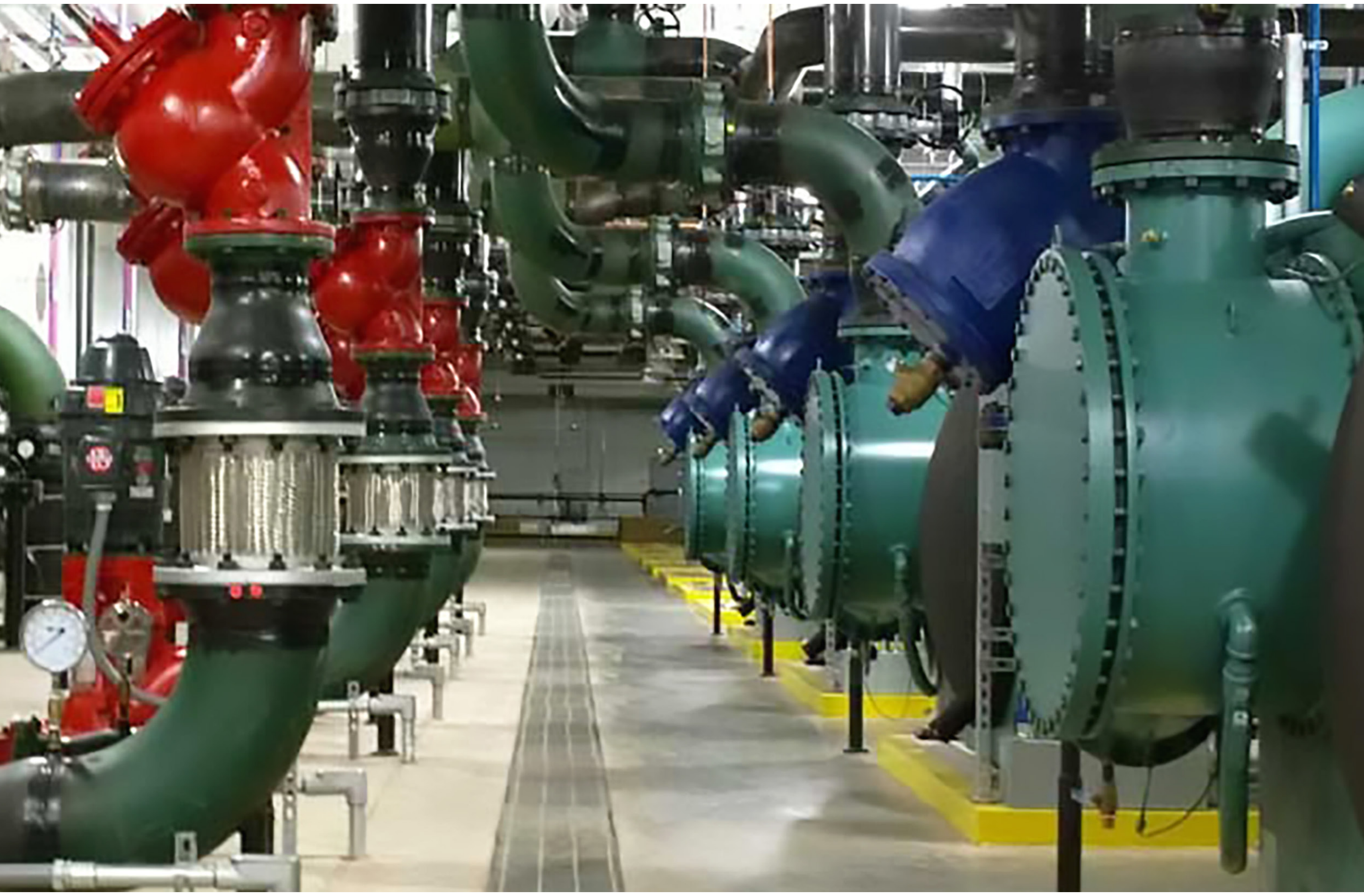
YORK

White Paper

# Series Counter-Flow

## Improving system efficiency with an advanced piping scheme



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# Introduction

In today's environment of energy conservation, engineers and owners are looking for building designs to decrease the overall energy consumption of the mechanical cooling system and improve the building comfort level. Chillers have become exponentially more efficient due to the advent of:

- magnetic bearings
- improved compressor aerodynamics
- new heat exchanger designs

These new improvements require the chilled water system to be evaluated more extensively since chillers are nearing the efficiency limit. One of the many system modifications that has the ability to improve efficiency greatly, is the use of a chiller piping strategy called "Series Counter-Flow (SCF)". This document will evaluate the impact of SCF on efficiency while keeping in mind what it requires on the building controls side as well as plant design (piping arrangement). This document will be directed toward water-cooled centrifugal chillers predominately but is not limited to centrifugal chillers.


# Efficiency

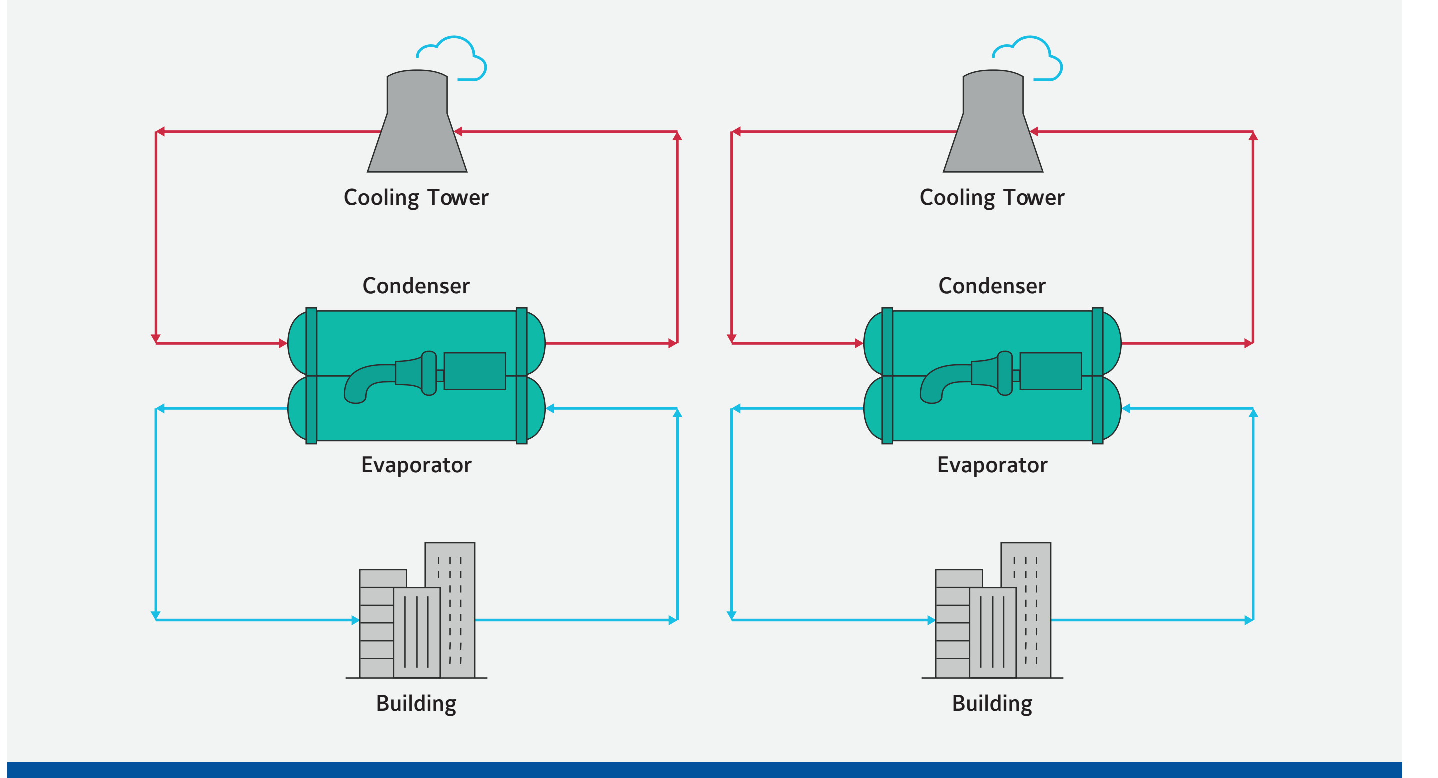


**Image 1: Illustrates two chillers in a parallel arrangement.**

In a typical chiller design involving multiple chillers, the chillers are set up in a "parallel" scheme where each chiller is equally sized. This would require the chillers to provide an identical chilled water set point and a dedicated cooling tower per chiller (headered towers and pumps are possible and recommended). This system design is most common in the industry due to the simplicity of the controls, plant layout and chiller configuration. Image 1, illustrates a typical plant design for two chillers in a parallel scheme.

A chillers efficiency level is based on the amount of power (kilowatt – kW) that is consumed to produce an output of chiller cooling capacity (tons of refrigeration). The amount of kilowatts consumed is dictated by both lift and the percent load on the chiller. Lift, the amount of work the chiller has to overcome, has a much bigger impact on the efficiency of the chiller than that of percent load. Lift can be calculated by taking the difference between the leaving condenser water temperature and the leaving evaporator water temperature (the lower the lift the more efficient the chiller becomes).

Using water temperatures is an approximation in today's industry because the tube efficiency has become very advanced in which to minimize the approach or small temperature difference (difference between the water temperature and refrigerant saturation temperature). Today's tube can have an approach of 1 degree (or less in some instances), therefore a true measurement of lift is calculated based on the difference in the condenser saturation temperature and the evaporator saturation temperature.

The industry standard for chiller conditions is set by AHRI (Air-Conditioning, Heating & Refrigeration Institute), at which they certify performance on chillers. The industry standard for conditions is the use of water in both the evaporator and condenser. The evaporator temperature split of 54°F [12.22°C] (entering) with 44°F [6.67°C] (leaving) and the condenser temperature split of 85°F [29.44°C] (entering) and 94.3°F [34.61°C] (leaving). Examine Image 2, each 500 ton [1758 kW] chiller within the parallel system has a “Lift” of 51°F [10.56°C]. This is calculated by the difference in the leaving condenser water, of 95°F [35°C], and the leaving evaporator water, 44°F [6.67°C].

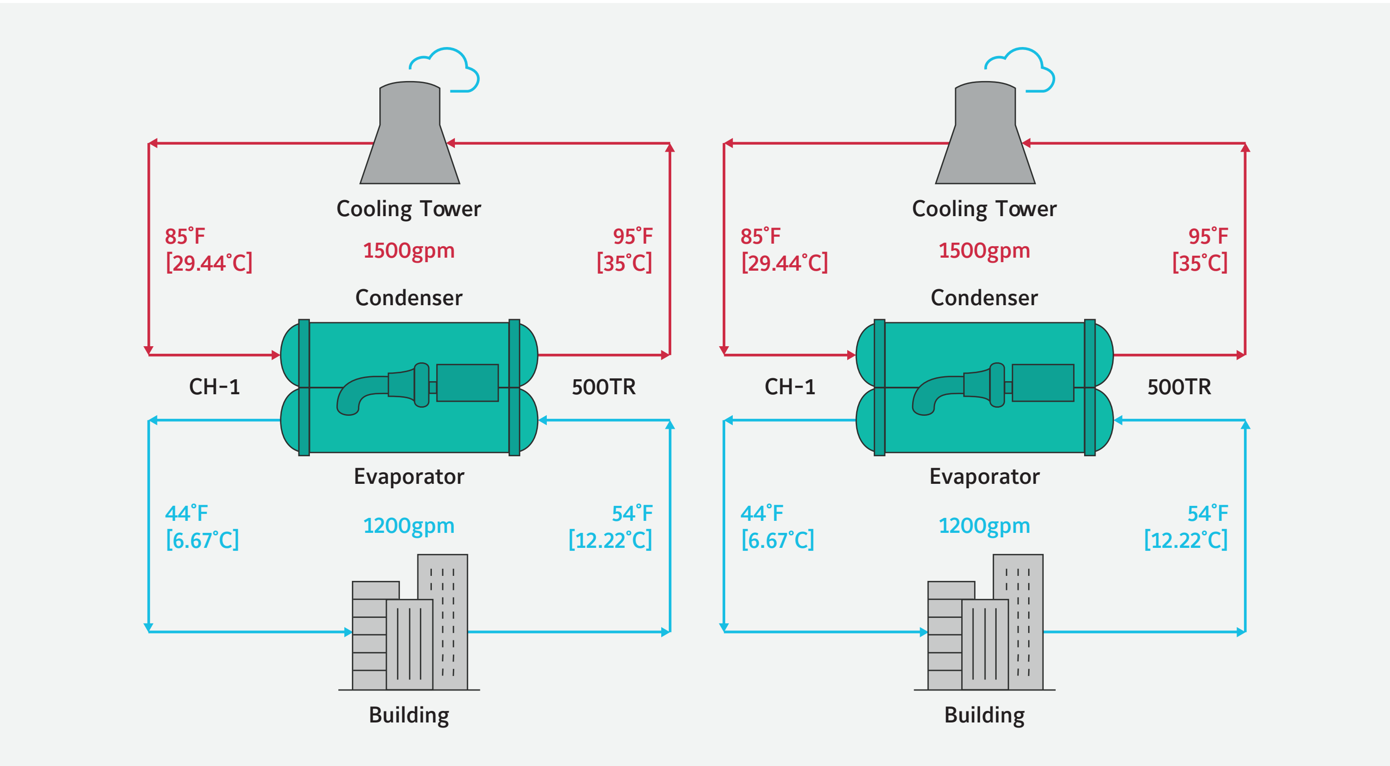


**Image 2: Lists the conditions seen across each chiller in a SCF arrangement**

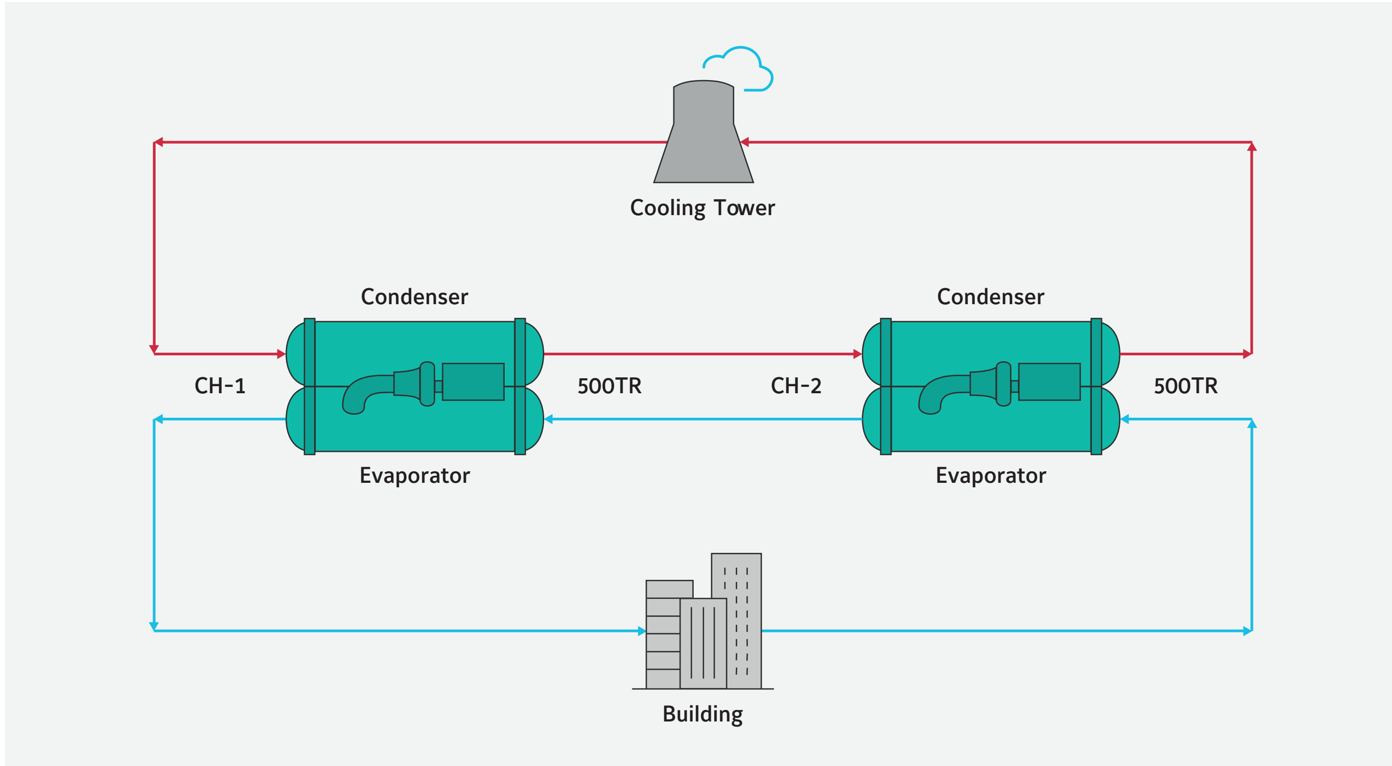


**Image 3: Illustrates two chillers in a series counter flow arrangement.**

For the parallel system, the plant is seeing 1000 tons [3516 kW] at 44°F [6.67°C] chilled water temperature to the building (i.e. the buildings required cooling is met). Now when series counter-flow is chosen from a plant design we take the same two 500 ton [1758 kW] chillers (typically they are identical in configuration) and re-pipe the flow of water differently.

As the condenser water enters chiller 1 (CH-1) it will then procced to chiller 2 (CH-2) directly after in the same direction. The opposite is happening with the evaporator side, the flow is going from CH-2 to CH-1 but in the opposite direction of the condenser flow (counter-flow). The direction of flow is key for SCF as piping the flow in a common direction will yield not as high as energy savings. CH-2 is commonly called the high side chiller or hot side chiller due to the leaving condenser water being warmer than that of the leaving condenser water of CH-1. CH-1 is commonly called the low side chiller or cold side chiller, due to the leaving chilled water being colder for CH-1 compared to CH-2 chilled water temperature. Image 3, previously shown, is a common system set up for two chillers in a series counter-flow arrangement for 1000 ton [3516 kW] cooling load.

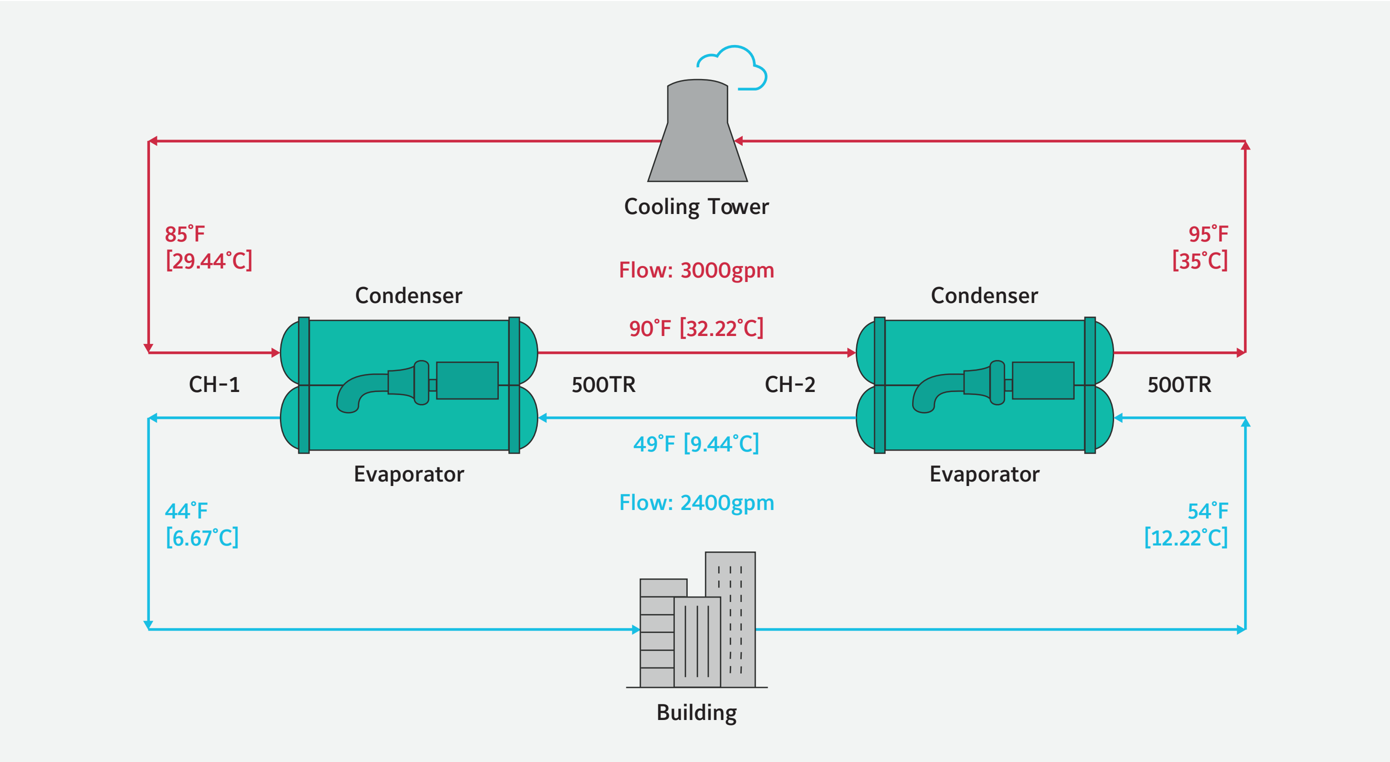


**Image 4: Details the entering and leaving water temperatures of two chillers piped in a SCF arrangement.**

A series counter-flow arrangement offers efficiency savings by decreasing the lift of each chiller within the pair. This can be seen in Image 4. When evaluating the leaving water temperatures of CH-1, the lift on CH-1 is no longer 51°F [10.56°C] (what the parallel system has), instead CH-1 now has a lift of 46°F [7.78°C] (this is reflective by the difference in leaving condenser water of 90°F [32.22°C] and leaving evaporator water of 44°F [6.67°C]). By continuing to evaluate the system, CH-2 is also seeing a reduction in lift to 46°F [7.78°C] (this is the difference in leaving condenser water of 95°F [35°C] and leaving evaporator water of 49°F [9.44°C]). Overall, with the reduced lift on each chiller within the SCF pair, the overall pair of chillers becomes 6-8+% more efficient, thus yielding energy savings to the owner over the life of the equipment (20-30+ years).

# Piping

Piping arrangement will be the largest modification to the mechanical space design and this is due to flow passing from one chiller to the other. In a parallel arrangement the piping of both chillers is commonly connected to a header for the building flow. The piping of one chiller does not impact that of the other chiller in a parallel system. When it comes to piping chillers in a SCF arrangement, there is no limitation to the layout of the chillers.

The chillers could be positioned:

- next to each other like a typical parallel system (chiller barrels side by side with proper clearances),
- staggered
- in line with one another sharing a common tube pull space between them or not

All these layouts can be seen in Image 5.

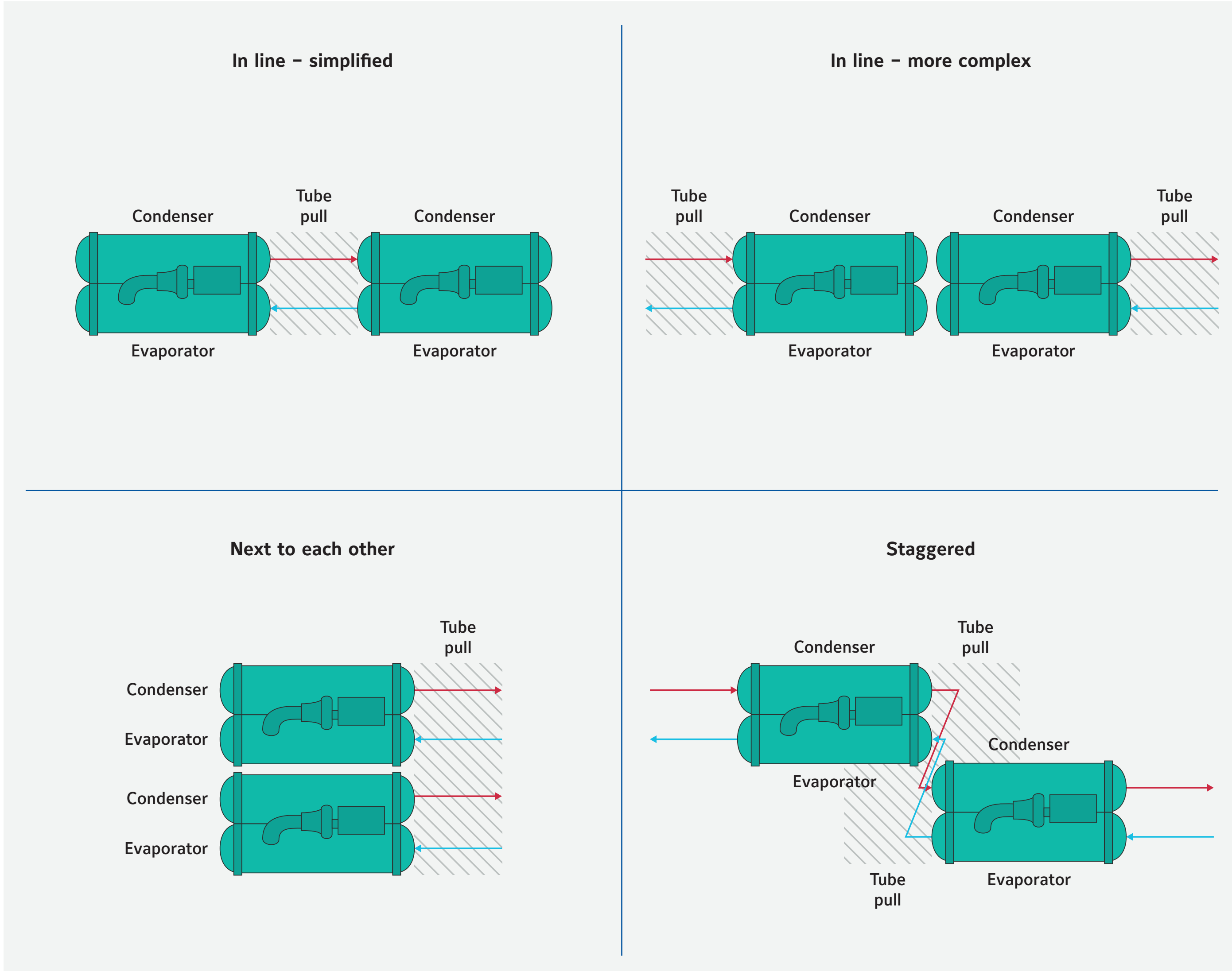


**Image 5: Illustrates different chiller layouts that are possible when dealing with a SCF system.**

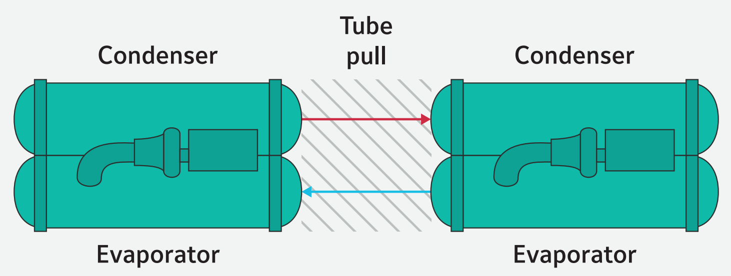


**Image 6: Illustrates the optimal chiller layout when trying to minimize space**

The most advantageous layout is to position them in line with one another with a space (length of the barrel) in between the chillers (this can be seen in Image 6). This is the most optimal chiller layout for SCF because the chillers are sharing the tube pull clearance space where in the other layouts it would be necessary to plan on additional footprint for tube pull clearance. In addition, for any of the piping schemes, it is recommended (not required) that marine water boxes (MWB) be utilized.

These are recommended because the piping connections are at the top of the water box and assist in routing water pipe closer to the ceiling (out of the way for walking paths and providing easier access for maintenance). This is illustrated in the below image (Image 7).

Marine water boxes also assist in making tube cleaning easier as the water connections do not need to be removed to clean tubes (a cover plate is removed to access the tubes.

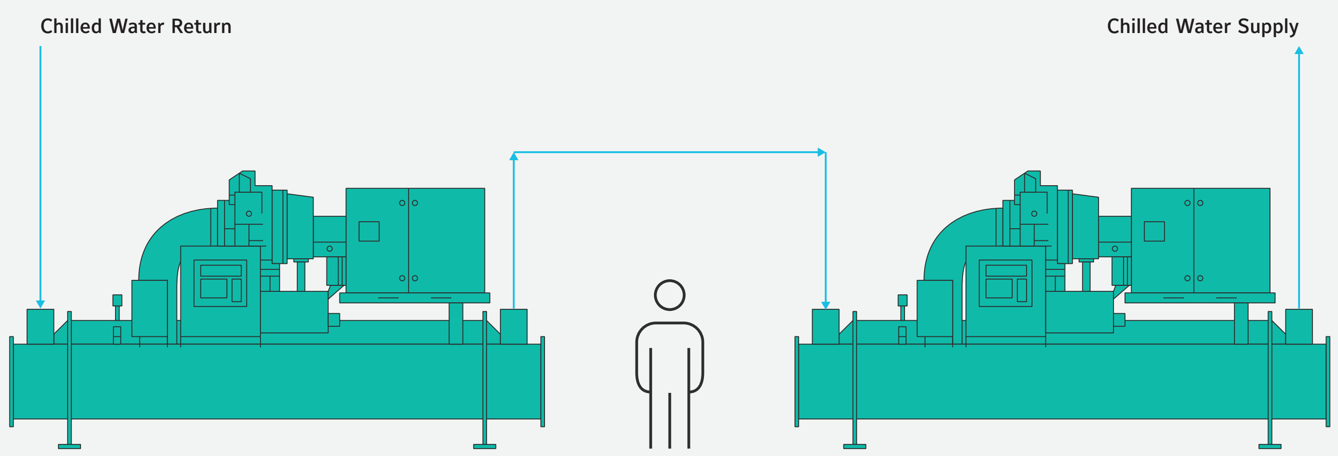


**Image 7: Shows an image of one piping scheme that can be utilized with the use of marine water boxes on the chillers.**

| | Parallel Arrangement | SCF Arrangement |
|---|---|---|
| Pass Arrangement (evaporator / condenser) | 2 pass / 2 pass | 1 pass / 1 pass |
| Evaporator PD (ft) | 22.1 | 22.8 |
| Condenser PD (ft) | 19.5 | 19.3 |

**Table 1: Describes the pressure drop, of the same chiller models with minor water box changes, each chiller in a parallel system vs a SCF chiller system**

The next piping consideration is the use of a one pass water box. It is very common for a parallel arrangement, each chiller will have a 2 pass water box due to the ten degree temperature split across the shell. Since each chiller is now only seeing a five degree temperature split per chiller (54°F/44°F [12.22°C/6.67°C] split across the pair of chillers), a 2 pass water box is not commonly needed (but is possible). The benefit to a one pass water box are to minimize the pumping requirement of the system (one pass water box have a lower pressure drop than a two pass water box for the same flow rate). The below, breaks down the difference in pressure drop for a parallel system (with two pass water boxes) versus a SCF arrangement (with one pass water boxes) of a specific chiller model.

With the pressure drops being very similar, the pumping energy favors the SCF arrangement. Why the SCF arrangement actually has pumping energy savings is due to larger pumps with larger motors (larger motors are more efficient than smaller motors). This also leads to only needing two pumps for the SCF system rather than four smaller pumps for a parallel system of two chillers. So although the water pressure drops between the systems are similar, total energy spend will be less in a SCF arrangement due to larger motors.

For higher chilled water delta T, other pass arrangements can be used. For example, in a twenty degree temperature split (64°F/44°F [17.78°C/6.67°C]) a two pass water box would be more advantageous. Each design and application should be evaluated individually.

Lastly, bypass valves should be recommended to isolate a chiller that is being serviced or a chiller that is in an off position. A bypass provides a flow path around the off chiller where the water is only going through the running chiller. However, YORK YK, YMC² and YZ chillers can allow flow through them even in a non-running chiller but please check with other chiller vendor's products on their recommendation about passing flow through an "off" chiller. The additional bypass valves is the one downside to the SCF arrangement as this is a minor added cost to the installation.

# Controls

With the implementation of series counter-flow into a plant design, the chiller control sequence must be evaluated on multiple levels. These levels include the staging of chillers when the load increase/decreases within the building, as well as set-point control (depending on your pumping strategy) for each chiller.

If the system is using a primary pumping strategy (dedicated primary or primary/secondary) then the controls becomes slightly more complex. In Image 9, the design conditions on the evaporator are a ten degree delta T (54°F/44°F [12.22°C/6.67°C]) for a 1000 ton [3516 kW] SCF pair (each chiller is 500 tons [1758 kW]).

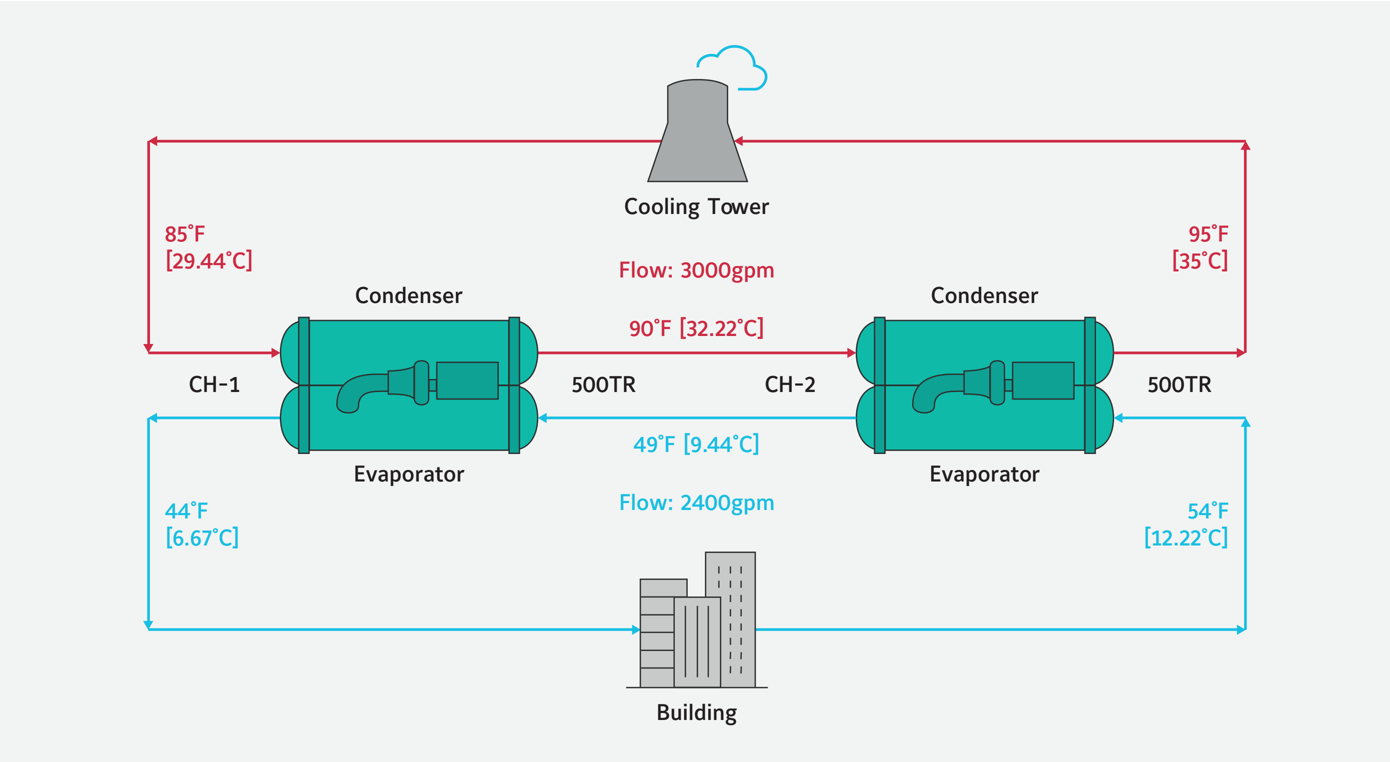


**Image 9: Depicts a 100% design condition with constant flow on the evaporator and condenser for a 1000 ton SCF pair.**

With a design scenario being ideal for ease of controllability, this is not reflective of how the system will operate. The system will only see this design condition less than 1% of the year (reflective of the hottest point in a given year), which is stated by AHRI (Air-Conditioning, Heating, and Refrigeration Institute). The BAS/controls now has to understand the controls strategy of CH-1 and CH-2 as the load decreases within the plant. Image 10 is reflecting a system that is operating at 50% load (500 tons [1758 kW] required by the system on a design wet bulb day).

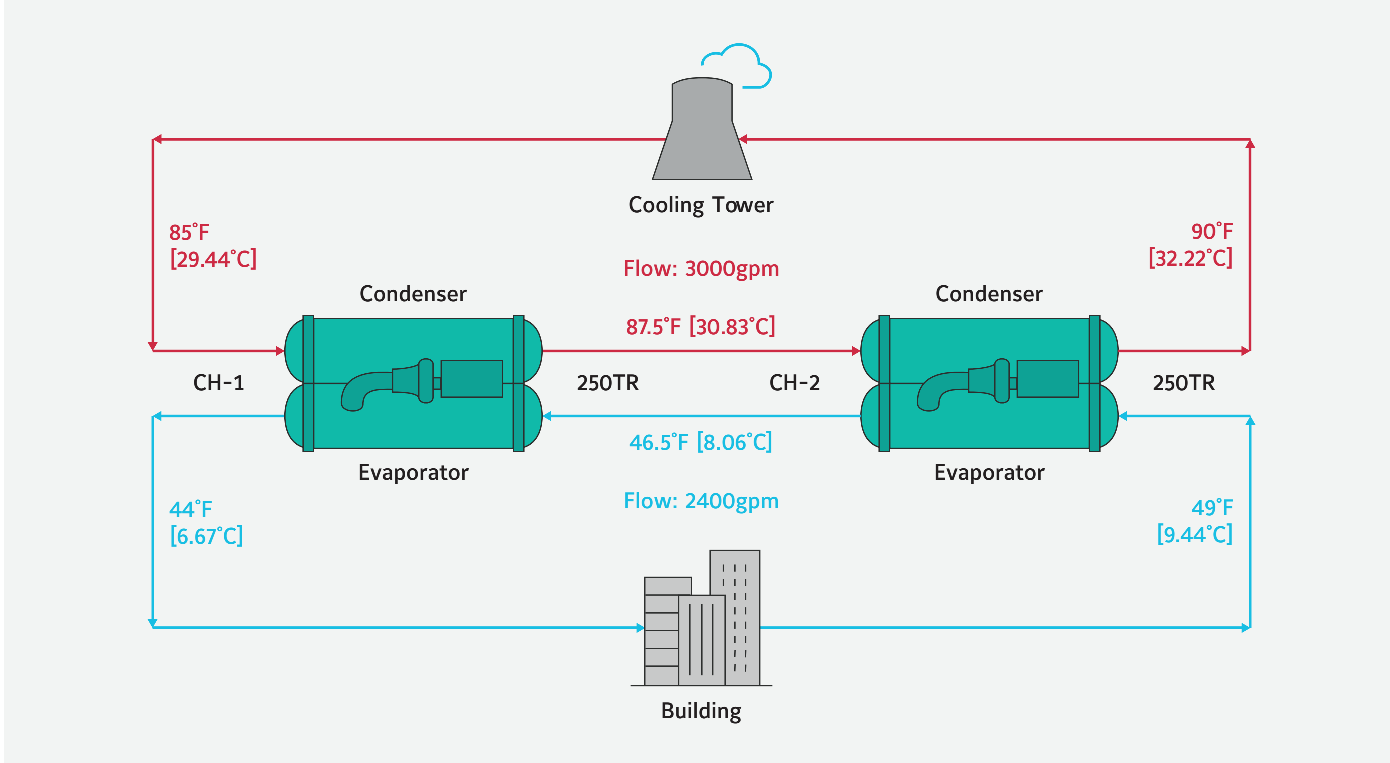


**Image 10: Depicts a 50% design conditions with constant flow on the evaporator and condenser for a 1000 ton SCF pair.**

CH-1 primary purpose is to produce a chilled water set-point of 44°F. CH-1 will continuously meet the set point of 44°F [6.67°C] regardless of load, since it is the low side chiller. The new chilled water set point for CH-2 is 46.5°F [8.06°C] at a 50% load point on the system. This change in set point happens due to the fact that the delta T across the chiller shrinks with the load. The BAS needs to accommodate the new chilled water set point, by evaluating the chilled water return and adjust the leaving water set point of CH-2 correspondingly (as the return temperature drops the leaving chilled water needs to drop as well). This can be easily set up within the BAS system. A common approach is when the return water decreases by 1 degree (Fahrenheit) the leaving chilled water set point on CH-2 will decrease 0.5 degree (Fahrenheit).

If the system is using a VPF (variable primary flow) pumping scheme the chiller controls becomes simpler. This is due to the varying flow rate on the evaporator side resulting in the delta T of the two chillers, in series counter-flow, to be constant. This alleviates any chilled water set point changing on CH-2 since it will be maintaining a 49°F [9.44°C] chilled water set point (this is the case for the example above with a 54°F/44°F [12.22°C/6.67°C] split on the chillers evaporators). The only time a modification would need to be done to the chilled water set point on CH-2, would be when the minimum flow of the chillers' evaporator is met (this will cause the delta T to change from the initial 54°F/44°F [12.22°C/6.67°C] evaporator split). Depending on the load and lift seen by the chillers, it may be in the interest of the plant optimization to turn off one of the chillers. This can be evaluated with performance reports per the manufacturer. Image 11, describes a 100% load scenario when using VPF with the corresponding flow rate for a 1000 ton SCF pair. Image 12, describes the same SCF pair but at a 50% system load. Please note that the flow rate is changing while the delta T across the chillers remains constant (this is due to VPF).

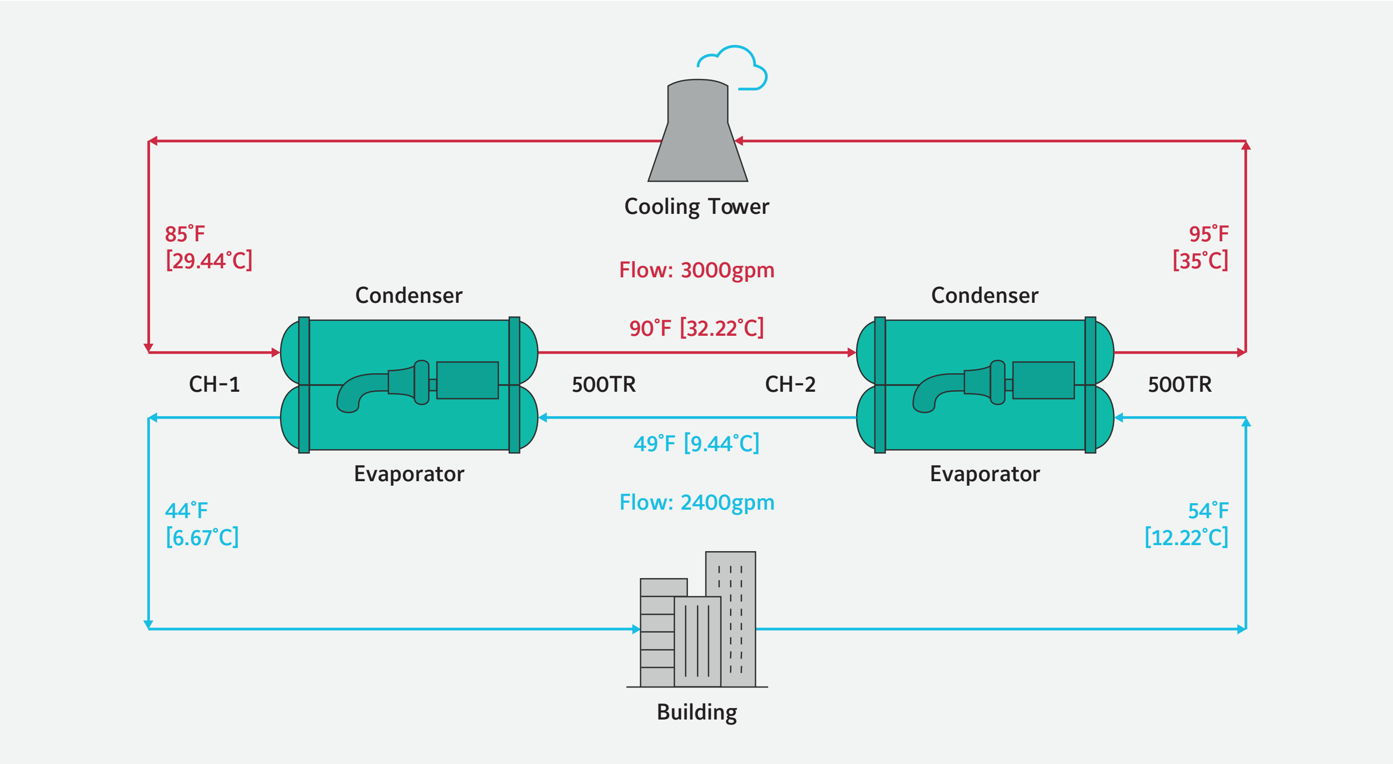


**Image 11: Illustrates the 100% design conditions with VPF on the evaporator and constant flow on the condenser for a 1000 ton SCF pair.**

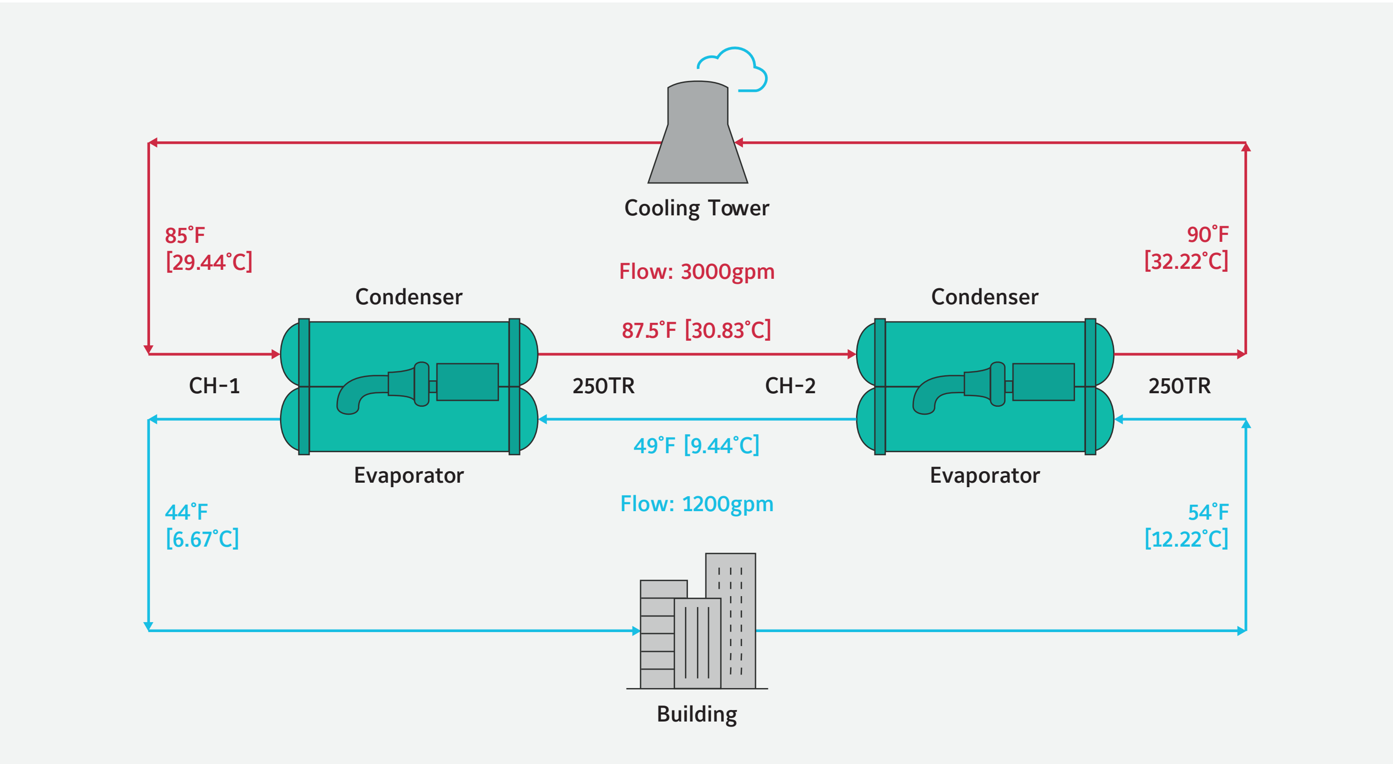


**Image 12: Illustrates the 50% design conditions with VPF on the evaporator and constant flow on the condenser for a 1000 ton SCF pair.**

# Reliability

It is important that the SCF design does not negatively impact the life of a chiller. A common question that gets asked about SCF is "am I not adding run hours now on both chillers, where as I can lead lag chillers more often in a parallel system? i.e. distribute run hours across two chillers?" This question is common as it is pertaining to hourly based maintenance that some chillers are required to perform. For some chiller manufactures, their centrifugal chillers require a "compressor teardown". A compressor teardown is needed to inspect the wear on gears, bearings and driveline assembly. These teardowns are commonly needed at 40,000 hours, thus approximately five years if the chiller is running 24/7 or approximately ten years if the chiller is running half the day. The primary issue with this maintenance item is that there is a high cost to perform this maintenance. On the scale of $40,000 - $60,000 per compressor (please reach out to service department for quotes regarding this maintenance item for your market). So if you have two compressors or two chillers running all the time then it is possible to have a maintenance bill of approximately $100,000 every 5-10 years. YORK chillers do not share this approach on chiller design.

YORK, oil based chillers, utilize an oil lubricated journal bearing (oil film separating the metal components so they never touch, ever) that has an L10 life (bearing life measurement) of infinity, thus never needing an hourly based routine maintenance item for a compressor teardown. This reliability item is also carried over on the YORK magnetic bearing chillers, since the driveline is magnetically levitated never having a metal to metal contact (L10 life of infinity). Please always check with your chiller chiller manufacturer to determine this cost prior to chiller design and schedule. By not having these costly hourly based maintenance items, series counter-flow offers a system that is just as reliable as a parallel scheme with improved efficiencies.

# Other Chiller Types

Series counter-flow is most advantageous to water-cooled centrifugal chillers due to the ability to use colder tower water temperature more so than other compressor technology. However, this does not restrict the use of series counter-flow for a system that has screw compressor chillers or scroll compressor chillers. With the restriction in tower water to approximately 65°F [18.33°C] ECWT (with screw and scroll technology) you do not get as great as savings as you would with centrifugal chiller (that can use 40°F-50°F [4.44°C-10°C] ECWT). Also certain heat exchangers design, such as a DX (direct expansion) evaporator or brazed plate heat exchangers are used on scroll chillers and when put in series (two chillers), the water pressure drop increases significantly since they do not have an option for 1 pass. If there are further questions about putting air-cooled chillers or other water-cooled chillers in series or series counter flow, please reach out to your Johnson Controls Sales Representative to discuss further.

# Conclusion

Series counter-flow is one of the many items that can be implemented on a new or older plant (SCF can be retrofitted to existing plants) to lower the total energy bill of the system. With a piping layout change and updating building control sequence it is possible to save 6-8+% efficiency on the chillers themselves. With the advent of variable speed drives and magnetic bearing technology we can take SCF to greater heights in improving system efficiency with the ability to utilize 40°F [4.44°C] entering condenser water (40°F [4.44°C] ECWT can also be utilized in a parallel arrangement too). If you have any questions or concerns, please reach out to your local Johnson Controls Sales Representative to find out more on how series counter-flow can be implemented into your current project or plant designs.

# Appendix

| | YMC² – Parallel Arrangement | YMC² – SCF Arrangement | % Improvement |
|---|---|---|---|
| Full Load Eff (kW/ton) | 0.5340 | 0.5026 | 5.88% |
| NPLV (kW/ton) | 0.3113 | 0.2908 | 6.59% |
| Pass Arrangement | 2 pass / 2 pass | 1 pass / 1 pass | -- |
| Evaporator PD (ft) | 15.6 | 16.4 | |
| Condenser PD (ft) | 13.1 | 14.1 | |

**Energy comparison**

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