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ENGINEERING

SYSTEM SOLUTIONS

As energy costs continue to rise, high efficiency HVAC systems and sustainable building design have become both practical and popular. In Edition 21 of Engineering System Solutions, Designing Green Does Not Have To Cost More *(October 2004), we demonstrated that greater returns can be generated by pursuing savings in fan energy versus chiller energy. However, because they represent the largest single motor in a building, saving energy on chillers represents an irresistible opportunity.*

In this newsletter, we present one such opportunity – using a variable frequency drive (VFD) on a centrifugal chiller. In the right application with the right load profile, adding a VFD to a centrifugal chiller can help achieve significant energy savings with a simple payback in less than three years.

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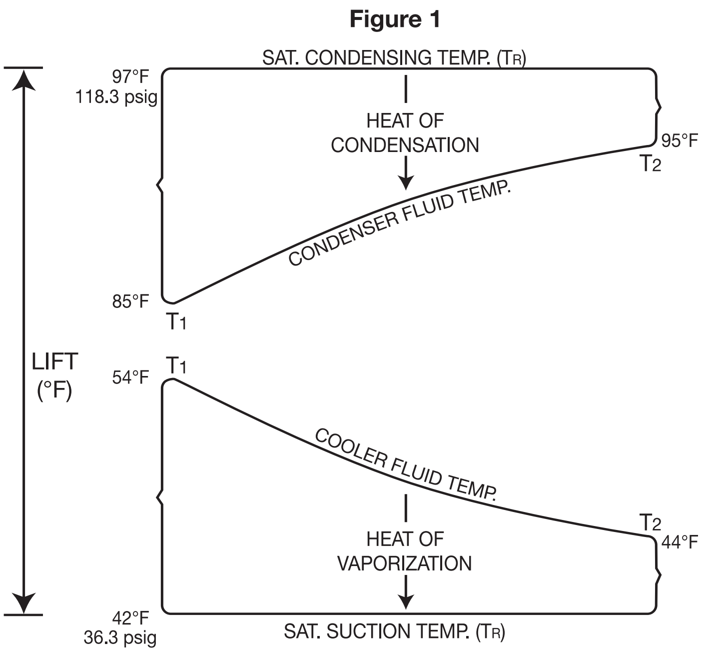
Saving Energy With a Centrifugal Chiller and a VFD

The cost for large horsepower Variable Frequency Drives (VFD) continues to decline, making their application on centrifugal chillers more economically viable. *For the right conditions,* a VFD can contribute to outstanding improvements in part load performance with a very favorable payback. Because centrifugal chillers spend most of their operating time at part load, the operating savings can offset the higher cost of a VFD. A simple refresher on how a centrifugal chiller operates will help set the stage for our payback discussion.

Centrifugal Compressor Refresher

Centrifugal compressors convert velocity pressure to static pressure to complete the refrigeration cycle. The compressor impeller rotates to generate the required velocity pressure to move refrigerant from the evaporator to the condenser. The speed at which the impeller rotates is referred to as “tip speed”. The higher the lift (the velocity pressure required to overcome the static pressure of moving refrigerant) the faster the refrigerant must travel. Figure 1 shows the required lift at ARI conditions.

Figure 1 – Required lift at ARI conditions.



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For centrifugal chillers using HFC-134a, the condenser pressure at 97°F is 118.3 psig. The evaporator pressure at 42°F is 36.6 psig. At these conditions, the compressor must provide a lift of 81.7 psig.

Imagine a ball on the end of a string that you are swinging above your head in a circular motion. The faster you swing the ball, the further it will travel when you let go of the string. The same is true for a centrifugal compressor. The faster the tip speed, the more lift it will generate. If the tip speed is not sufficient to meet the lift requirements, the chiller will stall or surge, causing it to shut down due to the instability of the conditions.

While this explanation describes what happens at full load, this is only one point in the operating cycle of a centrifugal chiller. The majority of chiller operating hours are at part load conditions. At part load, some sort of capacity control must be included to avoid flooding the evaporator with refrigerant, resulting in inefficient operation.

Centrifugal Chiller Capacity Control

Capacity control is accomplished in one of two ways when a centrifugal chiller operates at part load. For chillers without a VFD, inlet guide vanes are used to modulate the refrigerant flow. The vanes are located at the inlet to the impeller and look like inlet guide vanes on a fan. As the vanes begin to close, they impart a pre-swirl effect on the refrigerant gas. This efficiently lowers the capacity of the compressor. Further closing of the vanes "throttles" the refrigerant flow through the impeller by imposing more pressure drop and less pre-swirl.

Figure 2 shows the efficiency curves of a chiller without a VFD. Although inlet guide vanes would improve these efficiency curves slightly, Figure 2 demonstrates that as the lift is decreased, the system moves from an efficiency of 87%, down to about 70% efficiency at 75% refrigerant flow. That's a 20% drop in compressor efficiency.

Centrifugal chillers with a VFD also have inlet guide vanes that operate the same as a chiller without a VFD. The VFD works by slowing the impeller down. As the impeller slows, the lift capability of the compressor is reduced. This allows the chiller to more exactly match the lift requirements of the load at any given time.

Figure 3 explains why chillers with a VFD have much better part load values. The efficiency curves are much larger because the chiller is able to more exactly match the load. Therefore, as lift on the chiller is decreased, the efficiency of the compressor stays within the same 87% efficiency curve down to about 75% refrigerant flow.

If the condenser water temperature stays constant, chillers with or without a VFD will operate the same, using their inlet guide vanes to control capacity. For this reason, chillers that operate at full load a majority of the time, or applications in climates that do not have a wide range in wet-bulb temperature, are poor choices for a VFD. An example would be a hot, humid climate, such as Miami, FL, where the wet-bulb is relatively constant. In this case, the condenser water temperature stays relatively constant and the inlet guide vanes will provide sufficient capacity control.

Climates where the condenser water temperature decreases due to wet-bulb relief are ideal for a VFD. Referring back to Figure 1, condenser water temperature clearly affects lift. A reduction in condenser water temperature means less compressor work is required, which reduces the lift. These reduced lift conditions, where the wet-bulb is lower than design wet-bulb, occur throughout the year in many climates. Figure 4 shows the average wet-bulb temperatures in 4 major cities in warmer climates in North America.

What about the efficiency at full load?

An often debated point about chillers with a VFD is the efficiency of the chiller at full load. The line losses of the

Figure 2, Centrifugal compressor efficiency without a VFD

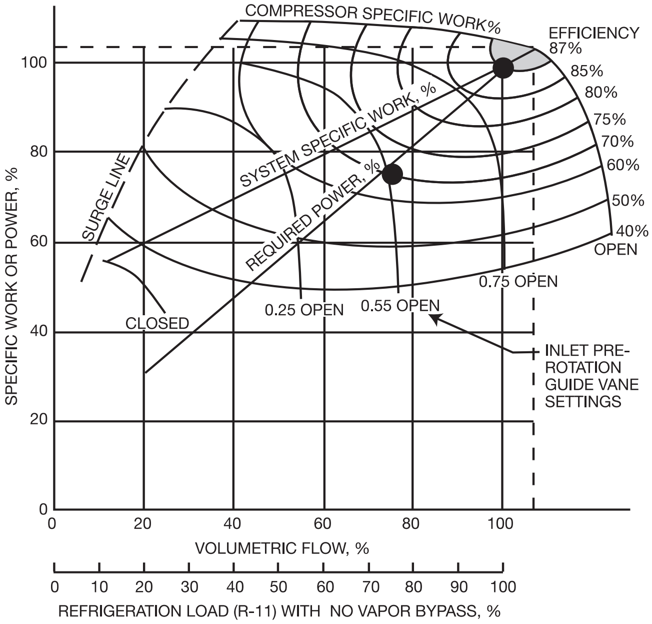

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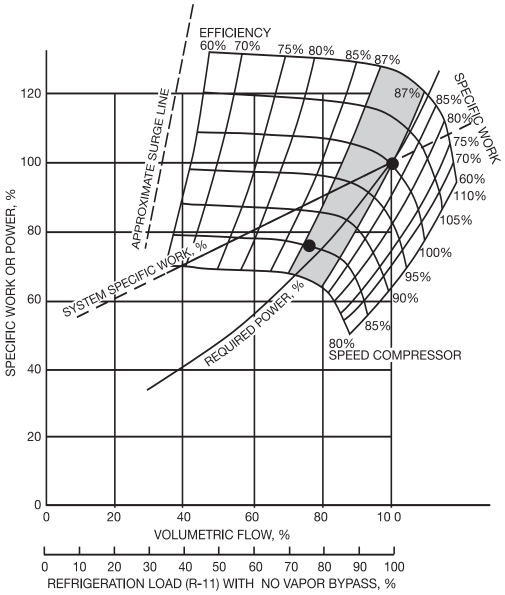
Figure 3, Centrifugal compressor efficiency with a VFD



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VFD must be accounted for in the chiller system, so a chiller with a VFD will have a higher kW/ton than an equal chiller without a VFD. However, these losses are fairly minor and usually fall in the 1 to 2% range (refer to *ASHRAE, Systems and Equipment 2004,* page 40.2).

For example, a 0.55 kW/Ton chiller without a VFD might be rated at 0.567 kW/Ton with a VFD. While on surface it would appear that the chiller without a VFD is more efficient, it is important to look at to look at how the chiller will be run throughout its entire life cycle. In particular, how many of its operating hours are at part load.

Assuming that a chiller installed in the building matches the design load of the building, the chiller with a VFD will consume its full kW/ton rated power only during design conditions. At these conditions, the chiller must have no condenser water relief and must see a full delta T on the return side. According to ARI 550/590, which is the test method for rating chillers, this occurs for 1% of its operating hours. During the remaining 99% of operating hours, if the return water temperature and/or the condenser water temperature drops off, the chiller immediately begins to use less power. Because the chiller with a VFD will be more efficient during non-design conditions, the difference in full load efficiency can be overcome. As a result, the chiller with a VFD may use less energy over its life cycle. Energy analysis can be used to demonstrate this difference.

What about cost?

Tables 1 and 2 look at the energy savings and simple payback achieved by replacing one or two starters with a VFD on centrifugal chillers. The baseline was a 1,000-ton office building with 2 centrifugal chillers in various cities. Table 1 looks shows the results of adding one VFD. Table 2 shows the results of adding a VFD to both chillers. The additional capital cost for each chiller with a VFD was estimated to be $25,000.

In order to keep the analysis simple, energy rates were kept constant for all cities. This allows us to compare how each chiller performs based on the climate where it is located. In addition, the cities used in this analysis are all located in warmer climates to provide a balanced comparison in terms of operating hours. While cities in colder climates will tend to have lower wet bulbs during Winter months, the number of operating hours during this timeframe will also be reduced compared to a similar building in a southern climate.

Table 1 – Energy Savings and Simple Payback for 1 Chiller with VFD

City	Energy Savings	Payback (years)
San Diego	$ 9,789	2.6
Phoenix	$10,272	2.4
Houston	$ 5,441	4.6
Miami	$ 4,954	5.0

Table 1, shows that the simple payback ranges from just over 2 years to just over 5 years. The most significant energy savings and the shortest paybacks are from cities located in climates with reduced wet bulbs all year long (San Diego and Phoenix).

Table 2 – Energy Savings and Simple Payback for Both Chillers with VFD

City	Energy Savings	Payback (years)
San Diego	$12,690	2.6
Phoenix	$14,615	2.4
Houston	$ 7,150	7.0
Miami	$ 8,124	6.2

Table 2 shows that the second VFD will provide additional energy savings at the expense of increasing the payback period. Again, cities located in climates with reduced wet bulbs all year long are the most favorable for using a VFD.

It is important to note that these examples only considered an office building. There may be other cases where using a VFD makes sense in Miami or other climates where the wet bulb is relatively constant. Figure 5 shows typical dry bulb and wet bulb weather data for Miami. It demonstrates that there are periods of wet bulb relief in Miami. A process chiller load, or a chiller operating during the Winter months of December, January and February, would benefit from a VFD.

Figure 4 – Average Monthly Wet-bulb for Four Cities in North America

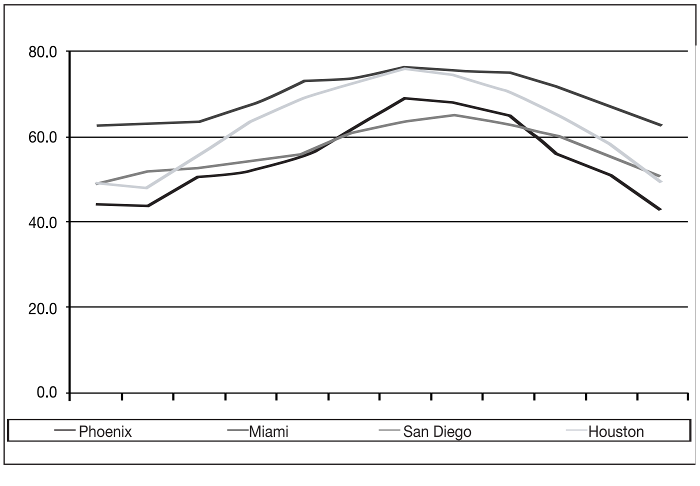
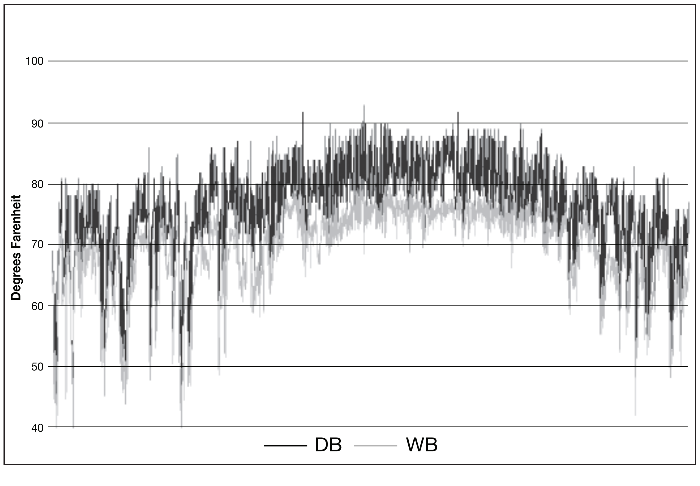


Figure 5 – Annual hourly wet bulb and dry bulb temperatures for Miami, FL



Conclusion

Adding a VFD to a centrifugal chiller consistently results in energy savings, which helps mitigate the initial cost of the design. Warmer climates with wet bulb temperatures that vary throughout the year are most favorable for using a VFD. When the wet bulb is lower than design conditions, a chiller with a VFD can respond more effectively to the reduced lift than a chiller with standard inlet guide vanes. Simple energy analysis using McQuay's Energy Analyzer™ program can help you determine if the payback for a VFD justifies its use in a given application. Talk to your local McQuay Representative or visit www.mcquay.com about using a VFD on your next centrifugal chiller.

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