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# Avoiding Centrifugal Chiller Surge

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Centrifugal chiller surge puts strain on many parts of the compressor (e.g., seal, bearing, blades). Severe damage can occur if the compressor is unable to handle it. Eventually, if no actions are taken, surge will result in chiller damage.

Most designers and operators that have worked around centrifugal chillers have experienced the violent nature of a surge condition in the compressor. This month, I provide some background on this operating condition and discuss what causes surge and ways to avoid it in your chiller plant design and operation.

## Chiller Refrigeration Basics

It is important to have a basic understanding of what is happening inside a centrifugal chiller. A centrifugal chiller uses the vapor compression cycle to chill water and reject the heat through a condenser. The condenser could be air-cooled or water-cooled. *Figure 1* shows a basic refrigeration cycle consisting of an evaporator, compressor, condenser and expansion device. Normal refrigerant flow through the system should be from compressor to condenser to evaporator and back to the compressor.

The evaporator in a centrifugal chiller is usually a shell and tube heat exchanger that removes heat from the entering chilled water and lowers its temperature. Chillers typically use a flooded type evaporator meaning the chilled water is in the tubes that are completely submerged in the refrigerant. The refrigerant pressure

remains constant in the evaporator as the refrigerant changes from liquid to gas. Evaporator approach is the difference between evaporating temperature measured at the well in the evaporator, and leaving chilled water temperature.

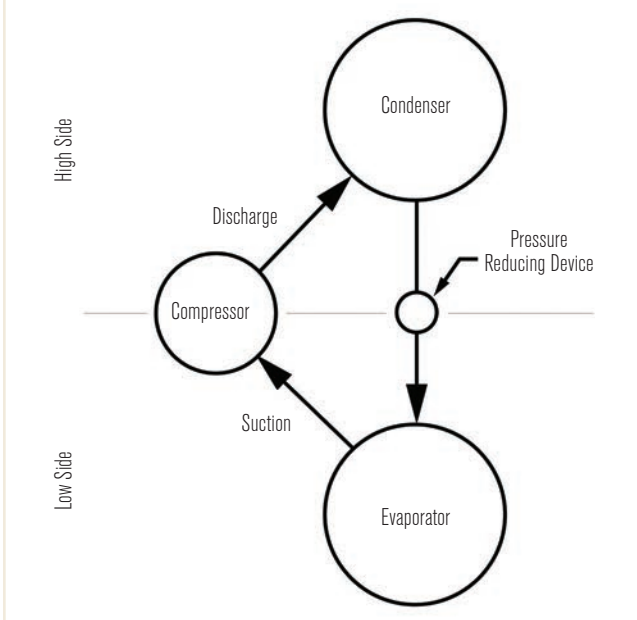
The centrifugal compressor physically moves and compresses the refrigerant and raises both the refrigerant pressure and temperature. Lift is the difference between condenser refrigerant pressure and evaporator refrigerant pressure. The condenser removes the heat from the refrigerant gas causing it to condense to a liquid where it can be rejected to water through a cooling tower or through an air-cooled condenser. The refrigerant remains at a constant pressure in the condenser. Condenser approach on a water-cooled chiller is the difference between the liquid refrigerant temperature and the leaving condenser water temperature.

After the refrigerant condenses to a liquid, it passes through a pressure-reducing device that today is usually a thermal expansion valve, electronic modulating expansion valve or orifice. The expansion device reduces liquid refrigerant pressure to cause change

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FIGURE 1 Basic chiller refrigeration cycle.



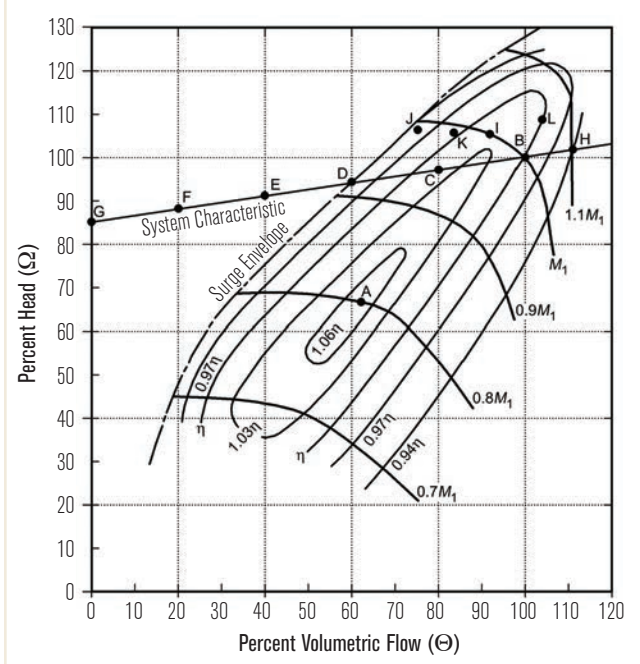
of state from a liquid to a mixture of vapor and liquid entering the evaporator—where the cycle begins again.

Inlet guide vanes are used to control the capacity of the compressor. As the inlet guide vanes start to close they change the gas entry angle to the impeller and reduce gas flow and compressor capacity. Variable speed compressors can also control compressor capacity, to some extent, by reducing the compressor speed. This changes the impeller tip speed. As the tip speed is lowered, the lift the compressor can produce is lowered. On variable speed chillers, the chiller controller monitors the operating conditions and uses a combination of the inlet guide vanes and speed control. In general, speed control is used until any further drop in speed will produce insufficient lift. Beyond that point, inlet guide vanes regulate capacity.

### Chiller Surge

It is useful to recognize that a centrifugal compressor is not a positive displacement compressor. A positive displacement compressor does not surge, it simply continues to move refrigerant at higher and higher lift as long as the power is available and the pressures are within the ability of the compressor to move without breaking. A centrifugal compressor, by contrast, relies on kinetic energy and when the combination of tip speed, refrigerant volume and lift means that there is insufficient kinetic energy to achieve lift, then the refrigerant will

FIGURE 2 Typical compressor performance curves.



reverse direction just long enough to ease the pressure in the condenser, thus lowering the lift. The refrigerant direction will continue to cycle back and forth as the compressor provides insufficient lift.

Surge is a dynamic instability that occurs when the refrigerant flows backwards through the compressor wheel every few seconds until the pressure builds up and the refrigerant moves forward again. Surge conditions create excessive radial vibration, a banging sound on the compressor casing, loud screeching sounds (think screaming banshee), extreme changes in motor current and violent fluctuations in the discharge pressure.

To understand surge it is best to review a typical centrifugal compressor curve as shown in Figure 2,<sup>1</sup> where percent of rated head (lift) is plotted with efficiency contours against percent of rated refrigerant gas volumetric flow at various speeds. Surge points are the peak points on the compressor characteristic curves. Point A is the design point at which the compressor has maximum efficiency. Point B is the selection or rating point for which the compressor is being applied to a particular system. The system characteristic line is the system load line. The slope of this line is a function of the reduction in lift as load decreases. Lift often decreases as load decreases due to reduced condenser temperature, e.g., due to lower concurrent ambient dry-bulb temperatures

(air-cooled) or wet-bulb temperatures (water-cooled), an increase in evaporator temperature, e.g., if supply water temperature is reset upwards at lower loads, or a combination of the two. Many situations can occur where lift does not reduce significantly as load diminishes, particularly in multiple chiller installations where chiller staging does not directly relate to rate of change in ambient conditions. Examples would include data centers and process loads.

Like a centrifugal fan curve, the area to the left of the surge envelope represents unstable compressor operation. This means that if the compressor is required to operate with higher lift at a given volumetric flow, or at a lower volumetric flow at a given lift, such that it is above the surge line the compressor will surge.

Chillers subject to excessive surge will eventually experience damage and failure. When refrigerant gas flows backwards through the compressor it pushes against the rotating assembly. The rotating shaft can slam into the thrust bearing and the thrust bearing can experience excessive wear or damage. Excessive surge can lead to eventual impeller structural failure. Impeller structural failure can cause impeller fragments to end up in the condenser and even damage condenser tubes.

Centrifugal chillers are vulnerable to surge at part-load conditions and/or high lift conditions as shown in *Figure 2*. The author has seen many instances of centrifugal chiller surge and evaluated chillers that have had catastrophic failures from continued surge. The catastrophic failures investigated have always been due to continued surge over long periods of time without appropriate action to correct the conditions that led to surge. One instance was due to a low refrigerant charge, but most instances are due to the chiller being required to operate with a lift that is above the surge line.

Surge is also unfortunately common when poor chiller staging logic and/or a need for more primary loop flow causes too many chillers to be brought on-line at relatively low loads in primary-secondary arrangements. Surge limits must be considered in new “all-variable speed” plants where additional chillers are brought on-line in an attempt to increase system efficiency. When condenser water flow rate is reduced the leaving condenser water temperature (which sets the condenser refrigerant temperature and pressure) rises—so surge

can also be experienced if condenser water flow rate is reduced too quickly when the outdoor air wet-bulb temperature is high.

The most common causes of surge usually involve one or a combination of the following conditions:

**Poor Chiller Selection/Application**

- Chiller forced to operate at lower load with high lift.
- High lift chiller (ice-making machine) selected too close to the surge line.

**Water-Cooled Condenser**

- Low condenser water flow.
- Scaled condenser increasing condenser approach.
- Underperforming (e.g., due to scale or air recirculation) cooling tower, or unusually hot/humid weather, increasing CWS temperature.

**Air-Cooled Condenser**

- Low condenser airflow.
- Underperforming (e.g., due to scale or air recirculation) condenser, or unusually hot weather, increasing condensing temperature.

**Evaporator**

- Low evaporator water flow.

**Refrigerant**

- Low refrigerant charge.
- Non-condensable gas in refrigerant.

**Design Tips**

Simple attention to detail in equipment selection can minimize the risk of subjecting the centrifugal chiller to surge. In most applications understanding the minimum system load expected when the plant is installed and sizing the smallest centrifugal chiller with a compressor that can unload to meet the minimum load without surging is the best option. This is especially important when the plant is built in the early stages of a large multi-year development with an initial low minimum cooling load.

The designer should verify the expected running conditions by requesting the manufacturer to provide part load information of the chiller down to the low load condition at the expected entering condenser water temperature to confirm the machine can operate at these conditions. Requesting minimum chiller load at the design entering condenser water temperature allows the design team to verify possible surge conditions. Be cautious of chiller selections that only show part load information with ambient relief. AHRI Standard

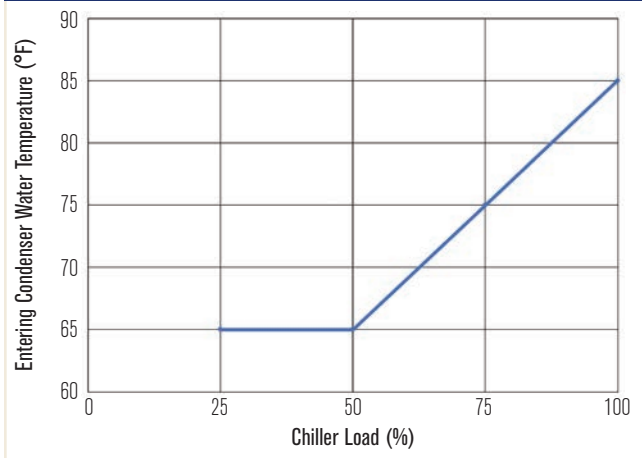
550/590<sup>2</sup> part-load entering condenser water conditions are based upon a lift reduction vs. load relationship that might be typical of a single chiller installation in a commercial building. The more chillers that are present, the less likely the AHRI relief assumptions are to reflect reality. For example, a water-cooled chiller with AHRI relief would assume the chiller will have 65°F (18°C) entering condenser water when operating at 50% cooling load as shown in *Figure 3*.

Selecting chillers that can operate at a constant entering condenser water temperature may require more heat transfer surface area but will also increase efficiency. Another option is selecting a chiller at entering condenser water temperature a few degrees above the design conditions. While this reduces design efficiency a little, it may allow the chiller to stay out of surge and on-line even in unusually hot weather, which can occur given the fact that weather design conditions are seldom at the annual extremes, and may become even more common due to climate change.

Hot gas bypass can be used to maintain a minimum refrigerant gas volume flow rate through the compressor to avoid surging during low load conditions but is inefficient and should be avoided in water-cooled chillers whenever possible. Inefficient operation is the reason ASHRAE/IES Standard 90.1-2016 limits hot gas bypass to 10% of chiller capacity for chillers greater than 20 tons. 10% hot gas bypass may not be enough to avoid surge. Hot gas bypass recirculates hot discharge refrigerant from the compressor back to the evaporator. The refrigerant passes through a hot gas bypass valve to reduce the pressure. It is typically used in process applications where the chiller is not allowed to cycle while the system maintains a constant chilled water supply temperature from zero load to full load. It is also used in air-cooled centrifugal chiller applications and sometimes referred to as a load balance valve where it can be used to false load the evaporator in low load situations or decrease the pressure ratio between discharge and suction pressures during high head conditions caused by high ambient temperatures.

Since low condenser water flow or undersized cooling towers lead to increased lift, proper cooling tower selection and condenser water flow can help avoid surge. Select the cooling tower for the highest ambient wet-bulb condition expected and provide adequate head in

FIGURE 3 AHRI Standard 550/590 ambient relief.



the condenser water pump selection to ensure the condenser flow at least meets the chiller selection requirement. Installing cooling towers in a manifold offers the operational flexibility to reduce chiller lift at part load by running more cells.

### Operational Tips

Plant control logic<sup>3</sup> should be designed to minimize the chance for surge to occur, which also often enhances energy performance at the same time. For instance:

- Chilled water supply temperature should be reset upward at low loads to reduce lift. The reset logic should be based on chilled water valve position, as required by Standard 90.1, to ensure coils are not starved, which can result in loss of temperature and humidity control.
- Condenser water supply temperature should be reset downward, where possible, based on ambient conditions to reduce lift.
- Staging points for variable speed chillers must be adjusted as a function of current operating lift. It is well known that variable speed chillers can be more efficient at low load and low lift, but staging on more chillers to operate at low load can push the chillers into surge if the current lift is not low enough.
- Minimum tower flow must be maintained at the rate recommended by the tower manufacturer to ensure the fill remains fully wetted at the air entry, thus avoiding scaling on the fill which will decrease tower efficiency over time. The optimum control logic for cooling towers is to enable as many cells as possible without causing flow to fall below the recommended minimum.
- If condenser water flow rate is being reduced

dynamically, avoid reducing the flow rate when the outdoor air wet-bulb temperature is high.<sup>4</sup>

Maintenance is critical for chiller plants. Following the manufacturer's recommended maintenance will avoid many problems. Actively trending and monitoring evaporator and condenser approach temperatures using the chiller plant control system can help avoid surge conditions. Proper water treatment and annual condenser cleaning will keep condenser approach temperatures near design conditions. When condenser approach goes beyond what is originally designed (0°F to 3°F [0°C to 2°C]), condenser pressure will increase.

When troubleshooting a surge condition, verify the chiller has the proper flow and entering condenser water conditions for the load condition experiencing surge. The chiller manufacturer can assist with troubleshooting the surge conditions by providing conditions at which the chiller can operate and not surge. It is very important to not let the compressor surge condition continue without action.

## Concluding Remarks

Designers and operators are likely to experience centrifugal chiller surge. Based on decades of experience with chiller plants using centrifugal chillers, it is best if chillers are selected and their auxiliary systems are designed to prevent compressor surge. Proper control sequences and maintenance practices can also minimize the chances of surge occurring, usually enhancing energy efficiency at the same time. Understanding what causes surge and how a centrifugal chiller operates will help designers and operators avoid or correct this situation.

## References

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