math gets a little funny here, I won't try and type it out, but you will only be able to do 70 gpm through coil #1, even if the control valve is 100% open. This will result in a hot gym because we are underflowing the CHW coil.

We have two options: the first is to go and open the circuit setter on branch #1. If we do that obviously our system is out of balance now, so maybe that is not desirable. The second is to "bump up" the DP setpoint until we get 100 gpm through coil #1. That is easy since its probably something that the facilities staff can do via the BAS, potentially even remotely, so no one must drive back to the school. However – do you think that the DP setpoint ever gets reduced again? I'd argue probably not. So, when Monday morning rolls around and the classrooms and library have all the load, and the gym doesn't, we are making the pump work harder because of the increased DP setpoint. We have not changed the flow come Monday morning, because the load is a function of the envelope load, number of students, etc. That control valve will open until it gets the gpm it needs. However, the pump is going to work harder on head because of that increased differential setpoint. Remember, energy is a function of flow and head, and therefore energy consumption will be higher.

You might ask, why don't we put the DP somewhere else? It is possible that you have even seen a DP sensor at the CHW plant right on the discharge of the pump. This is not uncommon. The critical branch is a long way away and means a lot of wire between the VFD and the pump to get there. Sometimes one is put at the pump discharge because the sensor is not wired to the VFD but is instead wired to the AHU controller and pressure values are passed over the BAS network back to the VFD. This can cause issues if the network is slow or fails, so one is put at the pump because of the issues. The sequence is the same: determine the needed setpoint and let the pump modulate. The problem is the pump will modulate much less! Let me prove it to you.

Let's go back to Figure 2 and move the DP from the critical branch (branch 3) and put it right at the discharge of the pump. Using the same logic as described to figure out the original setpoint of 17 feet, we can determine the setpoint at the discharge of the pump to be 89 feet.

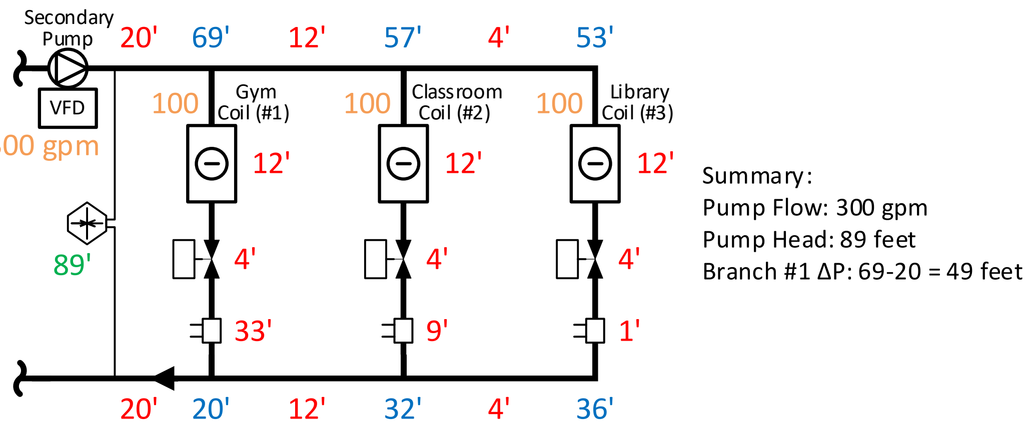

Figure 5 – Balanced CHW System, Relocated DP Sensor (at 100% Load)

So, when our system drops to 50% load, what happens? The pump is going to maintain 89 feet still, but the flow will decrease. The resulting system is shown in Figure 6.

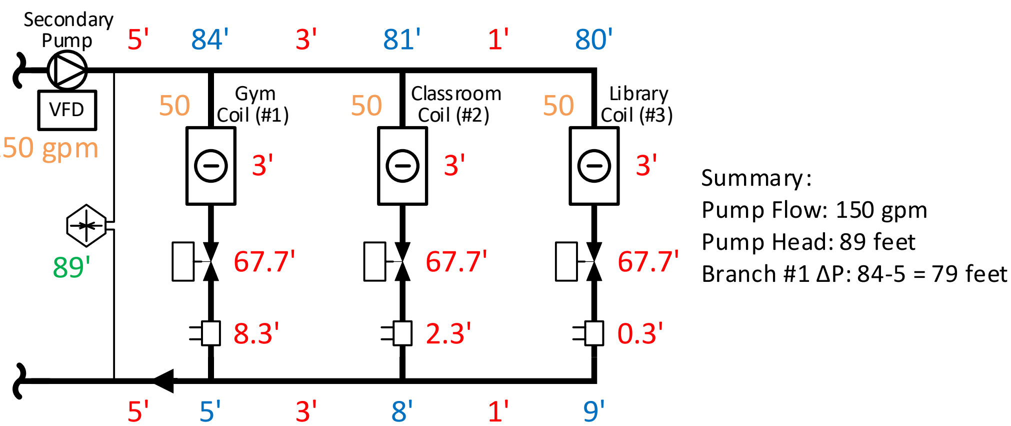

Figure 6 – Balanced CHW System, Relocated DP Sensor (at 50% Load)

As you can see, our control valves have had to absorb a huge amount of the pressure drop due to the excess pressure the pump is creating. If you are thinking, "well you need to just decrease your DP setpoint," you would be correct…but only for this operating point. When you needed 100 gpm through branch 3, any DP setpoint less than 89 would result in less than 100 gpm of flow. You do still save energy in this case, since the flow has decreased, but it is nowhere near the amount of energy as in Figure 3. Note: you can also damage a pump operating it at constant head variable flow, depending on the pump curve, and this large pressure drop across a control valve is noisy.

The last point: the system above is pretty egregious and perhaps obvious to many of you that that was a bad idea. However, this might happen more than you think. Often engineers will not know the critical path. The critical path is easy at 100% flow to all coils, but that is not how the system operates. The flow is constantly changing and potentially altering the critical path. We saw this on our Saturday basketball game – the gym coil became the critical path and we underflowed as a result. As such, they will make some logical assumptions and maybe put multiple DP sensors, which control to the “worst case.” That ensures we have adequate flow 100% of the time and we never underflow for a Saturday basketball game. Sounds good in theory, right? This is shown in Figure 7.

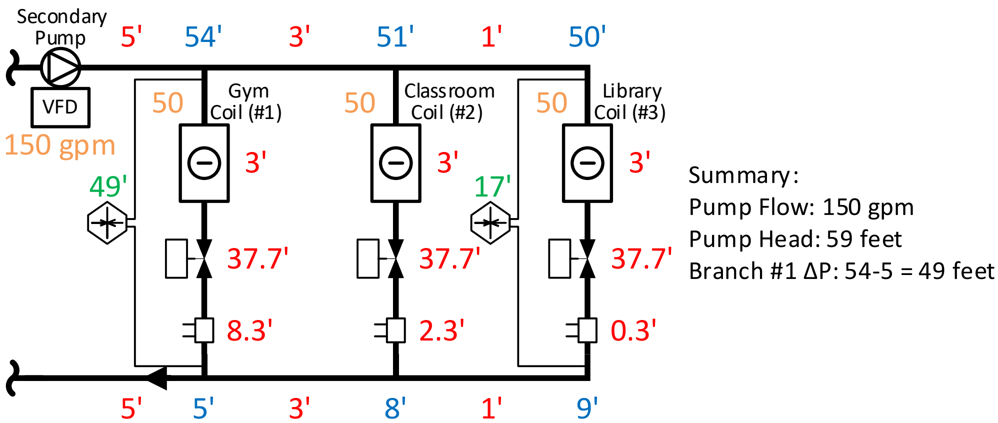

Figure 7 – Balanced CHW System, Dual DP Sensors (at 50% Load)

The setpoint for coil 1 has already been calculated, during our discussion about underflow for Figure 3 & 4, where we said we needed a branch 1 pressure drop of 49 feet to get a flow of 100 gpm. Our other DP sensor setpoint is still 17 feet. The BAS will control to maintain the “worst” DP sensor. In other words, the sensor will always be at or above setpoint. In Figure 7, not surprisingly, branch #1 is the worst and the pump speeds up to maintain 49 feet. The branch 3 setpoint is exceeded and is actually 41 feet. So, while yes, we have ensured no coil will underflow, we have cut our energy savings by a relatively decent margin from Figure 3 to Figure 7 due to the increased pump head.

If you have been “yes, but…” as you went through this, that is great! There are a lot of things I ignored here: automatic flow control valves instead of circuit setters, DP setpoint reset based on valve position, sensor-less pumping… The list goes on; we will get to those in future newsletters. For now, the takeaways are: 1) ensure your DP setpoint is across your critical branch, is working properly, and not using a “fallback” mode where it defaults to a pressure sensor at the plant. 2) Ensure the DP setpoint is appropriate for the system as determined in Figure 2. If someone has increased the DP setpoint since the original TAB, why was it done and can it be reduced? 3) If you do not know the original TAB setpoint, hold off on getting your system “re-TAB’d.” There might be better things you could do to make use of your money. 4) Check and make sure you do not have conflicting DP sensors which negate your potential energy savings.