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ENGINEERING

S Y S T E M   S O L U T I O N S

Over the years I have heard many reasons to lower chilled water supply temperature and increase the delta T. On several occasions the reason for 42°F supply temperature has been to counter heat loss through the piping and make sure that the chilled water is truly 44°F at the air handling unit. This doesn't sit well with me because it means 20% of the chilled water plant capacity is lost! If this really happened, there wouldn't be enough chiller capacity to meet the loss and the air conditioning load.

Lowering the chilled water temperature just to improve air handling unit coil performance is rarely a good idea either. The concept is the coils can be smaller, the air pressure drop is less and the fan savings can more than pay for the penalty on the chiller. The potential savings have to be checked on a job by job basis. Many consultants are not comfortable with coils having 4 rows or less. If the coils are unilaterally specified, the air pressure drop savings are not realized and the chiller is still penalized. The ARI design conditions (44°F-54°F chilled water) weren't picked out of a hat. They truly work best for a wide range of buildings.

There are times when low supply water temperature and large delta Ts make sense. Large health care or university campuses are one example. This month's Engineering System Solutions addresses the idea that not all chilled water plant designs "scale down" evenly. More simply put, low supply temperature, high delta T chilled-water systems need different designs than conventional chiller plant arrangements. A series counter flow chiller plant is one of the best solutions.

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Series Chillers—
What's Old Is New Again

The concept of series chillers is not new. Designers have always been challenged to find effective ways to use multiple chillers in their chiller plant designs because they afford redundancy over single chiller plant designs. More complex systems often use decoupled designs in a primary/secondary arrangement, but with smaller systems the choices traditionally have been series or parallel chillers. Figure 1 shows a typical series arrangement. Figure 2 shows a typical parallel arrangement.

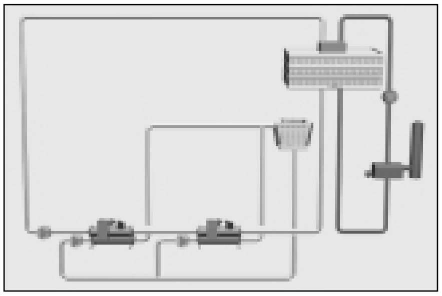

Figure 1. Typical Series Chiller Arrangement

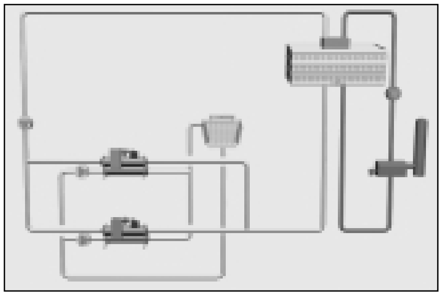

Figure 2. Typical Parallel Chiller Arrangement

SERIES VERSUS PARALLEL CHILLERS

Table 1 shows chiller selections a for a typical 375,000 ft² office building in Minneapolis. The building is 7 stories tall with a design load of 800 tons. The HVAC design is VAV with reheat, floor-by-floor central air handling units and a water-cooled chilled water plant.

Table 1 – Series Versus Parallel Chiller Selections At ARI Conditions (44°F/54°F on the evaporator and 85°F /3gpm/ton on the condenser)

Chiller Model	Qty	Capacity (tons)	Performance (kW/ton)	NPLV (kW/ton)	kW Input (kW)	Evap. WPD (ft)	Cond.WPD (ft.)
Parallel arrangement							
WCS 087	2	400	0.550	0.504	217.1	7.1	5.0
Total	2	800	0.550	N/A	434.2	7.1	5.0
Series arrangement							
WSC 079	1	320	0.579	0.552	185.2	14.3	5.0
WSC087	1	480	0.530	0.487	254.5	3.5	4.9
Total	2	800	0.550	N/A	439.7	17.8	5.0

The series chillers were selected to optimize their performance for the specific design conditions of the application. Series chillers are often selected with single pass evaporator arrangements, which can lead to higher evaporator pressure drops. The total chilled water system pressure drop for series chillers is determined by adding the chiller pressure drops, usually resulting in a higher pressure drop than a parallel arrangement.

At first glance there is little difference in the overall chiller plant kW input. Using McQuay's Energy Analyzer™ software, the annual energy usage for both chiller plants was estimated. Table 2 shows the annual energy usage for the main components in the HVAC system.

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Table 2 – Series Versus Parallel Chiller Energy Analysis With Constant Primary Flow At ARI Conditions

System	Chillers kWh/yr	Chiller Pump kWh/yr	Cooling Towers kWh/yr	AHU Fans kWh/yr	Total KWh/yr
Parallel	286,292	221,801	20,977	422,629	951,699
Series	256,248	204,307	21,107	422,629	904,291

Not what you would expect…

From Table 1, one could conclude that the series layout would use the same power to operate the chillers and more power for pump work. From Table 2 you can see that this is not what happens. There are over 30,000 kWh/yr of electrical savings for the series chillers and another 17,000 kWh/yr pump savings. To understand why, the sequence of operation of parallel chillers must be reviewed.

Parallel chiller systems are a challenge to operate below 50% plant capacity. When the plant load drops below 400 tons, in theory, one chiller could carry the load. The difficulty is that there is no easy way to turn off the other chiller without adversely affecting the chiller plant. If one chiller is simply turned off, the chilled water flow through that chiller will continue but the water will not be cooled. Instead, it will mix with the water from the chiller still operating and raise the supply water temperature. Chilled water that is warmer than the intended design temperature may not provide the necessary cooling or dehumidification in the building. Isolating a chiller with a valve will not provide flow to all the coils in a constant (3-way valve) flow system.

The setpoint for the chiller that is still operating can be lowered so that when its chilled water mixes with the chilled water bypassing through the chiller that is off, the desired (44°F) supply temperature is met. This increases the lift on the chiller and the work required to operate it. There is also a possibility that the chiller may stall or surge at the higher lift conditions.

The textbook solution is to operate both chillers all the time, even if the plant load is less that 50%. This means two chillers running whenever there is a load (hence the higher chiller energy consumption as compared to series chillers) and both condenser water pumps running all the time (hence the higher pump energy as compared to series chillers even though they have higher water pressure drops.)

The key issue to note here is that the energy consumption outcome was the opposite of what was indicated by looking at the design full load chiller performance!

What about variable primary flow?

Resolving the issue of how to shut down one chiller in a parallel arrangement when not required leads right into the idea of variable primary flow. Why not shut down one chiller, turn off the cooling tower fan and condenser pump, and close a valve to shut off the flow? To really make this work, the entire system must be converted to variable primary flow including 2-way valves at the terminal devices, bypass lines, variable flow pumps and so on. Table 3 shows the results of switching the Minneapolis office building to variable flow. The total energy consumption is a wash between parallel and series chillers and substantially better than constant flow. However, the system complexity is higher which results in more commissioning and greater demands on the building operator.

Table 3 – Series Versus Parallel Chiller Energy Analysis With Variable Primary Flow At ARI Conditions

System	Chillers kWh/yr	Chiller Pump kWh/yr	Cooling Towers kWh/yr	AHU Fans kWh/yr	Total KWh/yr
Parallel	258,938	79,877	17,618	422,629	779,062
Series	256,248	76,973	21,107	422,629	776,957

For basic two chiller systems, series chillers are a strong candidate. If more energy savings are desired, moving to either parallel or series chillers with variable primary flow is an excellent choice.

SERIES CHILLERS WITH HIGH CHILLED WATER DELTA Ts

Large delta T chilled water systems can reduce chilled water pump and pipe sizes, resulting in capital savings. They can also reduce chilled water pump work, resulting in operating cost savings. The supply water temperature may need to be lowered to strike a better balance between the air handling unit coil performance (deeper coils result in a higher air pressure drop) and chiller performance (higher lift results in reduced performance). Remember, the pump and pipe savings are connected to chilled water delta T – not supply water temperature. Several manufacturers suggest low supply water temperatures as a means to generate savings in pump work, which is simply wrong.

Table 4 shows series and parallel chiller selections based on 14°F delta T from 56°F to 42°F. The high delta T and low supply water temperature favor the series chiller arrangement as can be seen in the chiller performance.

Table 4 – Series Vs. Parallel Chiller Selections With 42°F Supply Temperature And 14°F Delta T

Chiller Model	Qty	Capacity (tons)	Performance (kW/ton)	NPLV (kW/ton) (kW)	kW input (ft)	Evap WPD (ft)	Cond. WPD
Parallel arrangement							
WCS 087	2	400	0.580	0.543	231.8	5.1	5.0
Total	2	800	0.580	N/a	463.6	5.1	5.0
Series arrangement							
WSC 079	1	320	0.589	0.553	188.6	6.1	5.0
WSC087	1	480	0.538	0.488	258.2	6.1	5.0
Total	2	800	0.559	N/A	446.8	12.2	5.0

Table 5 shows the annual energy costs for the HVAC equipment for the Minneapolis office building using 14°F delta T chilled water supplied at 42°F. The lower supply chilled water temperature allows air handling unit coils to be selected with the same air pressure drop as at ARI conditions. The result is no change in annual fan work.

Table 5 – Series Versus Parallel Chiller Energy Analysis With Variable Primary Flow With 14°F Delta T Chilled Water Supplied At 42°F

System	Chillers kWh/yr	Chiller Pump kWh/yr	Cooling Towers kWh/yr	AHU Fans kWh/yr	Total KWh/yr
Parallel	273,062	72,376	17,618	422,629	785,685
Series	260,907	68,102	21,107	422,629	772,745

When compared to ARI conditions, the series chiller annual energy consumption went up slightly, as would be expected. The increased delta T improved the annual pumping work by over 11%. Overall, the series chiller arrangement realized a modest improvement over the ARI design conditions. Taking into account the capital savings in chilled water pumps and piping, series chillers is an attractive option.

The parallel chiller annual energy consumption went up more dramatically. The chillers are not optimized by the parallel piping arrangement. The pump work savings are around 9% and the total energy consumption of the parallel chiller arrangement increased by almost 2% over the ARI design conditions.

As seen earlier, reviewing only the full load design performance does not show the complete picture. It's easy to conclude that the annual pump work would be the same for series or parallel chillers if the head and flows were identical. However, condenser pump staging and minimum flow for bypass (among other things) result in a 5% difference in annual energy usage. Looking at the chiller full load performance, the series chillers are slightly better by 3.8%. Reviewing the annual chiller energy consumption shows the series chillers outperformed the parallel chillers by 4.7%.

SERIES COUNTER FLOW CHILLERS

Figure 3 shows series chillers with the condensers piped in series counter flow to the chilled water. The arrangement enhances the chiller performance by "cascading" the chillers. Figure 4 shows the lift requirements for series chillers with parallel towers. Chiller 1 has a smaller lift because it sees the return chilled water. Chiller 2 has a higher lift because it cools the water to 42°F. Since both chillers have the same discharge pressure requirement (dictated by using 85°F-95°F condenser water), the chiller lifts are different.

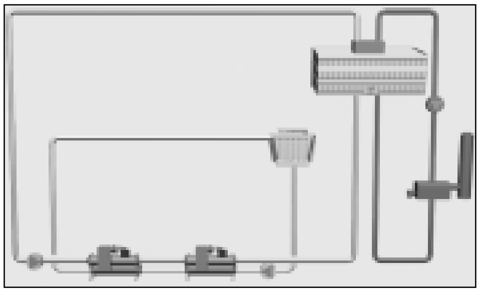

Figure 3 – Series Chillers With Series Counter Flow Condenser Arrangement

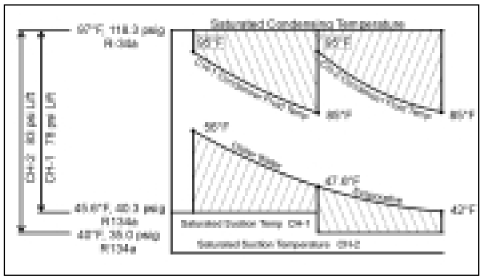

Figure 4 – Series Chillers, Parallel Towers Lift Requirements

Figure 5 shows the lift requirements for series counter flow chillers. Now chiller-2 sees a lower lift because the discharge pressure has been reduced as a result of the lower condenser water temperatures. The chiller lifts are almost balanced, which will always provide the best refrigeration performance.

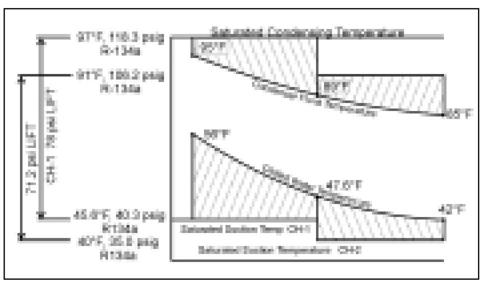

Figure 5 – Series Chillers, Series Towers Lift Requirements

Table 6 shows design performance for series counterflow arrangement vs. a single chiller. Cascading the lift requirement for the chiller plant improves the design chiller efficiency by almost 7% over a single chiller.

Table 6 – Series Counterflow Vs. Single Chiller With 42°F Supply Temperature And 14°F Delta T

Chiller Model	Qty	Capacity (tons)	Performance (kW/ton)	NPLV (kW/ton) (kW)	kW input (ft)	Evap WPD (ft)	Cond. WPD
Single Chiller							
WSC 100	1	800	0.586	0.561	469.1	7.8	5.0
Total	1	800	0.586	0.561	469.1	7.8	5.0
Series arrangement, series counter flow towers							
WSC 079	1	320	0.564	0.507	180.4	6.1	5.0
WSC087	1	480	0.536	0.480	257.3	6.1	5.0
Total	2	800	0.547	N/A	437.7	12.2	10.0

Table 7 shows the annual energy usage for series counterflow vs. single chiller. There is more than a 20% savings in chiller energy usage with series counterflow. Comparing series counterflow to series parallel cooling towers from Table 5 shows an increase in overall energy usage. Although the series counter flow chillers are more efficient, the additional pumping penalty negates the savings. The pump work increased because a single 2400 gpm condenser pump must operate whenever there is a chiller load as opposed to two 1200 gpm pumps staging on with the chillers. Again comparing the design full load performance of series parallel vs. series counterflow does not yield the expected results.

Table 7 – Single Chiller Energy Analysis Versus Series Counterflow Condenser Arrangements With 42°F Supply Temperature And 14°F Delta T

System	Chillers kWh/yr	Chiller Pump kWh/yr	Cooling Towers kWh/yr	AHU Fans kWh/yr	Total KWh/yr
Single	307,113	117,786	20,977	422,629	868,505
Series counterflow	254,850	89,992	21,107	422,629	788,578

SERIES COUNTERFLOW CHILLERS IN LARGE PLANTS

Large chilled water plants, used to service health care and institutional facilities or several office buildings in a downtown city core, are excellent candidates for high delta T, low supply temperature systems. Figure 6 shows a typical 3 chiller primary/secondary chiller plant. Figure 7 shows a six chiller series counterflow primary secondary plant.

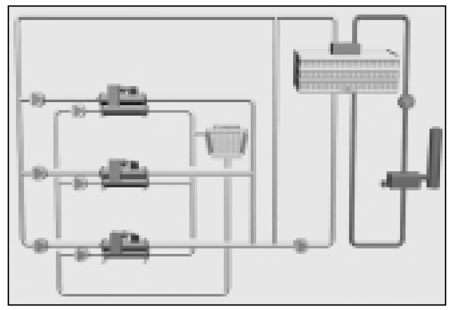

Figure 6 – Three Chiller Primary/Secondary Arrangement

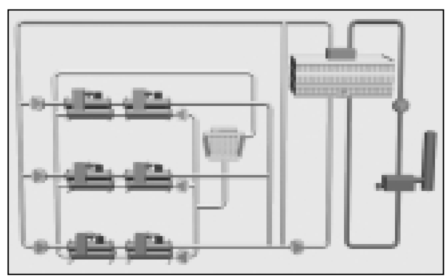

Figure 7 – Primary/Secondary Arrangement With Series Counterflow Chillers

Consider a 6,000-ton plant designed to service office buildings in a downtown city core. The system delta T is 18°F and the supply water temperature is 40°F. Table 8 shows the design chiller performance for both arrangements.

Table 8 – Series Counterflow Vs. Single Chiller With 40°F Supply Temperature And 18°F Delta T

Chiller Model	Qty	Capacity (tons)	Performance (kW/ton)	NPLV (kW/ton) (kW)	kW input (ft)	Evap WPD (ft)	Cond. WPD
Single Chiller							
WDC 126	3	2000	0.597	0.434	1194.0	32.2	22.1
Total	3	6000	0.597	N/A	3582	32.2	22.1
Series arrangement, series counter flow towers							
WSC 126	3	800	0.578	0.548	462.2	10	12
WSC126	3	1200	0.554	0.454	665.4	10	12
Total	6	6000	0.564	N/A	3382.8	20	24

The series arrangement offers a 6% improvement in design performance over a single chiller. To get the best performance for a single chiller, a three-pass arrangement was chosen. While this provides the best performance, it also raises the chilled water pressure drop above the two chillers in series with single pass evaporators.

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Table 9 shows the performance for a large chiller plant in downtown Minneapolis with a 6,000 ton design load. Using series counterflow chiller in lieu of single large chillers offers about a 5% improvement in energy usage.

Table 9 – Primary/Secondary Single Energy Analysis Versus Series Counterflow Condenser Arrangements With 40°F Supply Temperature And 18°F Delta T

System	Chillers kWh/yr	Chiller Pumps kWh/yr	Cooling Towers kWh/yr	Total KWh/yr
P/S Single	2,077,655	977,758	140,550	3,195,963
P/S Series counterflow	1,947,161	946,366	140,550	3,034,077

CONCLUSIONS

Series chillers are an excellent solution for smaller constant flow chiller plants. They resolve issues generated by staging chillers in a parallel system and they are easy to operate. Variable primary flow systems offer better energy performance, but they also increase system complexity.

In applications where high delta T and low chilled water temperature make sense, a series arrangement enhances chiller performance and can significantly improve overall chiller plant efficiency. Finally, for large chiller plants, integrating series counterflow chillers into primary/secondary systems offers one of the most efficient solutions.

In many instances throughout this article, the performance of the equipment at full load design conditions did not indicate which system would have the best annual energy usage. Drawing conclusions from full load kW/ton has potential flaws and there is no substitute for annual energy analysis.

For the purpose of making this article more universal for all readers, annual performance has been judged on annual energy usage (kWh/yr) rather than annual operating costs. It could be argued that demand and ratchet charges could change some of the outcomes, but not as much as one might expect. The McQuay Energy Analyzer™ program can provide operating costs as well as energy analysis. It can account for consumption, demand and ratchets. Again, there is no substitute for annual analysis.

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