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Simplified Chiller Sequencing

For a Primary/Secondary Variable Chilled Water Flow System

BY MARSHALL SEYMORE, P.E., MEMBER ASHRAE

To fully automate the central chilled water plant operation at the University of West Florida in Pensacola, Florida, the challenge was to control the primary (production) chilled water flow to equal the secondary (distribution) chilled water flow demand for a variable primary flow and variable secondary flow system.

The central chilled water plant consists of four 1,200 ton (4,220 kW) centrifugal chillers, four dedicated primary chilled water pumps (PCWP), three secondary chilled water pumps (SCWP) and an automation control system. The chilled water system was a classic primary-secondary-decoupler piping arrangement with a check valve, temperature sensor and flow measurement element in the decoupler piping. The campus air-handling unit chilled water coils use two-way control valves. The chilled water plant had all the automation controls needed for full automatic control but was being manually operated.

In addition to fully automating the sequencing of chillers, actions were also needed to address:

- Underuse of installed chiller capacity. Chillers could only reach 70% of full load capacity.
- Unable to maintain the secondary chilled water design supply temperature equal to or less than 42°F (5.56°C).
- The chillers were selected based on an entering chilled water temperature of 60°F (15.56°C) and a leaving chilled water temperature of 42°F (5.56°C) (18°F (10°C) ΔT).
- The campus chilled water coil designs ranged from 10°F (5.56°C) ΔT to 15.0°F (8.34°C) ΔT with entering chilled water temperatures from 42°F (5.56°C) to 45.0°F (7.22°C).
- Over pumping through the decoupler piping.

Actions taken to address these issues:

- Remove the check valve from the decoupler piping. This was necessary to hydraulically decouple the primary and secondary pumping to allow flow through the decoupler piping in both directions to facilitate this control approach.
- Install a set of matched temperature sensors indicated in *Figure 1*.
- Develop a temperature based flow approach by analyzing and determining the flow dynamics in the decoupler piping shown in *Figure 2*.

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• Obtain confirmation from the chiller manufacturer that variable evaporator chilled water flow was possible and establish the maximum and minimum allowable evaporator chilled water flows.

• Install new primary pumps with variable frequency drives (VFD) selected to take advantage of the maximum and minimum evaporator chilled water flows allowable.

• Use the temperature based flow approach developed for sequencing chillers and controlling primary pump VFD speeds.

This intent of the actions taken was to:

• Minimize secondary pumping energy usage by minimizing the secondary flow in the decoupler piping.

• Minimize primary pumping energy usage by using VFD on primary pumps to minimizing the primary flow in the decoupler piping.

• Optimize chiller use by controlling the secondary chilled water supply temperature equal to or less than design.

• Simplify chiller sequencing.

• Simplify control of primary pump VFD speeds, and

• Facilitate maximizing chiller capacities.

Equations

$T2 = x_1 \times T3 + (1 - x_1) \times T1$ (Eq. 1)

$x_1 = (T2 - T1)/(T3 - T1)$ (Eq. 2)

$T4 = x_2 \times T1 + (1 - x_2) \times T3$ (Eq. 3)

$x_2 = (T3\text{-}T4)/(T3\text{-}T1)$ (Eq. 4)

Primary Flow % =
$100 \times [1\text{-}(T2\text{-}T1)/(T3\text{-}T1)]$ (Eq. 5)

Secondary Flow % =
$100 \times [1 - (T3 - T4)/(T3 - T1)]$ (Eq. 6)

FIGURE 1 Variable primary chilled water flow; variable secondary chilled water flow.

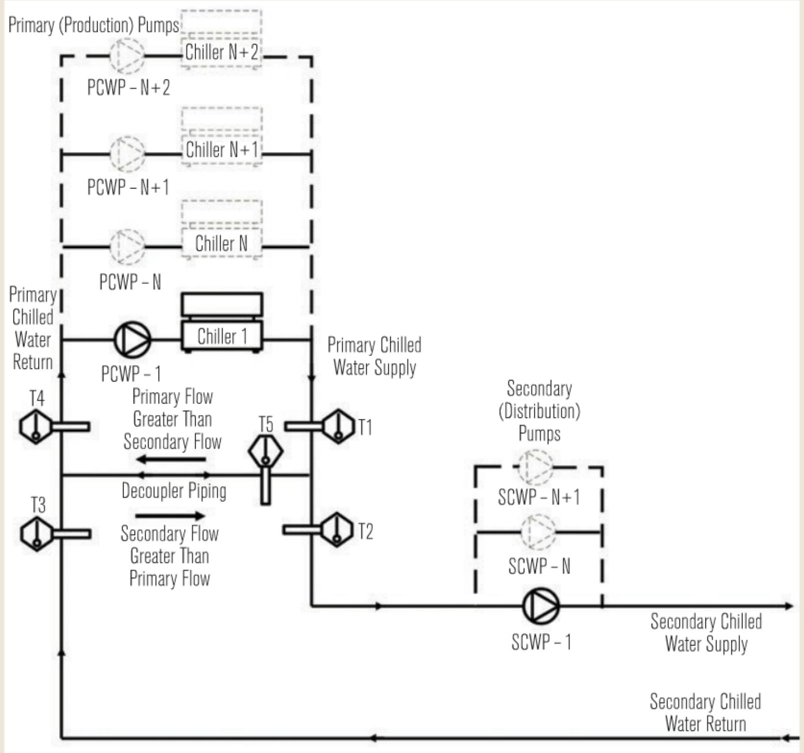
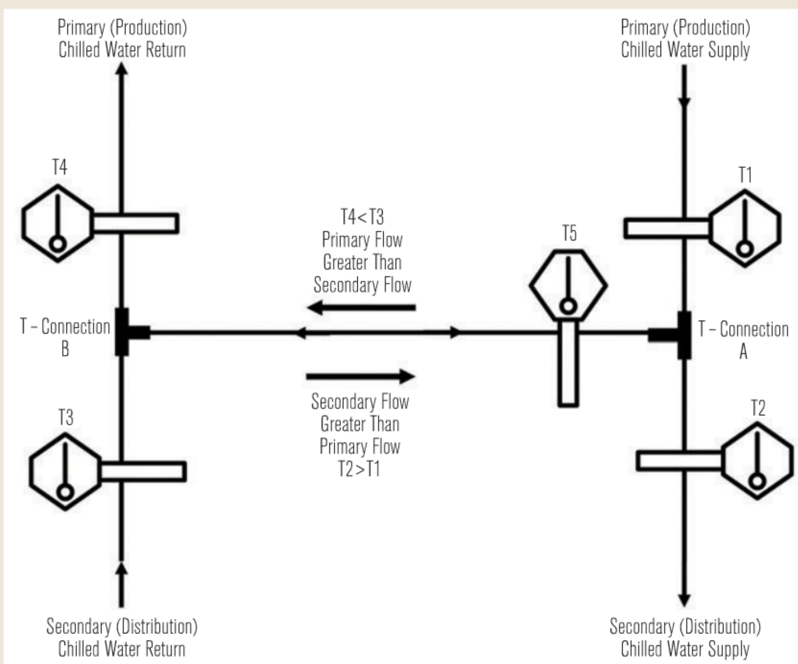


FIGURE 2 Decoupler piping.



Mixed Flow Temperature Calculations

Secondary Flow Greater Than Primary Flow (*Table 1*)

Analysis for "T-Connection A" Flow (*Figure 2*)

Secondary Supply Mixed Temperature (T2) Calculation

T1 = Primary Supply Flow Temperature

T2 = Secondary Supply Flow Temperature

T3 = Secondary Return Flow Temperature

T5 = Decoupler Flow Temperature

x_1 = Fraction of Secondary Flow in Decoupler Piping

$T2 = x_1 \times T5 + (1- x_1) \times T1$

$T5 = T3$

$\mathbf{T2 = x_1 \times T3 + (1 - x_1) \times T1}$ **(Eq. 1)**

$T2 = x_1 \times T3 + T1 - x_1 \times T1$

$T2 = x_1 \times (T3 - T1) + T1$

$T2 - T1 = x_1 \times (T3 - T1)$

$\mathbf{x_1 = (T2 - T1)/(T3 - T1)}$ **(Eq. 2)**

Primary Flow Greater Than Secondary Flow (*Table 1*)

Analysis for "T-Connection B" Flow (*Figure 2*)

Primary Return Mixed Temperature (T4) Calculation

T1 = Primary Supply Flow Temperature

T3 = Secondary Return Flow Temperature

T4 = Primary Return Flow Temperature

T5 = Decoupler Flow Temperature

x_2 = Fraction of Primary Flow in Decoupler Piping

$T4 = x_2 \times T5 + (1 - x_2) \times T3$

$T5 = T1$

$\mathbf{T4 = x_2 \times T1 + (1 - x_2) \times T3}$ **(Eq. 3)**

$T4 = x_2 \times T1 + T3 - x_2 \times T3$

$T4 = x_2 \times (T1 - T3) + T3$

$T4 - T3 = x_2 \times (T1 - T3)$

$\mathbf{x_2 = (T3 - T4)/(T3 - T1)}$ **(Eq. 4)**

Temperature Based Flow Approach

The temperature based flow approach uses mixed temperature calculations at the decoupler piping "T-Connection A" and "T-Connection B"(see sidebar, "Mixed Flow Temperature Calculations").

Primary Flow % Calculation

The Primary Flow % calculated value is used to control primary pump variable frequency drive (VFD) speeds and add additional chillers to meet secondary cooling load requirements while maintaining secondary chilled water supply temperature equal to or less than design.

$$\text{Primary Flow \%} = 100 \times (\text{Secondary Flow minus Decoupler Flow})/\text{Secondary Flow}$$

$$\text{Primary Flow \%} = 100 \times (1 - x_1)$$

$$x_1 = (T2 - T1)/(T3\text{-}T1) \qquad \text{(Eq. 2)}$$

$$\textbf{Primary Flow \%} = \mathbf{100 \times [1 - (T2 - T1)/(T3 - T1)]} \qquad \textbf{(Eq. 5)}$$

- When Primary Flow % is less than 100%, secondary flow is greater than primary flow;
- When Primary Flow % is greater than 100%, primary flow is greater than secondary flow; and
- When Primary Flow % is equal to 100%, primary flow equals secondary flow with zero flow through decoupler.

Secondary Flow % Calculation

The Secondary Flow % calculated value is used to subtract chillers to meet secondary cooling load requirements while maintaining secondary chilled water supply temperature equal to or less than design.

$$\text{Secondary Flow \%} = 100 \times (\text{Primary Flow minus Decoupler Flow})/\text{Primary Flow}$$

$$\text{Secondary Flow \%} = 100 \times (1 - x_2)$$

$$x_2 = (T3 - T4)/(T3 - T1) \qquad \text{(Eq. 4)}$$

$$\textbf{Secondary Flow \%} = \mathbf{100 \times [1 - (T3 - T4)/(T3 - T1)]} \qquad \textbf{(Eq. 6)}$$

- When Secondary Flow % is less than 100%, primary flow is greater than secondary flow;
- When Secondary Flow % is greater than 100%, secondary flow is greater than primary flow; and
- When Secondary Flow % is Equal to 100%, secondary flow equals primary flow with zero flow through decoupler.

Primary Pump VFD Speed Control

The Primary Flow % calculation (Equation 5) will be used to control Primary Pump VFD speed to maintain Primary Flow % calculation at a designated setpoint (*Table 2*).

- When Primary Flow % calculation is greater than setpoint (100%), decrease primary pump VFD speed,
- When Primary Flow % calculation is less than setpoint (100%), increase primary pump VFD speed;

TABLE 1 Decoupler piping temperatures.[1]

TEMPERATURE SENSOR	FLOW TEMPERATURE DESCRIPTION	PRIMARY FLOW EQUALS SECONDARY FLOW	SECONDARY FLOW GREATER THAN PRIMARY FLOW	PRIMARY FLOW GREATER THAN SECONDARY FLOW
T1	Primary Supply	T1	T1	T1
T2	Secondary Supply	T2=T1	T2>T1[2]	T2=T1
T3	Secondary Return	T3	T3	T3
T4	Primary Return	T4=T3	T4=T3	T4<T3[3]
T5	Decoupler Piping	T5=T1 or T5=T3	T5=T3	T5=T1

[1]See *Figure 2*
[2]Equation 1: T2 Mixed temperature equation; Primary Flow % calculation less than 100%
[3]Equation 3: T4 Mixed temperature equation; Secondary Flow % calculation less than 100%

TABLE 2 Chiller sequencing.

ITEM DESCRIPTION	PRIMARY FLOW EQUALS TO SECONDARY FLOW	SECONDARY FLOW GREATER THAN PRIMARY FLOW	PRIMARY FLOW GREATER THAN SECONDARY FLOW
T1 Primary Supply Temperature	42°F	42°F	42°F
T2 Secondary Supply Temperature	42°F	42.6°F	42°F
T3 Secondary Return Temperature	54°F	54°F	54°F
T4 Primary Return Temperature	54°F	54°F	53.4°F
T5 Decoupler Temperature	Between 42°F & 54°F	54°F	42°F
Primary Flow % Calculation[1]	100%	Less Than 100%[4]	Greater Than 100%[3]
Secondary Flow % Calculation[2]	100%	Greater Than 100%	Less Than 100%
Chiller Sequencing	None	Add[5]	Subtract[6]

[1]Equation 5: Primary Flow % calculation
[2]Equation 6: Secondary Flow % calculation
[3]Decrease primary pump VFD speed when the Primary Flow % calculation is greater than setpoint of 100%
[4]Increase primary pump VFD speed when the Primary Flow % calculation is less than setpoint of 100%
[5]Add chiller when the Primary Flow % calculation is less than add chiller set point of 95%
[6]Subtract chiller when the Secondary Flow % flow calculation is less than subtract chiller setpoint of 95%

Chiller Sequencing

Adding chiller sequence of operation (*Table 2*):

- When the Primary Flow % calculation (Equation 5) is less than add chiller setpoint (95%), add one chiller.

Subtracting chiller sequence of operation (*Table 2*):

- When the Secondary Flow % calculation (Equation 6) is less than subtract chiller setpoint (95%), subtract one chiller.

Advantages of This Approach

Primary pump VFD speed and staging of chillers is not dependent on:

- Chiller capacity;
- Chiller or cooling coil design temperature difference
- Primary, secondary or decoupler water flow measurement and/or chiller load calculations;
- Number of chillers;
- Decoupler piping size;
- Differential pressure controls;
- Complex system modeling and/or algorithms; and
- A constant system ΔT.

Primary pump VFD speed is controlled by using a control loop with a setpoint to maintain Primary Flow % calculations at setpoint.

System Design and Operation Considerations

Locate temperature sensors T2 and T4 far enough downstream from the decoupler piping T-connections to allow for thorough mixing of the different flow stream temperatures. Flow temperatures can stratify in piping and give incorrect temperature values and thus affect

Primary Flow % and Secondary Flow % flow calculations.

Control primary and secondary pump VFD speeds by using a step speed control with a time delay to prevent unstable flow condition in the chilled water piping that can be caused by using a modulating VFD speed control scheme.

The ideal Secondary Flow % setpoint to subtract a chiller for an ideal system would be 95%. When one chiller is subtracted, the Primary Flow % calculation should not be less than the Primary Flow % add chiller setpoint. This is a system specific value that must be determined by system observation and should be a field determined setpoint.

The ideal Primary Flow % setpoint to add a chiller for an ideal system would be 95%. When one chiller is added, the Secondary Flow % calculation should not be less than the Secondary Flow % subtract chiller setpoint. This is a system specific value that must be determined by system observation and should be a field determined setpoint.

The ideal Primary Flow % setpoint for an ideal system for zero flow through the Decoupler piping would be 100%. The best Primary Flow % setpoint would be for T1 to Equal T2 and T3 to equal T4 and T5 to equal T3. This should be a field determined setpoint.

Chiller discharge temperature controls must be stable with small variations from setpoint.

Conclusion

Each action item was completed and these control approach principles are currently being successfully used at the University of West Florida.

These control approach principles have been applied and have allowed:

- Chillers to be loaded to 100% capacity if required;
- Secondary chilled water distribution temperature to be controlled to less than 42°F (5.56°C);
- Chillers to be automatically sequenced;
- Decoupler flow to be minimized; and
- Production flow to equal distribution flow by controlling primary pump VFD speed. ■