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Series–Series Counterflow for Central Chilled Water Plants

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When a project is large enough to justify the evaluation of several prospective designs, engineers are more willing to explore new solutions to familiar challenges. Setting aside convention enables ideas to flow freely. The viability of prospective solutions can then be gauged using criteria such as life-cycle cost, simplicity, and first cost. The scale of a new central cooling plant located in Washington, D.C. was large enough to warrant this type of innovative engineering. Given the magnitude of the project, the owner elected to outsource the design, construction, and operation of the 10,500-ton (36 900 kW) chilled water plant to an energy service company.

Life-Cycle Cost

To ensure that the chilled water plant provided the owner with the best possible value, lowest life-cycle cost was chosen as the determining criterion for the plant's design. An independent financial consultant performed a cost analysis of each alternative to ensure an equitable comparison. Each of these analyses was based on a load profile *specific* to the plant. The profile was developed from the expected loads of the customer who had signed the contract to purchase chilled water. The primary cooling loads are from a convention center. In addition to significant weekday cooling loads, the center's meeting areas often are used on weekends. The loads are year-round. However, airside economizers reduce the need for mechanical cooling during many months of the year.†

The consultant developed a detailed spreadsheet to examine the life-cycle costs for the chillers, chilled water pumps, condenser water pumps, and cooling tower fans in each proposed design. The spreadsheet accounted for:

- Load profile,
- Ambient dry-bulb and wet-bulb conditions (Load does not vary directly with the dry bulb, but is internally driven. Wet-bulb temperature determines cooling-tower energy consumption at a given load.),
- Discount rate,
- 20-year service life,
- Installed, operating, and maintenance costs for chillers, pumps, and cooling tower fans (The method of accounting for pumping energy costs is discussed elsewhere in this article.), and
- A specific electric utility rate for the plant.

Fixed Parameters

As in most central chilled water plants, the initial costs for distributing the chilled water (pumps, piping) were considered critical. Using a larger-than-conventional difference between the entering and leaving chilled water temperatures permits a lower flow rate. Smaller pipes and pumps can then be used to satisfy the same capacity.[2,3] Based on that premise, the plant owner established these non-negotiable design parameters for the chilled water system:

- Entering-chiller water temperature: 55°F (12.8°C),‡
- Leaving-chiller water temperature: 37°F (2.8°C), and

†As can be the case when a third party performs an economic analysis, few details (including the actual plant load profile) were made available to the authors. Readers may find this frustrating—so did the authors. Although third-party analyses can ensure greater objectivity and "fair play" by the principals, full disclosure of the original data is necessary to verify the results and offer recommendations that might benefit the plant owner.

‡It may have been possible to achieve a higher entering chiller temperature, but doing so was not within the plant owner's direct control.

About the Authors

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Arrangement		Chillers#		Evaporator				Condenser				Cooling Towers		System	
Evaporator	Condenser	Units / Modules	Compressor Efficiency, kW/ton	Flow, gpm	ΔP, ft of Water	Number of Pumps	Power per Pump kW	Flow, gpm	ΔP, ft of Water	Number of Pumps	Power per Pump kW	Number of Cells	Power per Cell kW	Total Power, kW	Life-Cycle Cost, $ USD
Parallel	Parallel	5/5	0.649	2,800	3.26	5	2.18	4,200	3.66	5	3.67	8	60	7324	18,836,302
Parallel	Parallel	6/6	0.618	2,333	4.18	6	2.33	3,500	3.53	6	2.95	8	60	7001	18,076,391
Series	Series Counter-flow (1.5 gpm/ton)	6/3	0.560	4,667	17.96	3	19.99	5,250	14.8	3	18.54	8	48	6379	16,819,167
Series	**Series Counter-flow (2.0 gpm/ton)**	**6/3**	**0.535**	**4,667**	**17.96**	**3**	**19.99**	**7,000**	**25.2**	**3**	**42.08**	**8**	**60**	**6284**	**16,656,947**
Series	Parallel (2.0 gpm/ton)	6/3	0.555	4,667	17.96	3	19.99	3,500	3.53	6	2.95	8	60	6385	16,888,493

The chillers represented in this table all have two refrigerant circuits. The full analysis included single refrigerant circuit chillers at various flow rates and efficiencies.

Table 1: Comparison of projected life-cycle costs for central chilled water plant.*

- Flow rate/capacity: 1.33 gpm/ton (0.024 mL/J).

Certainly, supplying 37°F (2.8°C) rather than 40°F or 42°F (4.4°C or 5.6°C) chilled water would require more power from the chillers. Therefore, it was expected that the cost savings associated with reduced pumping power and pipe installation would offset any increase in chiller power. Historically, producing 37°F (2.8°C) water might have prompted concern that the low refrigerant suction temperatures would freeze the evaporator tubes. Experience shows that the advent of fast, accurate chiller controls and algorithms can safely accommodate temperatures as low as 34°F (1.1°C) without the addition of antifreeze.

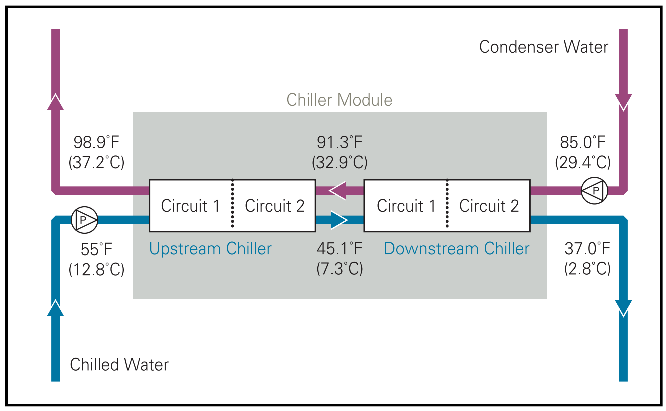

Figure 1: Series–series counterflow arrangement.

Selected Design

Various combinations of absorption chillers, electric chillers, and engine-driven generator/chillers were considered during the conceptual phase of design. The final evaluation examined 11 combinations of plant configurations and flow rates. Chillers with single compressors and dual compressors were examined, and manufacturers were allowed to submit cost and performance information for any configuration. Plant configurations ranged from four to nine chillers, and included proposals with:

- Both evaporators and condensers in parallel;
- Evaporators in series and condensers in parallel; and
- Both evaporators and condensers in series.

Table 1 shows five of the combinations that were examined. The system with the lowest life-cycle cost consisted of six electric centrifugal chillers with dual refrigeration circuits, that used 2 gpm (0.0358 mL/J) of condenser water per ton of cooling, and was piped in a "series evaporator–series condenser" arrangement.

As *Table 1* indicates, arranging the chiller evaporators in series reduced life-cycle costs by more than $1.4 million when compared with parallel arrangements. Series arrangements of chiller evaporators have been used, when prudent, in many applications.[7, 16] However, the chilled-water plant design that was selected for this project not only arranges the evaporators in series, but also arranges the condensers in series using a counterflow configuration (see *Figure 1*). At design conditions:

- Chilled water enters the upstream chiller at 55°F (12.8°C) and exits at 45.1°F (7.3°C).
- Chilled water enters the downstream chiller at 45.1°F (7.3°C) and exits at 37°F (2.8°C).

Condenser water flows in the opposite direction of the chilled water, thus the term "counterflow:"

- Condenser water enters the downstream chiller at 85°F (29.4°C) and exits at 91.3°F (32.9°C).
- Condenser water enters the upstream chiller at 91.3°F (32.9°C) and exits at 98.9°F (37.2°C).

Chiller Energy Consumption

A chiller's power demand reflects the amount of lift provided by the compressor. "Lift" describes the difference between evapo-

* gpm × 0.0631 = L/s; gpm/ton × 0.0179 = mL/J; ft of water × 2.99 = kPa

rator pressure and condenser pressure:

Evap. Refrigerant Temperature = Lvg. Chilled Water Temperature – Evap. Approach Temperature

Cond. Refrigerant Temperature = Lvg. Cond. Water Temperature + Cond. Approach Temperature

At saturation, these temperatures relate directly to the refrigerant pressures in the evaporator and condenser.

It is clear from *Table 1* that the series–series counterflow arrangement yields the lowest full-load chiller power (about 14% lower than the parallel–parallel configuration). The dramatic reduction in chiller power occurs because the upstream chiller in the series–series counterflow arrangement operates at a higher chilled water temperature, which means that the refrigerant temperature and refrigerant pressure in the evaporator are also higher in the upstream machine. Similarly, the downstream chiller "sees" a lower condenser leaving water temperature—and therefore has a lower condenser refrigerant pressure—than it would in a plant with the chiller condensers arranged in parallel.

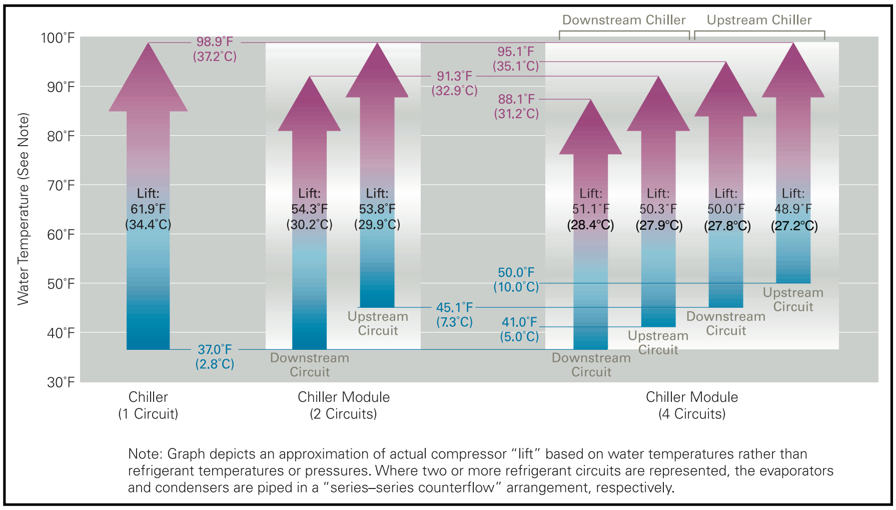

Figure 2: Conceptualization of reduced lift.

Figure 2 illustrates the concept of reduced lift using the design parameters for this chilled water plant. Although lift is the difference between the *refrigerant pressures* in the evaporator and condenser, its magnitude can be approximated using the difference between the *water temperatures* leaving the evaporator and condenser. Chiller power can be reduced by decreasing compressor "lift." In this case, the difference in average lift at design is approximately 13%:

$$1 - \{[(54.3 + 53.8)/2]/61.9\} = 0.126$$

The reduction in lift provided by the series–series counterflow arrangement also occurs at part-load conditions. Why? The temperature of the water leaving the evaporator of the upstream chiller is always warmer than the system water, and the temperature of the water leaving the condenser of the downstream chiller is always cooler than the system water. Because each of the chillers in this design has two refrigeration circuits (*Figure 1*), the reduced lift effect is multiplied. Instead of two lifts, there are four (*Figure 2*). Therefore, the difference in average lift at design for the system with four independent refrigeration circuits in a series–series counterflow arrangement exceeds 19%:

$$1 - \{[(51.1 + 50.3 + 50.0 + 48.9)/4]/61.9\} = 0.191$$

The upstream chiller need not be equally loaded at all times; the anticipated savings come from that chiller's ability to produce chilled water at an elevated temperature. (When this article was written, the plant had not operated through an entire cooling season.) How the plant should respond to varying system conditions was discussed with the design engineer, plant owner, and plant operators. For example, if the entering chiller water temperature did not reach design conditions, the operators could:

- Increase pump speed or the number of active pumps to increase flow rates through, and fully load, the active chillers.
- Reset the setpoints of the upstream chillers to 55% of the total temperature difference. Lowering the setpoint of the upstream chillers as the result of a drop in entering-chiller water temperature lessens the benefit of reduced lift. However, the upstream chillers will always run at a higher evaporator pressure than the downstream chillers, which saves energy consumption and costs.

Chiller sequencing was also discussed. It was determined that the most cost-effective startup strategy would fully load one chiller module, and then activate the remaining chillers in modules (pairs). Activating the upstream chiller and operating it at the higher water temperature would take advantage of all of the available heat-transfer surface area without increasing the energy consumed by ancillary equipment.

At the design conditions defined for the system, chiller performance is well below the 6.10 COP (0.576 kW/ton) requirement set by ANSI/ASHRAE/IESNA Standard 90.1-2001, *Energy Standard for Buildings Except Low-Rise Residential Buildings*. At standard ARI rating conditions, each chiller module would operate with an efficiency of 0.445 kW/ton.[†] The performance conditions for this application, however, were carefully selected to optimize the *overall* energy consumption of the entire chilled water plant.[1]

† Standard ARI rating conditions are 44°F, 2.4 gpm/ton (6.7°C, 0.043 L/s per kW) for the evaporator and 85°F, 3 gpm/ton (29.4°C, 0.054 L/s per kW) for the condenser.

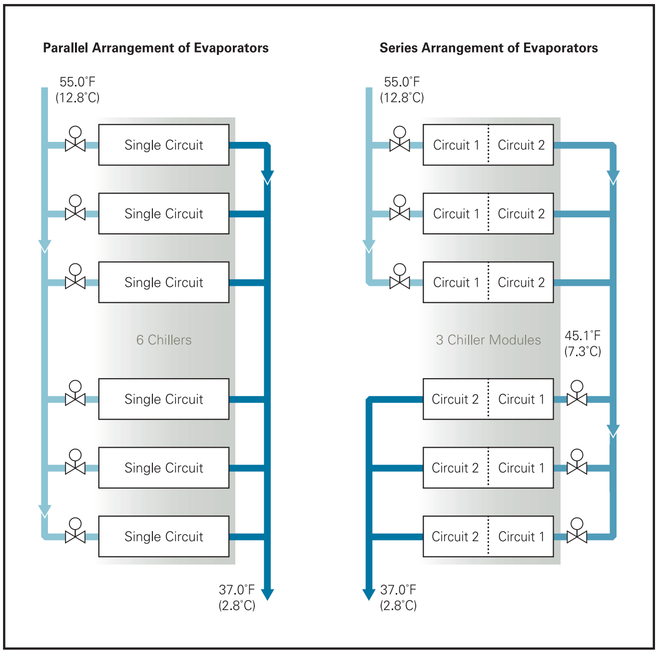

Figure 3: Comparison of evaporator layouts.

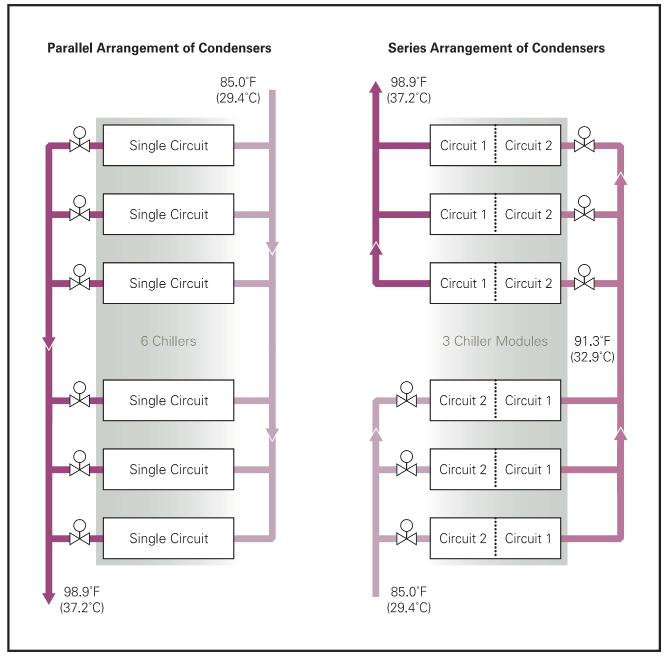

Figure 4: Comparison of counterflow condenser layouts.

Focus on the System

The reduction in chiller power comes at the expense of increased pumping energy. With the utility meter measuring the consumption of the entire plant—not the chillers alone—the ultimate goal must be to reduce *plant* power. Would the series–series counterflow arrangement reduce the compressor power enough to make up for the increase in pump power? *Table 2* compares the overall power consumption for the chilled water plant based on three different arrangements of six chillers. In each case, the condenser-water flow rate is 2 gpm/ton (0.0358 mL/J).

Chilled Water Pumps. The five chilled water pumps in this design are piped in a manifold arrangement; one of the pumps is redundant.

Arrangement			Pumps			
Evaporator	**Condenser**	**Chillers**	**Chilled Water**	**Condenser Water**	**Cooling Tower**	**Total Plant**
Parallel	Parallel	6,489	14	18	480	7,001
Series	Parallel	5,827	60	18	480	6,385
Series	**Series Counter-flow**	**5,618**	**60**	**126**	**480**	**6,284**

Table 2: Comparison of power requirements (kW) at identical rates of condenser water flow.

Doubling the water flow through the evaporators created a water pressure drop that was significantly higher for the series arrangements than for the parallel configurations (*Table 1*). To minimize this "penalty" as much as possible, single-pass tube bundles were used in the series evaporators. Otherwise, the pressure drop and resultant pump power would have been even higher. Despite the high water pressure drop, reducing compressor lift by arranging the evaporators in series yielded chiller power savings that dwarfed the additional pump power needed at full load.

To further offset the economic impact of larger chilled water pumps, the plant design also varies primary flow through the chiller evaporators in response to system load. The "pump penalty" still exists at full load. However, it is significantly less at part load/partial flow because the differences in evaporator pressure drop and chilled water pumping power decrease rapidly as the flow rate slows. Combining variable primary flow and a series arrangement of evaporators circulates twice as much water through the evaporator of each chiller. This combination also creates a second advantage: each chiller can accommodate a much greater reduction in water flow, which postpones the need for a system bypass. (Use of variable primary-flow systems is increasingly common and well documented.)[4–6,9,11–12,14–15,17]

Condenser Water Pumps. The condenser water pumps are piped in a manifold arrangement. In the selected plant configuration, one active pump is provided per chiller module. Redundancy is provided by two smaller pumps, which enables one of the pumps to operate during low-load conditions and reduce pumping energy consumption. This is described later.

Basing an economic comparison of design alternatives on life-cycle costs requires an overall summation of the total costs for power (demand) and energy (consumption). Therefore, although the total *power* for the series–series counterflow plant was lowest (*Table 2*), it was also necessary to account for the costs related to energy consumption.

Water flow rates and configurations for the chiller condensers were evaluated in a manner similar to that used for the chilled water loop. When the results were compared, the life-cycle cost analysis (*Table 1*) pointed to a system design that combined a series arrangement of the chiller condensers with a condenser water flow rate of 2 gpm/ton (0.0358 mL/J). Choosing this design permitted a smaller cooling tower and reduced the size of the condenser piping. It also reduced the initial and operating costs of the cooling tower fans and condenser water pumps.[8,10] As *Table 1* reveals, arranging the condensers in series significantly increased the pressure drop and required pumping power. Yet, the savings in chiller (compressor) power and energy offset this penalty, too.

A further reduction in flow rate to 1.5 gpm/ton (0.268 mL/J) was also examined and would provide an even greater reduction in tower fan power, but the plant owner did not allow any pipe cost for flow rates below 2 gpm/ton (0.0358 mL/J). Nor did the owner account for pump savings due to cooling tower height and static lift requirements. Although the effects of variable condenser water flow were considered, the owner decided that constant flow would simplify plant operation.[‡]

Space Considerations. The selected design for the chilled water plant provided one chilled water pump and one condenser water pump for each chiller module. Two redundant pumps were provided as well: one for the chilled water loop and one for the condenser water loop. Collectively, these components occupy less space than a comparable primary–secondary system. Some variable primary-flow systems use fewer pumps than chillers to further reduce the space required for piping connections, variable speed drives, and electrical service for the pumps.

Clarifying the Economics

During the design phase, the owner sought to better understand the relationship between the operating characteristics of the series–series counterflow arrangement and the projected savings in life-cycle costs. Several questions of particular relevance are paraphrased here, along with their answers:

Q: Won't piping the chiller condensers in series, rather than in parallel, result in a significantly higher operating cost?

A: Arranging the condensers in series does increase the pumping power per chiller module by 36 kW at full load, given the increased condenser pressure drop of 22 ft (66 kPa). However, the *compressor* power reduction per module is 69 kW, which far exceeds the 36 kW increase in pumping power. Remember, too, that the series–series counterflow arrangement *always* reduces the required amount of compressor "lift," even when the plant operates at part load. Sequencing the constant-volume

[‡]The authors of this article speculate that the decisions made by the plant owner represented a "comfortable" compromise between the series–series counterflow arrangement, which was economically sensible but unfamiliar, and other more conventional (and familiar) aspects of chilled water plant design.

condenser pumps makes it possible to reduce flow to the modules as the load decreases. This control strategy significantly reduces pumping energy consumption when the plant operates at less than 50% of full-load capacity.

Q: Because the chillers are started in pairs, the series–series counterflow arrangement of this design requires two, four, or six chillers at load conditions while a parallel–parallel configuration would only require one, three, or five chillers. Did the analysis account for this difference in pumping energy?

A: Deciding to minimize the number of condenser water pumps used when three chiller modules operate led to the use of three large condenser pumps for this plant. All pumps operate whether the condensers were piped in parallel or in series. To save pumping energy when only one chiller module operates (that is, during "winter" load hours), the system is designed to supply only 3,500 gpm (220 L/s) of condenser water. Supplying two smaller pumps (rather than one large pump) for redundancy allowed this. In low-load conditions, only one of the smaller pumps is run. The manufacturer confirmed that the chillers would operate properly at half of the design condenser water flow.

Q: Compared with a parallel configuration, won't the series–series counterflow arrangement of chillers require awkward and more costly bypass piping and valves around each condenser and evaporator?

A: Operating chillers in pairs is a concept. As such, the series–series counterflow arrangement can be implemented by piping both loops, condenser and chilled water, in a similar manner to the more familiar parallel system. Such arrangements (*Figure 3, Figure 4*) provide virtually the same serviceability and redundancy, regardless of whether the chillers are piped in parallel or in series, unless all of the upstream chillers are simultaneously off-line for service.

With either arrangement (series or parallel), the system will run out of capacity at peak load if one chiller is not in service. Flow through the operating chillers can be increased until the pumps no longer have enough power. However, after system load exceeds chiller capacity, the chilled water setpoint will not be maintained.

Conclusions

The series–series counterflow (series evaporators–series condensers) design required discussion and resolution of potential drawbacks, however, an independent analysis of life-cycle costs demonstrated that the series–series counterflow arrangement was the most cost-effective solution for this central chilled water plant.

Since this project was awarded, at least two other chilled water plants have adopted similar configurations. The application discussed here was large (more than 10,000 tons [35 170 kW] of mechanical refrigeration), but the series–series counterflow concept can be, and has been, successfully applied to much smaller jobs. The same design challenges will be encountered and can be overcome when it makes economic sense.

In all cases, remember that the utility meter is on the building. The building owner pays the costs (demand plus consumption) of installing, maintaining, and operating the entire system—chillers, chilled water pumps, condenser water pumps, cooling tower fans, and controls. Analyze the actual load profile at ambient conditions to determine which design yields the lowest life-cycle cost.

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