CHILLED WATER PLANT PUMPING SCHEMES

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ABSTRACT

From the advent of central chilled water plants, the system for delivering chilled water to the end user has undergone significant changes as chilled water demands have increased, technology has improved, and energy efficiency has become an operational requirement. This paper reviews the history of chilled water pumping schemes and discusses the advantages of a direct-primary, variable flow system particularly on the impact to low ΔT syndrome.

KEYWORDS

Low ΔT Syndrome, Chilled Water Pumping Scheme, Primary-Secondary, Direct-Primary, Variable Flow

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PURPOSE AND OBJECTIVES

Chilled water has been a primary medium for the transfer of heat from building coils to the refrigeration system since the beginning of heating, ventilating, and air-conditioning design. Providing chilled water from a centrally located plant(s) has long been promoted as an energy efficient and low maintenance means of rejecting heat from air-conditioning systems across a localized campus, whether that campus is a university setting, industrial complex, or large urban site. Initially, when energy costs were low, primary-secondary systems provided a stable and simple operation of the chillers and distribution systems. However, as energy costs increased, particularly in the late 1970s, the efficiency of the chillers and the costs associated with operating the distribution system became more important. As a result, the need for new schemes to improve chiller performance and reduce energy costs drove the HVAC industry to advance chilled water technology, particularly in the manner that chilled water is delivered. The pumping schemes for delivering chilled water can be separated into two categories, each with several off-shoots:

1. Direct-Primary (constant volume or variable volume)
2. Primary-Secondary (constant volume primary, variable volume secondary)

While chillers and cooling towers are large contributors to chilled water plant performance, a primary player in determining how well a plant performs is the efficiency of the chilled water distribution system. To understand the hydraulic considerations associated with delivering chilled water and how they influence system performance, it is important to understand how technology and design challenges over the years have influenced today’s approach to chilled water pumping. This paper discusses the history of chilled water distribution systems and the development of a direct-primary system. Problems associated with the chilled water pumping schemes are defined and discussed and finally, this paper compares the advantages and disadvantages of primary-secondary and direct-primary pumping schemes.

DEVELOPMENT OF CHILLED WATER DELIVERY

Since the advent of central chilled water plants, the system for delivering chilled water to the end user has undergone significant changes as demands increase, technology improves, and energy efficiency became an operational requirement. Initially chilled water was delivered through a simple direct-primary, constant flow pumping scheme. This method delivers chilled water to the end user at a constant flow rate that is independent of the actual load. Three-way control valves at building coils are used to allow some of the water to bypass the coil during part load conditions. This varies the plant output to match load by varying the chilled water return temperature from the buildings (see Item 1 below). This method of control results in a significant waste of energy and loss of performance caused from two distinct sources:

1. Bypassed chilled water mixes with return water from the cooling coil yielding lower chilled water return temperature to the plant.[1] This lower return water temperature reduces the temperature differential (ΔT) across the chillers and decreases the overall performance and efficiency of the entire system.[2] This phenomenon is known as low ΔT syndrome and is discussed in greater detail under the section, entitled "Low ΔT Syndrome."
2. In some instances, chilled water flow to coils increases at part load conditions, which "starves" other buildings needing cooling.[3]

To overcome the capacity deficiency inherent with these problems, plant operators turn on additional chillers and pumps to provide the needed capacity.[4] Additional chillers and pumps increase a plant's energy usage. Compounding this problem, chillers operating at part load are inherently less efficient than those at full load. Therefore, not only are additional chillers and pumps used, they are operated at a higher energy rate per ton of cooling (i.e., kW per ton, lbs/hr of steam per ton).[5]

The effects of these phenomenons are put into perspective when you consider the only time chilled water is not bypassed around the coil is during design conditions. Since design conditions occur during 1 percent of the operational hours in a year, some chilled water will flow through the bypass of a three-way valve for most of a coil's operational life.

During the 1950s, the HVAC industry recognized the need to increase the allowable system design temperature differential, decrease the pumping power required to deliver chilled water, and allow chilled water systems to better match the varying cooling loads.[6] One means of accomplishing this is to vary chilled water flow rather than return water temperature. However, the chiller technology at the time did not allow variable flow through the chiller evaporators due to instability in operation. In 1954, Bell & Gossett's Gil Carlson introduced what has become known as the primary-secondary pumping scheme to address this problem.[7] A primary-secondary pumping scheme divides the chilled water system into two distinct loops that are

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[1] ITT Fluid Technology Corporation, 1996, Large Chilled Water Systems Design Workshop Manual. IV: 9-10.

[2] Durkin, Thomas H. November 2005, "Evolving Design of Chiller Plant." ASHRAE Journal 47: 11: 44

[3] ITT Fluid Technology Corporation, 1996, Large Chilled Water Systems Design Workshop Manual. IV: 14.

[4] Ibid, 15.

[5] Ibid.

[6] ITT Fluid Technology Corporation, 1968, Primary Secondary Pumping Application Manual. 1

[7] ITT Fluid Technology Corporation, 1997, "Primary Secondary Rules of Thumb." CounterPoint, 4: 2: 1. <http:/www.bellandgossett.com/Press/2ndpump.html>

hydraulically separated by a neutral bridge. These loops are known as the production or primary loop and the distribution or secondary loop.[8] The inherent separation of the primary and secondary loops allows variable flow through the distribution system to match the cooling load, while maintaining constant flow through the chillers.

As this pumping scheme evolved, it affected how chilled water plants were hydraulically arranged and altered the overall philosophy of how the entire system is to operate. By 1990, two-way control valves began replacing three-way control valves at building coils.[9] This changed the operational philosophy to one that, in theory, matched plant output to cooling load by varying the flow through and maintaining a constant temperature rise across the coil. This reduced the mixing of chilled water supply and return water at the cooling coils, but it did not eliminate all mixing. In this arrangement, three-way control valves are not entirely removed and are used together with two-way valves to provide a means of maintaining a minimum secondary pump flow.[10]

By 1996, improvements in chiller and control system technology reduced the constraints originally imposed upon the chilled water system. Design of the chiller evaporator and microprocessor-based controls allows for limited variation of chiller flow rates[11]. Chiller manufacturers are permitting designers to vary flow through the chillers, so long as the evaporator tube velocities are kept within a specified range and the allowable rate of change of flow through the evaporators is kept to a specified rate. These improvements allow a return to direct-primary pumping by combining the two loops from the primary-secondary system into a single hydraulic loop and varying chilled water flow through the entire system.

Today, central or district energy plants benefit from advances in chiller, pumping, and control technology and new developments are constantly being considered. Continual advances in chiller design in conjunction with the evolution of microprocessor controls allows the industry to consider direct-primary pumping schemes that include variable flow through a single, primary loop. With an understanding of how chilled water pumping is continually evolving to meet the challenges faced by the HVAC industry, this paper will next address problems associated with the chilled water distribution systems. Specifically, it will focus on the effects low ΔT syndrome has on the operation and performance of central chilled water plants.

LOW ΔT SYNDROME

Part of the criteria used when evaluating chilled water pumping schemes is how each scheme affects the overall performance of the chilled water system and how each scheme fits into the system as a whole. This section will address the impact that the chilled water distribution system has on plant operation and performance.

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[8] ITT Fluid Technology Corporation, 1996, Large Chilled Water Systems Design Workshop Manual. V: 2.

[9] Durkin, 41.

[10] McCauley, Gayle A. and Strause, Ralph C. September 1996, “Chilled Water Distribution Pumping Schemes.” Presented at the Central Association of Physical Plant Administrators (CAPPA) Annual Meeting. 4.

[11] Durkin, 41.

Measurement of the chilled water plant's performance is not simply the sum of the rated capacity, but must include the performance or efficiency of the chilled water distribution system. As previously defined, low ΔT syndrome results from the inefficient use of chilled water at the buildings and plant(s), yielding a lower than design return water temperature. This in turn decreases chiller ΔT.[12]

Common causes of low ΔT syndrome include[13]:

1. Improper Coil and Control Valve Selection: Oversized or undersized coils impact occupant comfort and contribute to mismatched chilled water design temperatures.
2. Dirty Coils (Air and Water Side): Reduces the overall heat transfer capacity of the coil, which results in the control system opening two-way control valves. This leads to increased flow and decreased return water temperature.
3. Laminar Coil Flow: Reduces overall heat transfer capacity of the coil.
4. Mismatched Design Conditions: System components designed for different chilled water ΔT can result in lower than plant design return water to the plant.
5. Use of Three-Way Control Valves: Allows bypass of chilled water around coil at part load resulting in lower return water temperatures for all conditions except design.
6. Low Supply Air Temperature Set Point: Arbitrarily lowering the supply air temperature set point below design can lead to uncontrollable operation and result in lower return water temperature.
7. System Differential Pressure Above Valve Shut-Off: Forces control valves open, leading to unwanted flow through coils, increasing system flow and resulting in lower return water temperature.
8. Coil Piping Configuration: Coils must be piped such that water is counterflow to air. If they are piped in reverse, the heat transfer efficiency of the coil will decrease resulting in lower chilled water return temperatures.
9. Plant Chilled Water Mixing: Flow from chilled water supply to chilled water return through the plant neutral bridge or de-coupler occurs at part load conditions when the primary loop is pumping more than the secondary loop (primary-secondary).
10. Building De-Coupler Mixing: Flow from chilled water supply to chilled water return through the building neutral bridge or de-coupler occurs in similar manner as with the plant neutral bridge.

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[12] Ibid. 44.

[13] Crowther, Hugh. July 2003, "Seminar on Chilled Water Plant Design: Variable Flow Systems and Low Delta T Syndrome."

The causes of low ΔT syndrome are primarily related to building operation and in many cases, cannot be controlled by the chilled water plant operators. However, the chilled water pumping scheme used and the design of that configuration can significantly magnify its effects. A primary-secondary pumping scheme, for instance, includes a neutral bridge which allows mixture of the two chilled water streams at the plant during part loads. This further reduces the return water temperature beyond what building inefficiencies have already started. Notwithstanding these problems, there are measures to mitigate the effects on plant operation and performance and even improve the situation.

To illustrate the impact of low ΔT syndrome on a chilled water plant, consider a central plant that serves a large university campus. This plant includes three 3,000-ton electric motor-driven centrifugal chillers, each designed for chilled water supply temperature of 42°F and a chilled water return temperature of 54°F (12°F ΔT) at a flow rate of 6,000 gallons per minute (gpm). For purposes of this example, let's assume that the plant is experiencing 6,000 tons of cooling load, but due to inefficiencies at the buildings, the chilled water return temperature has been lowered to 50°F (8°F ΔT).

In a constant flow operating scenario, each chiller includes a constant 6,000 gpm through their evaporators, regardless of the return water temperature. Since the usable capacity of a chiller is directly proportional to the evaporator flow rate and temperature differential, it follows that the capacity of each chiller decreases at a 50°F return water temperature (see Equation 1).

$$\text{Capacity} = \frac{500 \times \text{GPM} \times \Delta T}{12000\ \text{Btu} \cdot \text{h/ton}} \text{ ....(Equation 1)}$$

Specifically, each chiller experiences a one-third (4°F/12.0°F) reduction in nameplate capacity or 1,000 tons. Therefore, each machine is capable of producing only 2,000 tons with a constant flow through their evaporator. As a result, the operators are required to run three chillers at two-thirds capacity to meet the 6,000-ton load.

Increasing the flow rate to each chiller allows the operator to compensate for the reduction in chiller ΔT and "load up" the machines. Consider a variable flow operating scenario, in which the operators have the ability to adjust flow to each chiller from 4,500 gpm to 9,000 gpm. If the same 6,000-ton load is experienced by the plant, the operator can now increase the flow rate of each operating chiller to 9,000 gpm. This increase in flow matches the proportional decrease in chiller ΔT allowing each unit to produce 6,000 tons. With this flexibility, the operators are no longer required to bring on a third chiller, but can satisfy loads with two chillers operating at 100 percent capacity. See Table 1 for a side by side comparison of each operating scenario in this example.

Table 1 – Example Chilled Water Plant Summary

Scenario	Chiller Nameplate Capacity (Tons)	Campus Load (Tons)	Chiller Flow (gpm)	Chiller ΔT °F	Chiller Output (Tons)	Units in Operation
Constant Flow	3,000	6,000	6,000[1]	8.0	2,000	3
Variable Flow	3,000	6,000	9,000[2]	8.0	3,000	2

1. Flow rate based upon a design ΔT of 12°F or 2 gpm per ton.
2. Flow rate based upon a ΔT of 8°F or 3.0 gpm per ton.

Since the single largest energy users within a chilled water plant are the chillers themselves, bringing a third machine on-line to meet the load significantly impacts the plant energy usage and cost. Because the chiller motors are running at 100 percent, but working against partially closed inlet vanes, the efficiency (kW per ton) for each of these units is reduced. Two chillers running at full load are more efficient than three running at part load (two-thirds load in our example), which further increases the plant energy consumption.

Making the change to a variable chiller flow is more complex than simply adding a variable speed drive to the chiller pumps. It becomes an evaluation of the philosophy behind the operation of the central chilled water plant as well as a comparison of the two hydraulic pumping configurations.

So what are the differences between these two pumping schemes and how is each equipped to address the problems associated with chilled water distribution systems? The next section outlines the significant features and operational vision of the two pumping schemes and how each addresses low ΔT syndrome.

CHILLED WATER PUMPING SCHEMES

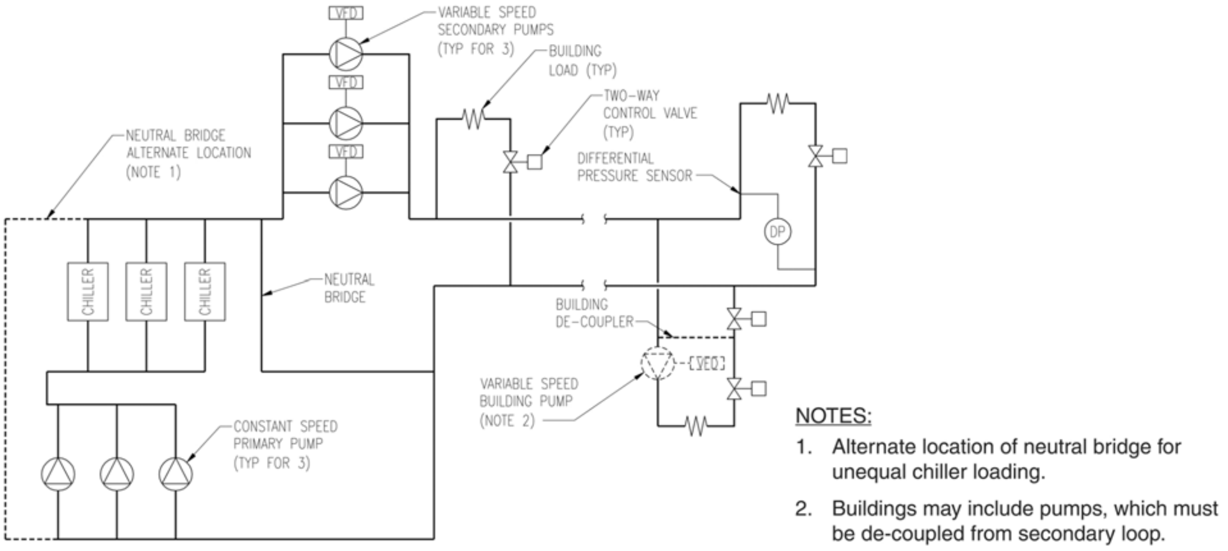
As previously outlined, chilled water pumping has been an evolutionary process built on the need to solve performance and operational problems associated with the delivery of chilled water. This process resulted in two pumping schemes that can be found throughout campuses and buildings around the world, namely primary-secondary and direct-primary.

Primary-Secondary Pumping Scheme

In the struggle to balance manufacturer requirements for the operation of chillers and match chilled water pumping to cooling load, the primary-secondary pumping scheme was developed. In general this pumping scheme consists of two hydraulically independent circuits connected by a de-coupler or neutral bridge. The two circuits include a constant volume production loop (primary) and a variable volume distribution loop (secondary). The primary loop circulates chilled water through the chillers and the secondary loop circulates chilled water through the distribution system (see Figure 1). The hydraulic independence of each loop prevents variable flow in the secondary loop from influencing the constant flow in the primary loop[14].

Each loop includes a set of pumps sized to deliver the same flow rate against the individual total dynamic head of each loop. The chilled water circulation (primary) pumps are constant volume and the chilled water distribution (secondary) pumps are variable volume operating from a variable speed drive. This allows the chillers to receive a constant chilled water flow rate, while the distribution system flow rate can vary to match load.

The neutral bridge consists of two tees that are typically located at the suction header of the secondary pumps and at the suction header of the primary pumps and connected by a de-coupling pipe, as shown in Figure 1. Minimizing the pressure drop through this line is what allows the two loops to maintain their independence from each other.[15]



NOTES:

1. Alternate location of neutral bridge for unequal chiller loading.
2. Buildings may include pumps, which must be de-coupled from secondary loop.

Figure 1 –Primary-Secondary Pumping Scheme

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[14] McCauley and Strause, 3.

[15] ITT Fluid Technology Corporation, 1996, Large Chilled Water Systems Design Workshop Manual. V: 2.

During part load conditions, the two-way control valves begin to close causing an increase in system differential pressure as detected by the differential pressure sensor. Consequently, the control system will reduce the pump speed and flow of the secondary pumps to match load. The decrease in flow from the secondary loop means the chilled water will flow from the supply side to the return side to maintain the constant volume through the chillers. Ideally, no flow is desired through the neutral bridge as this contributes to low ΔT syndrome. Rarely is there no flow through the neutral bridge because plants operate at part load during most of the year.

The secondary pumps are typically driven by a variable frequency drive (VFD), which varies the frequency of the electrical power delivered to the pump motor. Since electrical frequency is proportional to motor and pump speed and chilled water flow, this provides an accurate means of varying the flow rate of a pump. The VFD is controlled from a differential pressure sensor located at the hydraulically most remote location in the system (see Figure 1).

Central chilled water plants are tied to a multiple array of building types that range in function, age, and load. Consequently, these building systems probably were not installed at the same time or designed by the same engineer. As a result, the designer of any pumping scheme must consider what influences the buildings may have on the operation of the plant. Specifically, some building systems may or may not include a building pump. If a building pump is included, it is important that the building pump and piping be decoupled from the secondary loop as shown in Figure 1. Failure to do so effectively places the building pump in series with secondary pumps at the plant. The building pumps can then pressurize the chilled water return piping and actually produce a negative system differential pressure.[16] To compensate, the secondary pump VFDs will run the pumps to full speed and the system becomes uncontrollable. Insufficient chilled water will be supplied to buildings that do not include pumps and/or are hydraulically remote from the plant. As a result, the ability of the building operators to control comfort may be lost.[17]

The following is a list of the advantages to implementing a primary-secondary system:

1. Constant Flow Through Evaporator[18]: The primary-secondary system maintains a constant flow through the evaporator of the chiller. This eliminates the concern for chiller performance and inadvertent shutdowns. Chiller capacity controls have traditionally lagged behind sudden changes in load. If the load suddenly drops, the chilled water supply temperature drops until the controls catch up. This sudden drop in supply temperature causes nuisance trips, due to low evaporator temperature. This is less of a concern today than it was in the past because of microprocessor-based controls.

2. Simplified Controls: Controls within a primary-secondary system are relatively simple and well established. Typical chiller controls packages do not have difficulty with the staging sequence for the chillers and responding to varying loads.

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[16] Hyman, Lucas B. and Little, Don. February 2004, "Overcoming Low Delta T, Negative Delta P at Large University Campus." ASHRAE Journal. 46: 2: 31.

[17] Ibid.

[18] Kirsner, Wayne. November 1996, "The Demise of Primary Secondary Pumping Paradigm for Chilled Water Plant Design." Heating/Piping/Air Conditioning Engineering. 74

3. Past Experience: The primary-secondary system is a well established operational philosophy and plant personnel are familiar with its operation. In addition, this pumping scheme has been proven reliable if operated properly.

4. Divided Hydraulic Head: By dividing the total dynamic head between two hydraulically independent loops, the required motor size for each pump type (primary and secondary) will be smaller when compared to a direct-primary system.[19] This also reduces the risk that the system discharge pressure will exceed the design of equipment, piping, and valves in the buildings.

The following is a list of the disadvantages to implementing a primary-secondary system:

1. Does not Resolve Low ΔT Syndrome: The primary-secondary system does not allow an increase in flow through the evaporator above design and; therefore, does not adjust to chilled water return temperatures that are lower than design. In addition, this pumping scheme can further exacerbate the problem during off-peak conditions. As the cooling load decreases, the secondary pump VFDs will ramp down to a lower speed, thus allowing these pumps to produce less flow. The constant volume circulation pumps will then over pump the primary loop causing supply water to flow through the neutral bridge and mix with return water. This mixing lowers the return water temperature and deteriorates the system ΔT as described previously.[20]

2. Capital Investment: The greater quantity of pumps and the longer piping runs associated with this pumping scheme can yield a higher capital investment when compared to the direct-primary system.[21]

3. Higher Operating and Energy Costs: The primary-secondary system uses both constant speed and variable speed pumps to circulate chilled water through the plant as well as the distribution system. Because the primary loop will always have a constant flow, energy is wasted within this loop at off-peak loads. In addition, this pumping scheme does not allow adjustable flow through the chillers and is subject to the part load operational inefficiency described above. These features and the need for two sets of pumps will generally yield higher energy and operating costs per annum when compared to the direct-primary system.[22]

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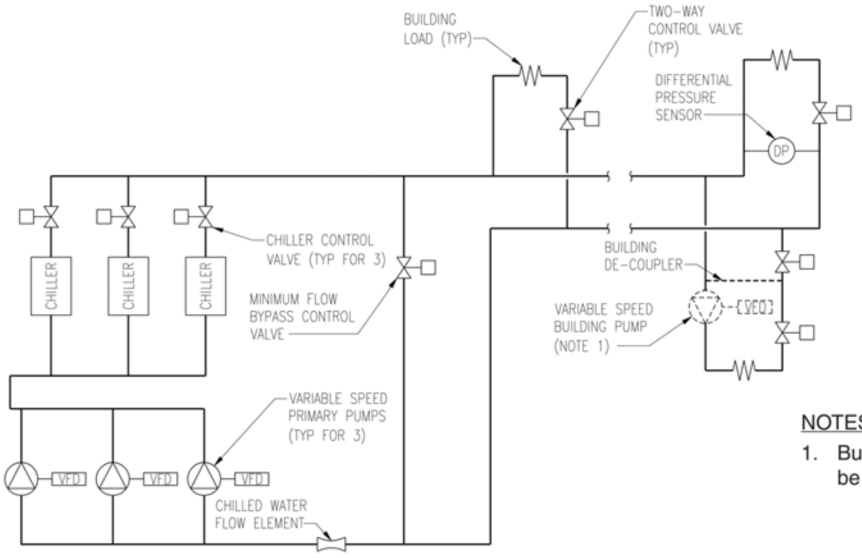
[19] Taylor, Steven T. February 2002, "Primary-Only vs. Primary-Secondary Variable Flow Systems." ASHRAE Journal. 44: 2: 27.
[20] Kirsner, 74.
[21] Taylor, 27.
[22] Ibid.

4. <u>Requires More Plant Space</u>: Two sets of pumps are needed to circulate chilled water through the chiller evaporator and the chilled water distribution system. This requires more floor space, more spare parts, and results in higher capital costs and pump maintenance costs when compared to the direct-primary system.[23]

Direct-Primary Pumping Scheme

With the advent of more sophisticated control systems and improvement in chiller technology over the last ten years, the direct-primary pumping scheme is being more widely used. It consists of a single variable volume chilled water loop (primary), which combines the chilled water plant and distribution systems. In order to vary chilled water flow to match the cooling load (position of two-way control valves), this pumping scheme allows the flow through the chillers to adapt to varying distribution conditions instead of having an independent secondary loop. The primary pumps perform double duty, circulating chilled water through the chillers as well as the distribution loop (see Figure 2). The pumps are equipped with variable frequency drives (VFD) to vary chilled water flow within the system to meet current operating conditions. This eliminates the need for chiller circulation pumps, but requires varying the flow through the chiller evaporator.

This configuration was the long awaited answer to the problems presented by primary-secondary pumping. However, it is not without its own limitations. While chiller manufacturers have been allowing adjustable flow through the chillers, upper and lower limits have been placed on the flow rates. These manufacturers are typically limiting tube velocities from 5.0 feet per second to 10.0 feet per second. In addition, careful attention must be given to the allowable rate of change in evaporator flow. Typically, manufacturers limit this rate of change to 1,000 gpm per 15 minute period.



<u>NOTES:</u>

1. Buildings may include pumps, which must be de-coupled from primary loop.

Figure 2 –Direct-Primary Pumping Scheme

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[23] Ibid.

Because of these constraints additional design features are required with a direct-primary pumping scheme. The most significant of these features is the installation of a minimum flow bypass line and control valve as shown in Figure 2. Should the system load drop to the point where the flow rate needed to satisfy the buildings is less than the minimum flow required for the chillers, the minimum flow bypass control valve opens allowing some flow to re-circulate back to the chillers.[24] In order for this to work properly, the control of the system is dependent upon the accurate measurement of chilled water flow and proper selection of the bypass control valve.[25] The inability of the bypass valve to properly open and close may result in the chillers tripping due to low flow.

As with primary-secondary systems, the designer of this pumping scheme must consider what influences the buildings may have on the operation of the plant. Any building pumps that remain in operation must also be hydraulically decoupled from the primary loop otherwise there is a risk of negative differential pressure and its inherent control problems. Furthermore, the single set of pumps used in this configuration will develop a higher system total dynamic head. In selecting the system design pressure, the designer must pay careful attention to the design of existing building systems.

The following is a list of the advantages to implementing a direct-primary system:

1. <u>Low ΔT Syndrome:</u>

    a. *Neutral Bridge:* The direct-primary system does not include two hydraulically independent loops that are separated by a neutral bridge. As a result, the pump flow rate is better matched to the cooling load within the distribution system and the absence of a neutral bridge prevents mixing of supply and return water.

    b. *Adjustable Chiller Flow:* Allowing the flow through the chiller to vary above normal design flow lets the operator increase flow to the chiller and match the system ΔT. This maximizes the output of a given chiller and eliminates the need to start additional chillers and pumps prior to reaching nameplate capacity.[26] The combination of using less equipment more efficiently yields savings to the owner/operator. This advantage is dampened by the fact that increasing evaporator flow above design will increase the system pressure drop according to pump affinity laws.

2. <u>Capital Investment</u>: The smaller quantity of pumps and the more efficient piping runs associated with this pumping scheme can yield a lower capital investment when compared to the primary-secondary system.[27]

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[24] Ibid, 28.

[25] Ibid.

[26] Schwedler, Mick. March 2003, "Variable Primary Flow in Chilled Water Systems." <u>Heating/Piping/Air Conditioning Engineering</u>. 38.

[27] Taylor, 27.

3. Lower Operating and Energy Costs: Since the direct-primary system uses fewer pumps and is better equipped to match system load; it will generally yield lower energy and operating costs per annum as compared to the primary-secondary system.[28]

4. Requires Less Plant Space: Constant flow pumps serving a production loop are not needed because the primary pumps circulate the water through the chillers as well as the distribution system. This requires less floor space, fewer spare parts, and can result in lower capital costs and pump maintenance costs.[29]

The following is a list of the disadvantages to implementing a direct-primary system:

1. Control Complexity: Control of the direct-primary system requires more care so that chillers are not inadvertently shutdown during simultaneous flow and load changes. In addition, care must be taken in controlling the low flow bypass.

2. Chiller Staging: When plant operators desire to bring additional chillers online, the sudden drop in flow through the lead chiller may cause it to trip offline on low flow. A more complex control strategy is required to first unload the lead chiller, start the next unit and ramp them back up together.[30]

3. Low Flow Bypass: The direct-primary system requires the installation of a low flow bypass from the pump discharge to the chiller inlet header. It must include a normally closed valve that opens under low load conditions to maintain the minimum chiller evaporator flow rate. This establishes a cap to the energy savings that can be achieved using this system.[31]

4. Past Experience: The primary-secondary system is a well established operational philosophy and plant personnel are familiar with its operation. The direct-primary system represents a change in operating philosophy of many owners/operators and will require additional training. While this pumping scheme is relatively new, it has been proven reliable on several projects across the country over the last ten years.

5. Divided Hydraulic Head: Because the total dynamic head is produced by a single set of pumps and there is no separation between the plant and distribution systems, this pumping scheme will require larger motors.[32] In addition, a direct-primary system will increase the system design pressure and careful attention must be given to the design pressure of existing building equipment, piping, and valves.

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[28] Ibid.

[29] Ibid.

[30] Ibid, 28.

[31] Ibid.

[32] Ibid, 27.

One of the primary benefits listed above is the energy savings a chilled water plant can realize per annum just from operating the chillers to their full nameplate capacity. To demonstrate this, consider the 9,000-ton chilled water plant previously discussed operating over a cooling season, which lasts from April through November. Due to the low return water temperature, the plant operators are required to operate more chillers than are needed during part load conditions due to the constant flow through the evaporators. Consequently, the chillers cannot be fully loaded during these periods. The price tag associated with this operating scenario can be significant. For purposes of this example, assume the campus experiences a load profile as defined by Figure 3.

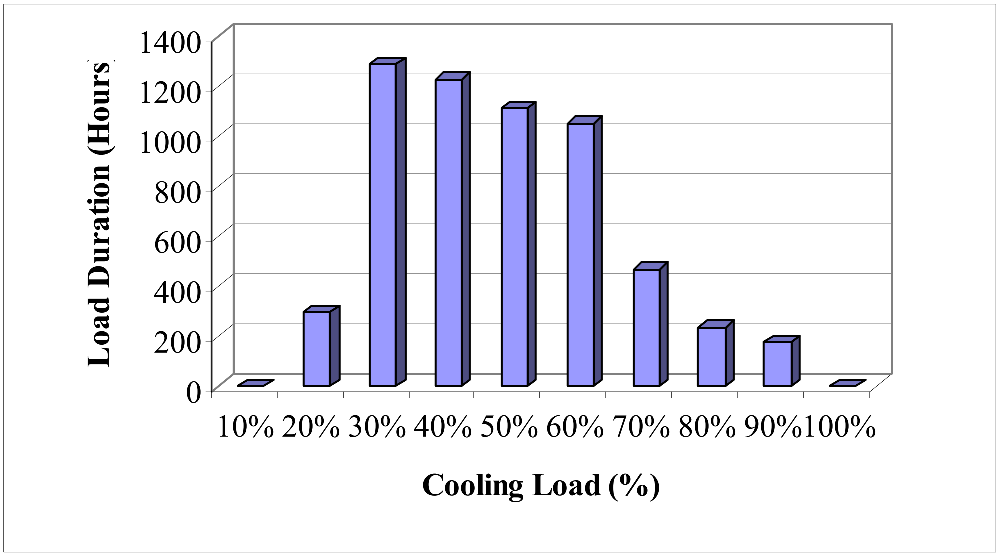

Figure 3 – Example Chilled Water Plant Load Profile

Assuming the chilled water plant sees a return water temperature of 50°F at part load conditions below 70 percent load, the chiller energy usage can be calculated. The particular chillers in this example are guaranteed to operate at the following efficiencies:

1. Full Load: 0.595 kilowatts per ton
2. 75 Percent Load: 0.559 kilowatts per ton
3. 50 Percent Load: 0.612 kilowatts per ton
4. 25 Percent Load: 1.019 kilowatts per ton

The results of this energy analysis can be seen in Table 2. The direct-primary pumping scheme with variable flow through the chillers will use 4 percent less energy over a single cooling season than a primary-secondary system with constant flow through the chillers. So simply operating the chillers to their full potential saves a significant amount of energy over the life of a plant.

In addition, to the savings in chiller operation, a single loop with variable flow will inherently result in a net energy savings in pumping power. Because the chilled water flow rate follows the cooling load, the flow rate being pumped is matched to what is actually needed in the buildings. Again, the limit to this savings is the minimum flow required through the chillers, which in the case of this example is 4,500 gpm.

Table 2 – Example Chilled Water Plant Energy Usage from Chillers

Cooling Load (%)	Load Duration (Hours)	Primary-Secondary Electrical Demand (kW)	Primary-Secondary Energy Usage (kWh)	Direct-Primary Electrical Demand (kW)	Direct-Primary Energy Usage (kWh)
10	0	917	0	917	0
20	293	1,037	303,575	1,037	303,575
30	1,288	1,871	2,410,576	1,871	2,020,988
40	1,230	2,074	2,550,030	2,074	2,550,030
50	1,113	2,754	3,064,211	2,754	2,798,846
60	1,054	3,110	3,278,610	3,110	3,307,071
70	468	3,522	1,649,846	3,522	1,649,846
80	234	4,075	954,575	4,075	954,575
90	176	4,706	826,768	4,706	826,768
100	0	5,355	0	5,355	0
Total			**15,038,190**		**14,411,698**

SUMMARY AND CONCLUSION

Chilled water delivery has undergone significant changes since the advent of central chilled water generation. Responding to the various demands of operations, equipment, and the drive for more efficient plants has led to a multitude of variations on two basic concepts, namely primary-secondary and direct-primary pumping schemes. Because the pumping scheme is the heart of a chilled water system, important lessons can be learned from our past as we look to the future of district energy.

The arch nemesis, as it were, of the central chilled water plant comes not from the plant itself, but ironically, from the buildings those plants serve. While solutions to low ΔT syndrome can and should be addressed with building HVAC improvements, the effects this phenomenon can have on chilled water production can be tempered with proper design of the chilled water pumping. We have reviewed the basics of these pumping schemes comparing them with one another. Table 3 summarizes their advantages.

Table 3 – Pumping Scheme Comparison Summary

Primary-Secondary Pumping Benefits	Direct-Primary Pumping Benefits
Constant flow through chiller evaporator.	Mitigates effects of Low ΔT Syndrome.
Simplified controls and operation.	Potential reduction in plant capital and operating costs.
Wide spread experience among plant operators.	Reduction in number of pumps, i.e., less plant space required.
Smaller motors and less impact to building system design pressure.	

Clearly, the benefits of the direct-primary system allow much greater flexibility for the operators in providing chilled water where it is needed in the most efficient manner possible. However, this system is more complex and requires training and understanding of how it is to operate. Even though primary-secondary systems remain the "comfortable choice," direct-primary, variable flow systems are picking up momentum as the preferred operational scheme.

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