Chapter 9

Hydronic System Architecture

Contents of Chapter 9

Instructions

Read the material of Chapter 9. Re-read the parts of the chapter that are emphasized in the summary and memorize important definitions.

Objectives of Chapter 9

Chapter 9 introduces you to the various hydronic distribution systems and some of their characteristics. Because this chapter is in a fundamentals course, we will not be developing detailed design information. For detailed information about water systems, you can take the ASHRAE Course, *Fundamentals of Water Systems*.[1]

When you have completed this chapter, you should be familiar with:

Steam systems: The general operation and some of the advantages and disadvantages of steam distribution systems.

Hot water heating systems: The main piping-layout options, pumping requirements and characteristics

Chilled water systems: The popular piping arrangements and characteristics

Open water systems: The behavior of a condenser, condenser requirements, and cooling tower operation

9.1 Introduction

In previous chapters, we have considered a variety of systems that need a source of heat or cooling to operate. Many of these systems use water or steam for this source. This chapter will introduce you to the basic layout options for heating and cooling piping arrangements that distribute water or steam, **hydronic circuits**. It will also provide a brief discussion of the differences in their hydronic characteristics.

In each case, a flow of steam or water is distributed from either a central boiler or a **chiller**, the refrigeration equipment used to produce chilled water, to the hydronic circuits. The hydronic circuits circulate the steam or water through the building, where it loses or gains heat before returning to be re-heated or re-cooled.

The steam or water is treated with chemicals to inhibit corrosion and bacterial growth in the system.

9.2 Steam Systems

Steam results from boiling water. As the water boils, it takes up latent heat of vaporization and expands to about 1600 times its original volume at atmospheric pressure. Steam is a gas, and in a vessel it quickly expands to fill the space available at a constant pressure throughout the vessel. In this case, the relevant space is the boiler(s) and the pipe that runs from the boiler and around the building. The pipe rapidly fills with steam, and the pressure is virtually the same from end to end under no-flow conditions. As flow increases, there is a pressure drop due to friction against the pipe wall and due to the energy needed to produce flow.

When the steam gives up its latent heat of evaporation in an end-use device, such as a coil, fan coil, or radiator, it condenses back to water, and the water is called "**condensate**." This condensate is removed from the steam system by means of a "**steam trap**." A steam trap is so-named because it traps the steam while allowing the condensate out of the higher-pressure steam system into the lower-pressure condensate return pipe.

Traps are typically thermostatic or float operated (*Figure 9-1*).

Thermostatic Trap: In the thermostatic trap, a bellows is used to hold the trap exit closed when heated by steam. The bellows is filled with a fluid that boils at just below the steam temperature. When the trap fills with air or condensate, the temperature drops and the bellows contract, letting the air or condensate flow out. As soon as the air or condensate is expelled and the trap fills with steam, the heated bellows expands, trapping the steam.

Float and Thermostatic Trap: This versatile trap uses the much higher density of condensate to lift a float to open the trap and release the large quantities of condensate produced under startup and high-load periods. When filling the system, large volumes of air must be vented. The thermostatic element works well for this function. During operation at low loads, the float functions well to drain the slow accumulation of condensate. In most systems, the condensate is gravity-piped to a condensate collection tank, before being intermittently pumped back to the boiler makeup tank. Due to the much smaller volume of condensate, the condensate return piping is smaller in diameter than the steam supply pipe.

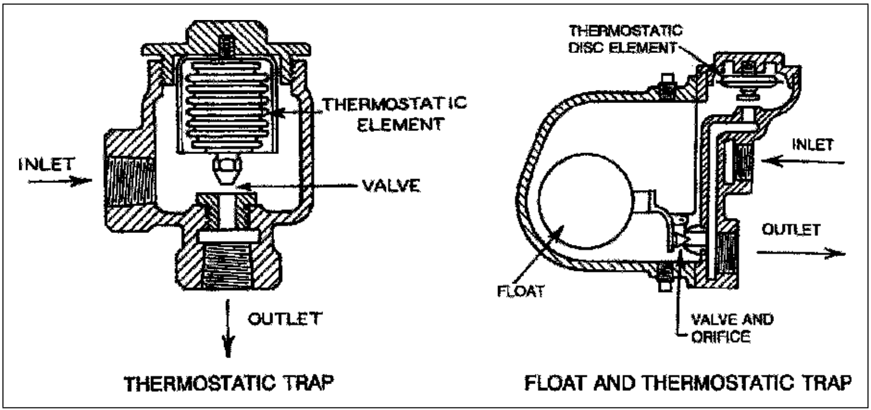

Figure 9-1 Steam Traps

Regardless of which trap is used, the returned condensate and any required makeup treated water are pumped into the boiler to be boiled into steam again. The initial water fill and all water added to the steam boiler must be treated to remove oxygen and harmful chemicals that could cause serious corrosion in the boiler and pipe work. The addition of these chemicals means that the water in the system is **not potable**, not suitable for human consumption. As a result, the steam from the heating distribution system is unsuitable for injecting into the air for humidification. However, the heating steam can be used to indirectly evaporate potable water for humidification, where required.

Because steam has low density and the ability to move itself throughout the system, it is ideal for use in tall buildings. The steam makes its own way to where it is needed and gravity brings the condensate back down again.

Figure 9-2 shows the main components of a small steam system. The condensate is pumped into the boiler where it is boiled into steam. The steam expands down the main and into any heater that has an open valve. As the heater gives off heat, the steam condenses. The condensate collects at the bottom of the heater and is drained away by the trap.

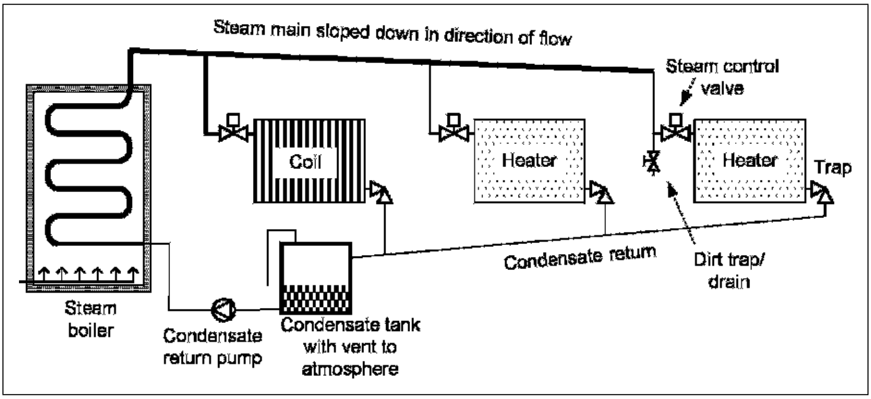

Figure 9-2 Steam System

Steam systems are divided into two categories: low-pressure systems and high-pressure systems. **Low-pressure systems** operate at no more than 100 kilopascals, kPa, meaning no more than 100 kilopascals pressure higher than the local atmospheric pressure. **High-pressure systems** operate above 100 kPa.

Safety issues

In order to maintain the system pressure, the boiler output needs to be continuously balanced with the load. Because steam has the capacity to expand at high velocity in all directions, a poor boiler operation can cause an accident.

The requirements for boiler operations on low-pressure systems are very much less stringent compared to high-pressure systems. Early in the twentieth century, there were numerous boiler explosions. As a result, the American Society of Mechanical Engineers wrote strict codes for the manufacture of steam boilers and associated piping and equipment. Those codes have drastically reduced the number of failures in North America.

The local pressure vessel regulations are relatively rigorously enforced in most countries. The rules and regulations for both manufacture and operation vary substantially in different countries, so having local information is always a high priority when you are designing or operating a steam pressure system.

Steam systems need to be installed carefully, maintaining a downward slope of 1 in 500 to avoid condensate collecting, called **ponding**, in the steam pipe. If condensate ponds in the steam pipe and the steam flow increases significantly, a slug of condensate can be lifted and carried by the steam at very high velocity until it reaches a bend or other obstruction. The slug of water can attain a high momentum and may break the joint or valve. Not only can the pipe be ruptured, but as soon as the pipe is ruptured, the steam is free to escape and can easily burn, or kill, anyone in the area.

The advantages of steam are:

- Very high heat transfer.
- No need for supply pumps.
- Easy to add loads because the system adjusts to balance the loads.

These systems are much less popular than they used to be, but they are still an attractive choice for distribution of large amounts of heat around numerous or high buildings.

9.3 Water Systems

Water systems are more commonly used for heating than are steam systems. The advantages of water over steam include the fact that water is safer and more controllable than steam.

Water is safer because the system pressure is not determined by continuously balancing the boiler output with load, and because water does not have the capacity to expand at high velocity in all directions.

Water is more controllable for heating since the water temperature can easily be changed to modify the heat transfer.

Water system design issues: Pipe construction

Water for heating and cooling is transferred in pipes that are generally made of steel, copper or iron. Steel is normally a less expensive material and is most popular for sizes over 25 mm. Copper is a more expensive material but it is very popular at 25 mm and narrower, due to its ease of installation. Long runs with few fittings favor steel, while the more complex connections to equipment favor the easy installation of copper.

Water system design issues: Pipe distribution

Heating or cooling water can be piped around a building in two ways, either "**direct return**" or "**reverse return**." The direct return is diagrammed in *Figure 9-3*.

The simple circuit in *Figure 9-3* consists of a boiler; four identical heaters A, B, C, D; a pump to drive the water round the circuit; and interconnecting pipes. When the pump is running, water will flow from the boiler to each heater, through the heater, and back to the pump, to be pumped around the circuit again.

There is friction to the water flowing through the pipes and the water favors the path of least resistance. The circuit: **boiler → pump → heater D → boiler**, is much shorter than the circuit: **boiler → pump → heater A → boiler**. As a result more water will flow through heater D than through heater A.

In order to have the same flow through all the heaters, extra resistance has to be added to heaters B, C, and D. Adding balancing valves, as shown in *Figure 9-4*, makes this possible.

After the system has been installed, a balancing contractor will adjust the balancing valves to create an equal flow through heaters A and B, then an equal flow through heaters A and C and finally an equal flow through heaters A and D. This simple, step-by-step, procedure will produce the highest balanced set of flows for the four heaters.

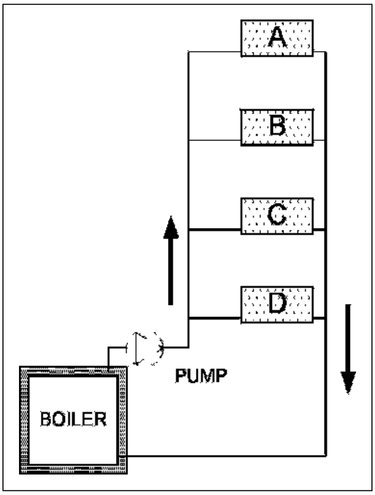

Figure 9-3 Direct Return Piping

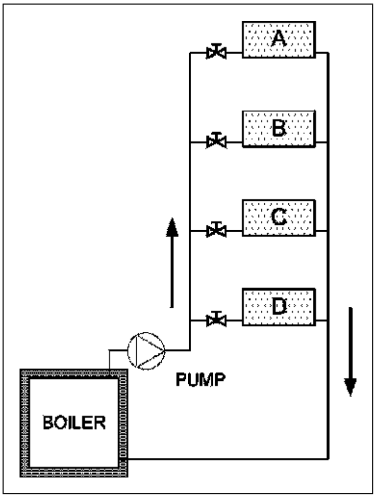

Figure 9-4 Direct Return Piping with Balancing Valves

The total flow may be more or less than design, but the flows will be equal. If the flow is more than required, it is possible, but difficult, to go back and rebalance to a specific lower flow.

In practice, a single balancing valve in the main loop, often between the pump and boiler, can be used to reduce the total flow. As the total flow is reduced, the flow in each heater will reduce in the same proportion. This circuit works well, once it has been balanced. On most systems, a valve is installed on each side of heaters so that the heater can be valved off and repaired without having to shut down and drain the whole system.

Let us now imagine that one of the heaters failed and in the process of removing it, the balancing valve is closed. When the heater has been replaced, the question is "How much should the balancing valve be opened?" Did anyone take note of the valve position before it was moved? If not, the balancing valve will likely be left fully open. The system may work satisfactorily with the balance valve open, or, it may not. This problem of being dependent on balancing valves can largely be overcome by using a different piping arrangement, the *reverse return* as shown in *Figure 9-5*. Here the pipe length for the flow loop **boiler** → **pump** → **heater** → **boiler** is the same for all heaters. Verify this for yourself by tracing the water path through heater D and then the path through heater A. As a result, the flow will be the same in each heater; the piping is self-balancing.

The reverse-return piping costs more due to the additional return length of pipe. There are cases where the flow is critical, for example, direct expansion refrigeration heat pumps. In this case, the additional cost of reverse return piping is worthwhile. The maintenance staff only needs to fully open the valves to a unit to know it has full flow.

In circuits where exact balance is not critical, a system with direct return and balancing valves is a good choice.

Having considered the two main piping arrangements let us now go on to the flow of water and pumps.

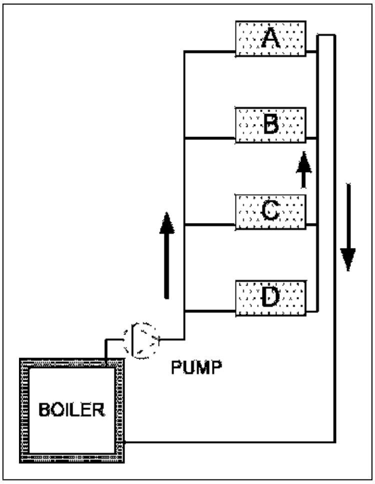

Figure 9-5 Reverse Return Piping

Water system design issues: Flow

The resistance to water flow in pipes, called the **head**, is dependent on several factors including surface roughness, turbulence, and pipe size. When we design a system, we calculate the expected resistance for the design flow in each part of the circuit. The sum of the resistances gives the total resistance, or **system head**.

Under normal flow rates, the resistance rises by a factor of 1.85 to 1.9 as the flow rises ($\text{flow}^{1.85}$ to $\text{flow}^{1.9}$). Doubling the flow increases the resistance about three and a half times.

The actual **head loss** in pipes is normally read from tables, to avoid repetitive complex calculations. Based on this table data and the knowledge that the head is proportional to $\text{flow}^{1.85}$ we can plot the **system curve** of flow or capacity, versus head.

Pump manufacturers test their pumps to establish what flows the pump generates at a range of heads. At a particular pump speed, measured in revolutions per minute, **rpm**, they will measure the head with no flow, and again at increasing flows, or capacities. They can then plot the pump head against flow or capacity to produce a **pump curve**. A pump curve and calculated system curve are shown in *Figure 9-6*.

The pump curve in this figure shows a peak head of 45 meters with no flow that gradually drops to about 33 meters at 7.4 liters per second, L/s, where it crosses the calculated system curve. If the design calculations were correct, the **operating point** for this pump will be at the intersection of the two curves.

In practice, the system curve often turns out to be higher or lower than the calculated design. The effects of this, and remedies for it, are covered in the ASHRAE course, *Fundamentals of Water System Design*.

The layout of piping in a building is very dependent on load locations and where pipe access is available. *Figure 8-8*, in the last chapter, showed a single riser in the building with a reverse return loop around every floor. This works well for heat pumps mounted in the ceiling, with the pipes running in the ceiling.

Conversely, it often does **not** work very well for equipment, such as radiators, fan coils, and induction units, mounted near the floor at the perimeter

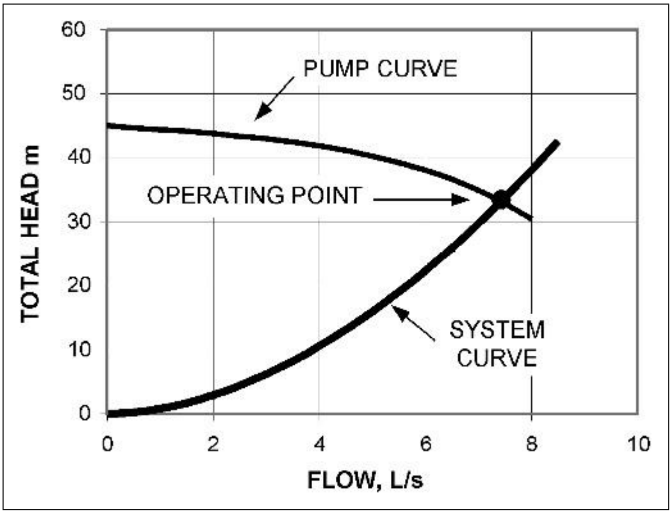

Figure 9-6 System and Pump Curves

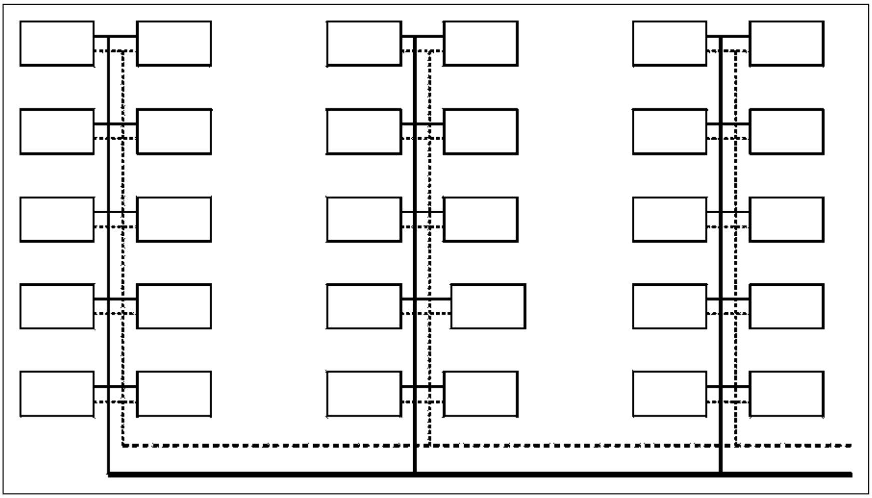

Figure 9-7 Multiple Risers

of the building. For these, multiple risers around the building may be a better solution, as shown in *Figure 9-7*.

Having introduced piping layouts and pumps let us go on to consider the three main types of water circuits and some of their characteristics.

9.4 Hot Water Systems

Within buildings, hot water is the fluid that is most commonly used for heat-distribution. The amount of heat that is transferred is proportional to the temperature difference between supply and return. Maximizing the supply-return temperature difference minimizes the water quantity and pipe size requirements. Unfortunately, the economy of smaller water quantities with a high temperature difference creates a need for larger, and more costly, heaters and heat exchangers. The design challenge is thus to find the best balance between cost to install and cost to operate.

For general use, in buildings where the public may touch the pipes, the normal operating supply temperature is 82 °C. In the past, return temperatures were 70 °C, but temperatures of 65 °C, or even 60 °C, are now often used for overall operating economy. Systems can also be designed to operate with an 82 °C flow, except under peak load conditions. Peak load conditions hardly ever occur, but if they do, then the flow temperature can be raised as high as 95 °C.

These systems can operate at very low pressure, since the only requirement is that the pipes remain full. For working temperatures above 95 °C, at sea level, systems must be pressurized to avoid the possibility of the water boiling.

As discussed in the previous chapter, radiant floors operate with a maximum surface temperature of 29 °C. They need heating water at 50 °C or less, much cooler than 82 °C. This can be achieved by mixing cool return water with the 82 °C water to provide a supply to the floor at 50 °C or less. Alternatively, and with greater fuel efficiency, they can be supplied from a condensing boiler or ground source heat pump, both of which have a maximum flow temperature of about 50 °C.

For distribution between buildings, higher temperatures—up to 230 °C—can be used. The high temperature hot water is passed through a heat exchanger in each building to provide the, typically, 82 °C water for distribution around the building and for heating domestic hot water.

Pipes should be insulated to avoid **wasteful** heat loss. Thus, pipes in the boiler room should be insulated, but pipes in a zone that is feeding a radiator may not need to be insulated, since the heat loss just adds to the radiator output. However, if a pipe presents an exposed surface that could cause a burn, insulation should be used.

Insulation thickness should take into account the temperature difference between the water and surroundings. Thus, thicker insulation should be used on pipes that run outside a building than inside the building.

Energy Efficiency in Hot Water Systems

There are many ways to control and increase energy efficiency in the hot water systems. The control method that we will discuss is the **outdoor reset**, a common control strategy that takes advantage of the temperature differential between the cold outside and the warm inside the building to adjust the heat output. Then we will consider pumps and the energy savings that we can obtain through reducing the flow in hot water systems.

The heat loss from a building in cold weather is proportional to the difference between the temperature inside the building and the temperature outside the building. Similarly, the heat output from a convection heater is roughly proportional to the difference between the space temperature and the heating-supply-water temperature. Outdoor reset makes combined use of these two relationships by adjusting the heating-water temperature with changes in outdoor temperature. With the correct schedule, the water flow remains constant and the heat output just balances the building heat loss.

This outdoor reset system has advantages, but it does mean that the heating water flow is 100% all through the heating season. This continuous full flow involves a significant pumping cost.

In the last section we noted that the head is proportional to the flow$^{1.85}$. The pumping power is proportional to the head, times the flow. So, doubling the flow requires

$$2(2^{1.85}) = 7.2 \text{ times the power!}$$

Here is an incentive to reduce flow. If, instead of modulating the water temperature, it remained constant at, say 82 °C, and the flow was varied by thermostatic valves, the required flow would be much less than 100% most of the time. In fact, since most heating systems are oversized, the flow would never reach 100%. However, as soon as the flow varies, we need a method of varying the pump capacity.

In the following sections, we will consider two methods of varying pump capacity:

1. Varying pump speed
2. Using pumps in parallel

Varying Pump Speed. Variable speed drives are now readily available and can be used to adjust pump speed according to load. The pump curve remains the same shape, but shrinks as the speed reduces. Typical pump curves for various speeds are shown in *Figure 9-8*.

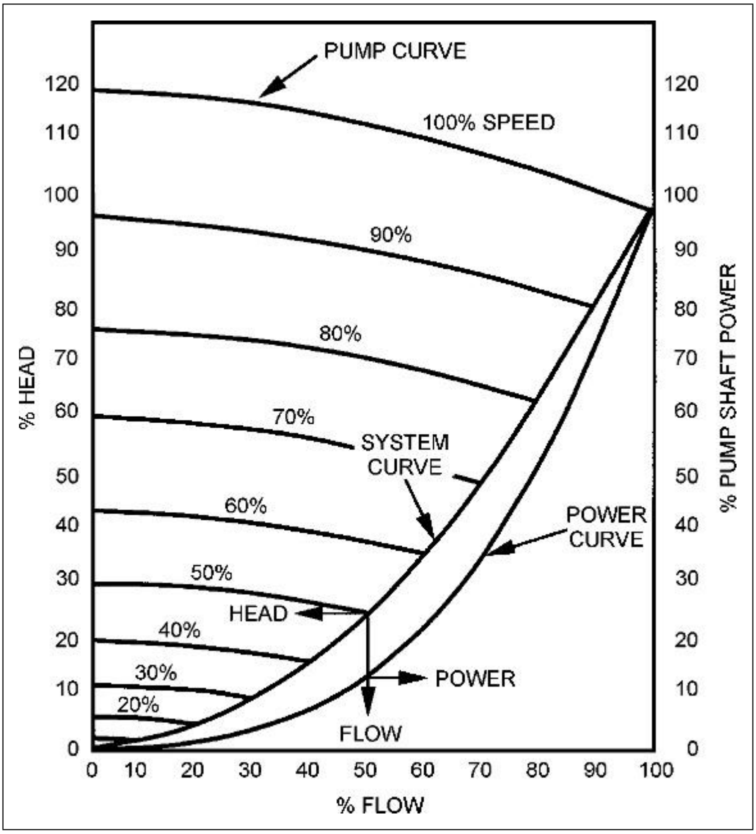

Figure 9-8 Variable Speed Pump Curves

The arrows in the figure indicate that the head is about 25% at 50% speed and 50% flow, while the power consumption is about 10% at 50% flow.

The figure also shows the **pump shaft power**, which is the power used by the pump, without consideration of any bearing or motor inefficiencies. Since motor efficiency generally drops significantly at low speeds, the overall reduction in power is much less than the figure indicates at low flows.

Pumps In Parallel. Another way to reduce flow is to use two identical pumps in parallel. Each pump experiences the same head, and their flows add to equal the system flow. A check valve is included with each pump, so that when only one pump is running, the water cannot flow backward through the pump that is "off." The piping arrangement is shown in *Figure 9-9*.

With both pumps running, the design flow is at the system operating point. When one pump is shut off, the flow and head drop to the single pump curve as shown in *Figure 9-10*. This flow is between 70% and 80% of full flow, depending on pump design. **Note** that the power required by the single pump is slightly higher when running on its own and the motor must be sized for this duty.

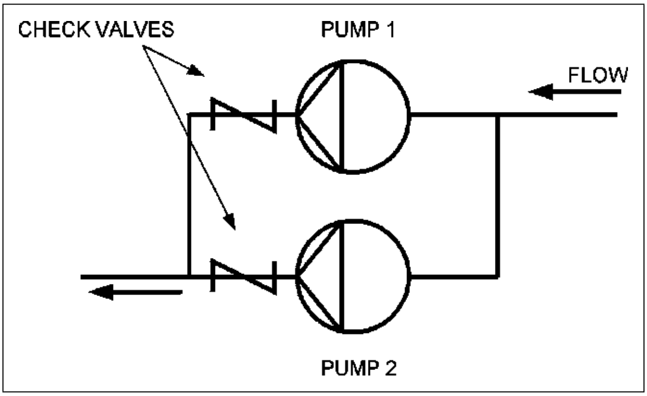

Figure 9-9 Pumps in Parallel

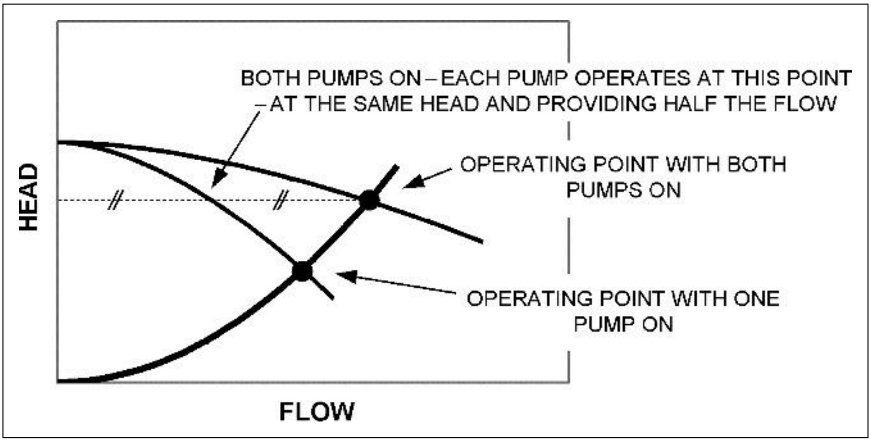

Figure 9-10 Operating Conditions for Parallel Operation

The use of parallel pumps for a heating system has two advantages: First, it produces a substantial reduction in energy use for all the hours the system is using only one pump; second, it provides automatic stand-by to at least 70% duty when one of the pumps fails.

9.5 Chilled Water Systems

Chilled water typically has a supply temperature of between 5.5 °C and 9 °C. Historically, the return temperature was often chosen to be 5 °C above the flow temperature. With the higher cost of fuel and the concern over energy usage, it is usually cost effective to design for a higher difference of 8 °C or even 11 °C. The higher return temperatures require larger coils, and create challenges when high dehumidification is required.

On the other hand, doubling the temperature difference halves the volume flow, and, consequently, reduces the purchase cost of piping and pumps, as well as substantially reducing ongoing pumping power costs.

With a flow temperature in the range 5.5 °C to 9 °C, the piping must be insulated to reduce heat gain and avoid condensation. The insulation requires a moisture barrier on the outside to prevent condensation on the pipe.

Chillers, the refrigeration equipment used to produce chilled water, mostly use a direct expansion evaporator. Therefore, the flow must be maintained fairly constant to prevent the possibility of freezing the water. The chiller requires constant flow but it would be both convenient and economical to have variable flow to the loads. To achieve this, the chiller and loads can be hydraulically "**decoupled**." Decoupled, in this context, means that the flows in the chiller circuit do not influence flows in the load circuit. Conversely, changes in the flows in the load circuit do not affect the chiller circuit.

A diagram of two chillers and loads is shown in *Figure 9-11*. The two chillers are piped in parallel in their own independent pipe loop, shown bold in the Figure. The chiller loop can run even if the distribution pumps are off. Similarly, the distribution loop can run with the chiller pumps off. The short

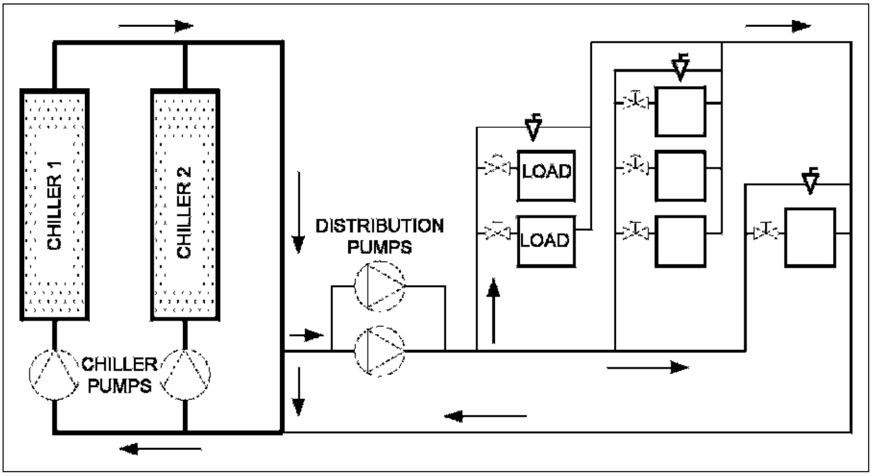

Figure 9-11 Chiller System with Decoupled Flows

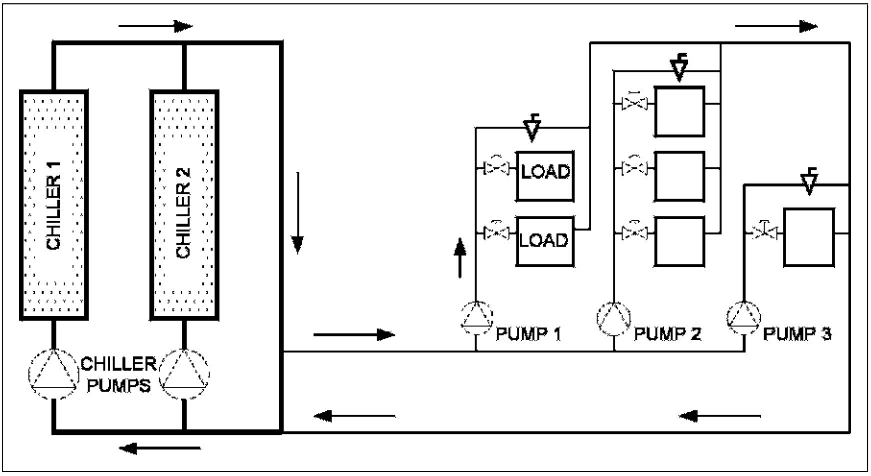

Figure 9-12 Distributed Secondary Pumping

section of shared pipe allows both loops to operate independently of each other, decoupled.

Each chiller has a pump that runs when the chiller runs, producing a chiller-circuit flow of 50% or 100%. The flow in the cooling-loads circuit is dependent on the distribution pumps and whether the valves are fully open or throttling (reducing) the flow. If the chiller flow is higher than the coil circuit, water will flow through the short common section of pipe as the excess chiller water flows round and round the chiller loop. If the chiller flow is less than the coil circuit flow, than some coil return water will flow through the short common section of pipe and mix with the chilled water. When this happens, a flow or temperature sensor will detect it and start another chiller.

The loads in *Figures 9-11* and 9-12 are shown as having two way valves which have no flow when they are closed. If all the valves were to close, the pump would be pumping against a closed circuit. To avoid problems occurring when this happens, a bypass valve is shown across the end of each branch circuit to allow a minimum flow under all conditions.

The arrangement in *Figure 9-11*, with distribution pumps serving all loads, requires these pumps to run regardless of the load. On projects where sections of load may be shut down while others are running, a "**distributed**" pumping arrangement may be more efficient. In *Figure 9-12* each secondary loop has its own pump, which is sized to deal with its own loop resistance and the main loop resistance. This system allows pumps 1, 2, and 3 to be run independently, when necessary, to serve their own loads.

The development of economical and sophisticated computer control and affordable variable speed drives, now enables designers to organize piping and pumping systems that really match need to power, compared to the historical situation where the system used full pump power whenever the system was "on."

9.6 Condenser Water

Condenser water is water that flows through the condenser of a chiller to cool the refrigerant. Condenser water from a chiller typically leaves the chiller at

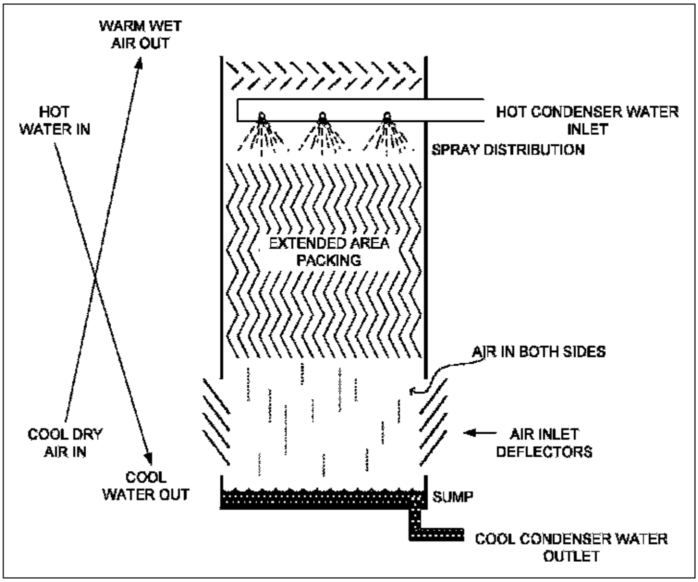

Figure 9-13 Evaporative Cooling Tower

35 °C and returns from the **cooling tower** at 29 °C or cooler. The cooling tower is a device that is used for evaporative cooling of water.

In *Figure 9-13*, the hot water (35 °C) from the chiller condenser flows in at the top. It is then sprayed, or dripped, over fill, before collecting in the tray at the bottom. Air enters the lower part of the tower and rises through the tower, evaporating moisture and being cooled in the process, before exiting at the top.

We will consider cooling towers in more detail in the next chapter, but the tower has a hydraulic characteristic that we will cover here. The water has two open surfaces: the one at the top sprays, and the other at the sump surface. This is an **open-water system**. An open-water system has two or more open water surfaces. A **closed-water system** has only one water surface.

Figure 9-14 shows an outline elevation of the complete cooling tower and chiller condenser water circuit. The water loop has two water surfaces: one at the top water sprays, and one below at the sump water surface. When the pump is "off," the water will drain down to an equal level in the tower sump and in the pipe riser, as indicated by the horizontal dotted line in *Figure 9-14*. When the pump starts, it first has to lift the water up the vertical pipe before it can circulate it. The distance that the pump has to lift the water is called the "**static lift**." Once running, the pump has to provide the power to overcome both the static lift and the head, to overcome friction, to maintain the water flow.

Figure 9-15 shows a closed water circuit. It is shown with one water surface open to the atmosphere. Whether the pump runs or not, the water level stays constant. When the pump starts, it only has to overcome friction to establish and maintain the water flow. When the pump stops, the flow stops, but there is no change in the water level in the tank. The open surface is required to allow for expansion and contraction as the water temperature changes during operation. In larger systems and most North American systems, the

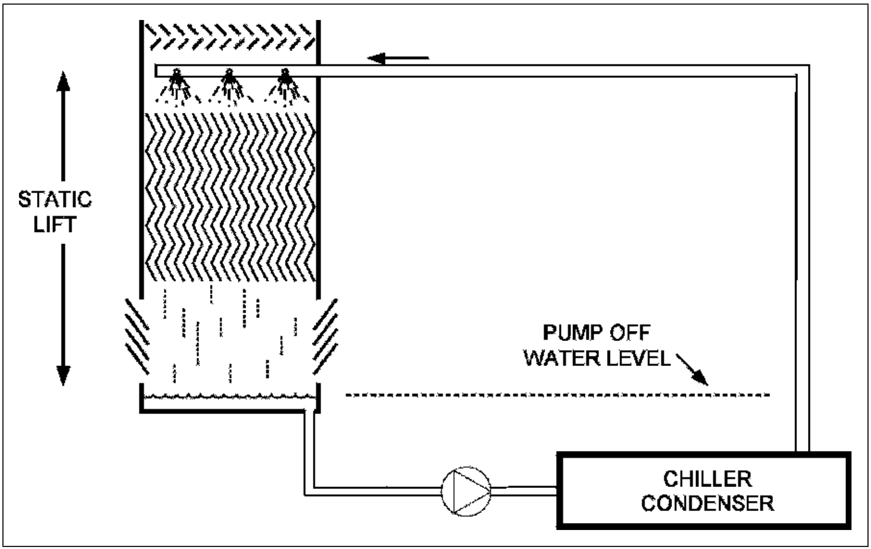

Figure 9-14 Open Water Circuit

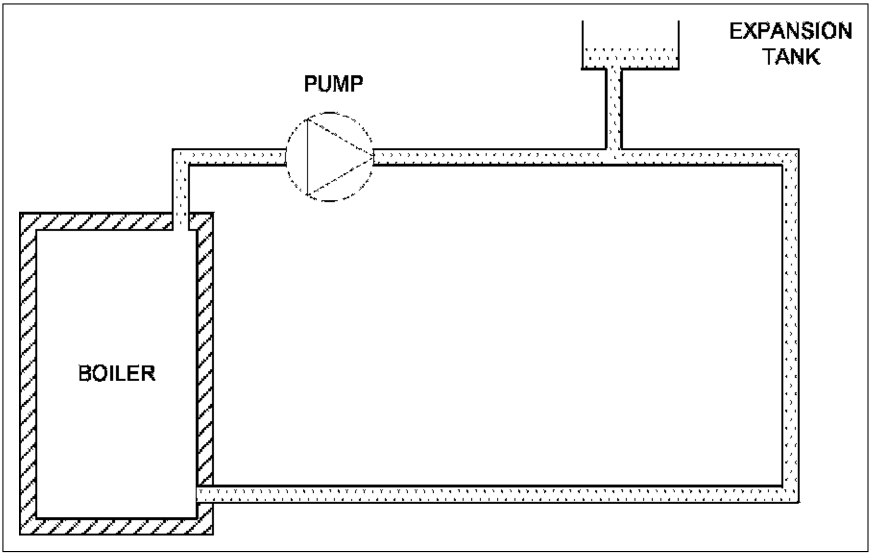

Figure 9-15 Closed Water Circuit

one open water surface is in a closed tank of compressed air rather than open to atmosphere, as is common in other parts of the world.

The cooling tower provides maintenance challenges. It contains warm water and dust, so it easily supports the multiplication of the potentially lethal bacteria, legionella.

We will return to cooling towers, their design, interconnection, and operation when we discus central plants in the next chapter.

The Next Step

This chapter has covered hydronics architecture, specifically the piping systems for steam, hot water, chilled water, and condenser water. In Chapter 10 we are going to consider the central plant boilers, chillers, and cooling towers that produce the sources of steam and water at various temperatures.

Summary

In this chapter, we covered hydronics systems, systems involving the flow of steam or water to transfer heat or cooling from one place to another.

9.2 Steam Systems

Principal ideas of this section include: how steam is used; its behavior as a gas and how it condenses as it gives up its latent heat; how the resultant condensate is drained out of the steam pipes by traps and then returned to the boiler, to be boiled into steam again.

9.3 Water Systems

In this section we described water systems and the economical direct arrangement and the more costly, but largely self-balancing, reverse-return piping arrangement. Once a system has been designed, the design flow and head are known and can be plotted on the same graph as the pump curve, to find the expected operating condition.

9.4 Hot Water Systems

From general water systems, we moved into hot water systems. The use and energy savings of variable speed pumps was introduced. This was followed by a discussion of how two pumps in parallel can be used to provide reduced energy consumption for most of the heating season, as well as substantial, automatically-available, stand-by capacity should a pump fail.

9.5 Chilled Water Systems

Because chilled water systems need constant water flow through the chiller evaporator, the economies of variable flow can be achieved through decoupled and distributed piping arrangements.

9.6 Condenser Water

Cooling towers were described as well as the difference between open and closed water systems. The hot water and chilled water circuits are normally closed systems, but the cooling tower is an open system. The open system has a modified design requirement, since the pump must not only overcome the friction, head, to flow around the circuit, but must also provide lift to raise the water from the balance point to the highest point in the system.

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