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Engineers Newsletter

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What drives

Chiller Efficiency

This *Engineers Newsletter* discusses the various considerations a chiller designer evaluates and how those design choices affect the overall efficiency of the chiller.

Introduction

As our utility infrastructure continues to age, investments in upgraded facilities and new production is not keeping up with the ever-increasing demand. So, how do we manage this disparity? Well, one method is through providing equipment that is more efficient. The concept is simple… reduce the demand on the system by introducing equipment that uses less power and energy.

Efficiency standards such as ASHRAE® Standard 90.1 drive manufacturers to develop equipment that meets these higher efficiencies. However, have you ever considered how manufactures continuously improve? Is it simply advances in technology or is there more than what we hear the marketers tout?

Importance of Design

When selecting equipment, particular features or options often draw us in with the promise of greater efficiency. However, a specific, marketed component may not in reality be the primary driver of performance. Furthermore, some design choices leave the consumer with a sub-optimized design and a large utility bill.

So, how do we avoid this? We must first have a basic understanding of how design drives efficiency and what elements contribute to it.

Application Inputs/Choices. The first step in any new design is to understand what the application requires. Items such as capacity needed, load profile, refrigerant constraints, pressure drop requirements, and other factors must be determined. With these in mind, the design engineer's choices affect chiller efficiency through four areas:

1. Compressor efficiency
2. Drive train efficiency
3. Refrigerant cycle efficiency
4. Water-to-refrigerant heat transfer efficiency

These areas considered together and not one component alone, define overall performance. This holds true not only at the equipment level, but also at the system level.

Efficiency Drivers

Compressor Efficiency. At the heart of the chiller, the compressor converts energy into compression, accounting for the vast majority of energy consumed by the chiller. The compressor is responsible for moving refrigerant throughout the system and creating the pressure differential between the evaporator and condenser. This last part is referred to as lift.[1] Figure 1 illustrates lift in terms of saturated refrigerant temperature and leaving water temperature. The amount of lift determines the quantity of work a compressor has to do. How efficiently it does that work is the fundamental issue we are exploring. We will come back to lift in the *Water-to-Refrigerant Heat Transfer* section since approach temperature also affects the lift the compressor must provide.

There are various types of compression used in air- and water-cooled chillers. For this discussion, we focus on centrifugal compression. A centrifugal compressor relies on the principle of dynamic compression, which converts kinetic energy to static energy. Operating at compression ratios of up to 4[8], multistage compressors reach theoretical efficiencies of up to 88 percent[2]. Single stage compressors have slightly lower theoretical efficiencies.[2] It should be noted that theoretical efficiencies do not account for system level loses.

Aerodynamic design of impeller(s) and the passageways through which refrigerant flows defines compressor efficiency. In other words, efficiency depends on how well passageways and impeller design optimize flow paths to create the desired refrigerant velocities (a.k.a. tip speed).

Figure 2 illustrates how the refrigerant vapor accelerates through the passages of the rotating impeller to increase its velocity and kinetic energy. The refrigerant velocity and associated kinetic energy then decreases as the volume of the diffuser passages open up. This reduction in kinetic energy is offset by an increase in the refrigerant's static energy or static pressure.

Finally, the high-pressure refrigerant collects in the volute around the perimeter of the compressor, where

Compression ratio is the ratio of discharge pressure to the suction pressure. In HVAC, the name of the game is to move the needed pounds of refrigerant (capacity) at the lowest compressor ratio[9] possible. In other words, move as much as we can with the least amount of work.

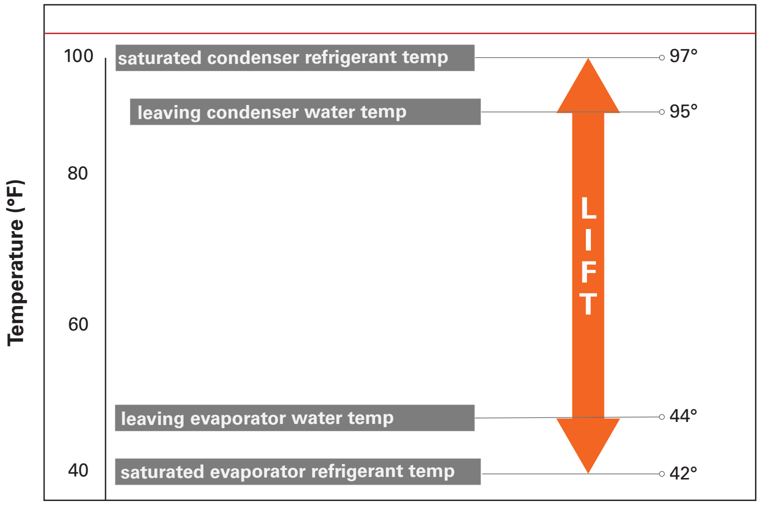


Figure 1. lift in terms of saturated refrigerant temperature and leaving water temperature

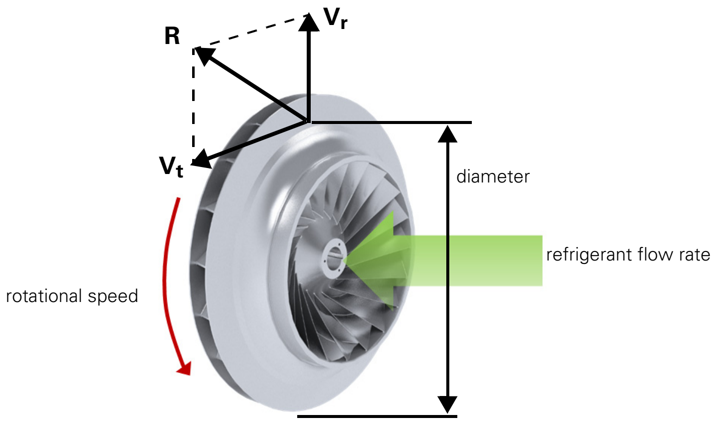


Figure 2. velocity vector

further energy conversion takes place. The resulting increase in pressure and temperature of the refrigerant transfers to the condenser. How efficiently a compressor's aerodynamic design handles this fundamental exchange of energy determines the chiller's efficiency rating.

As mentioned previously, there are other types of compression used for air and water-cooled chillers. Regardless of compressor type, aerodynamics and the subsequent management of losses play a significant role in the ultimate efficiency delivered.

Drive Train Efficiency. For this section, we focus on the efficiency of the rotating components. An element not discussed previously, but which goes hand-in-hand with aerodynamic design is the speed at which the compressor rotates. Specific speed (N_S) is a function of compressor speed, desired lift, capacity, and refrigerant type. Refrigerant type and its role in chiller efficiency will be discussed in the next section.

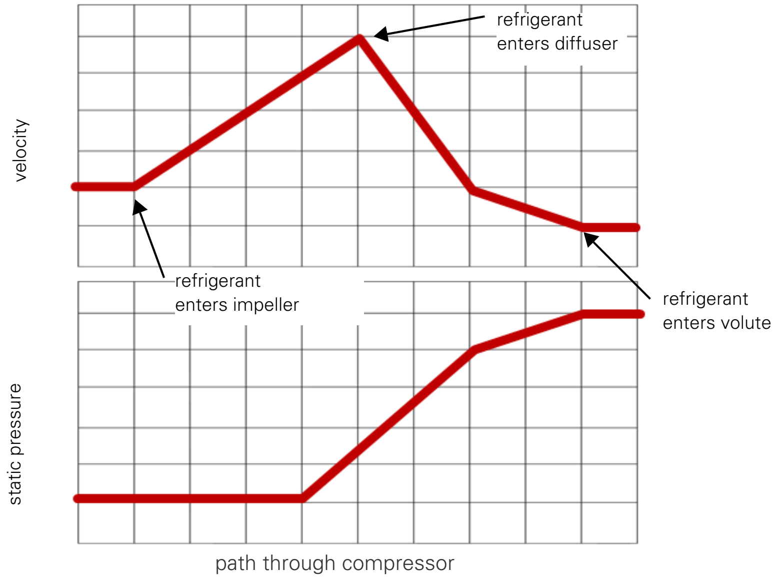
$$N_s \propto \frac{Speed \cdot Tons \cdot Refrigerant\ Choice}{Lift}$$

In essence, specific speed defines the speed needed to unlock the optimal efficiency of the compressor across the operating map. One way to think about this is to imagine a swimming pool. The compressor design defines the available volume of the pool and specific speed defines the optimum amount of water needed to fill the pool. You can swim in the pool without reaching this level, but you are under utilizing the design. Specific speed enables the compressor to take full advantage of the available efficiency.

Once the compressor speed is determined, several other design considerations remain:

1. Motor selection
2. Drive train
3. Bearing choice

Figure 3. centrifugal compressor energy conversion



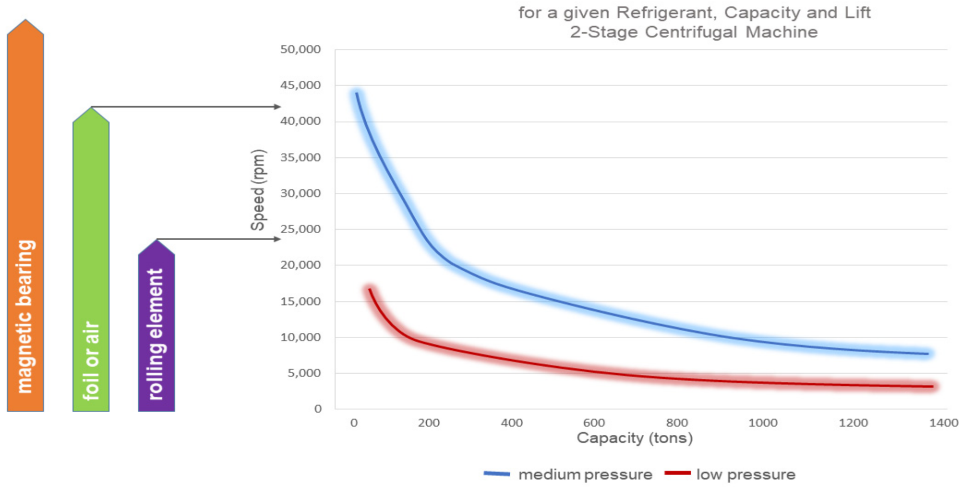
Motor selection. Motors consist of a stator and a rotor. As the names imply, the stator is stationary and the rotor rotates. In both induction and Permanent Magnet (PM) motors, alternating current flowing through copper windings in the stator generates a rotating magnetic field that permeates the space between the rotor and stator as well as into the rotor. This rotating magnetic field "pushes or pulls" the rotor and the compressor shaft to rotate. The effectiveness of this transmission determines the efficiency of the motor.

For induction motors, the stator magnetic field induces current flow through aluminum bars in the rotor that in turn generates a magnetic field on the rotor. The prevailing motor type seen in air and water-cooled chillers today are these type. Induction motors rely on copper windings to produce the electrical field needed to drive the rotor. With efficiencies ranging from as low as 88 percent to as high as 95 percent[2], they remain a cost effective choice.

In a PM motor, magnets on, or in, the rotor provide the magnetic field permanently as the name implies. A PM rotor rotates at the same speed as the rotating stator field; whereas, the induction rotor rotates at about 98% of that field due to magnetic slip. So, induction motors yield less compressor capacity and are less efficient for a given compressor. In addition, PM motors are generally smaller, but the high cost of rare earth magnetic materials used in rotor magnets have slowed PM adoption.

The other element to note deals with motor cooling. Historically, this has been debated amongst the centrifugal chiller community with definite opinions on both sides. However, in the past several years, the industry has seen a definitive move towards semi-hermetic designs. Much has been written on the benefits of semi-hermetic designs so we will not elaborate further here.

Figure 4. speed range for peak efficiency



Drive train. Along with the industry shift to semi-hermetic designs, there has also been a definitive move to direct-drive style drive trains. In the search for improved efficiencies, focusing on the elimination of losses provides a path towards better performance. With improvements in bearing technology, achieving higher speeds without the use of gears has become more practical from both a technical and cost perspective. Coupled with the fact that a direct-drive design over a gear-based design increases efficiency, by some estimates, upwards of 2%[3], this may explain this shift.

Bearing choice. This topic has arguably garnered the most attention in the chiller industry over the past decade. So, let's first understand why bearings are needed and then look at when to apply various types.

In centrifugal chiller design, bearings are needed to support both radial and thrust loads generated by the compressor's rotor shaft[4]. As we discovered in the ***Compressor Efficiency*** section, the rotor's speed is calculated using specific speed methodology. The resultant speed affects subsequent bearing type determination. Figure 4 illustrates how capacity and refrigerant choice are significant factors in the decision. Generally speaking, medium pressure refrigerants require higher compressor speeds as compared to low pressure refrigerants. Furthermore, the lower the capacity (tonnage) needed, the higher the compressor speed required to reach the desired specific speed.

This speed becomes important when one considers that not all bearing types are suitable at all speeds. For example, rolling element bearings begin to lose longevity when operating at speeds greater than 20,000 RPM. At higher speeds, magnetic, foil, or air bearing designs are better suited to maintain these higher speeds over a typical life span of a centrifugal chiller.

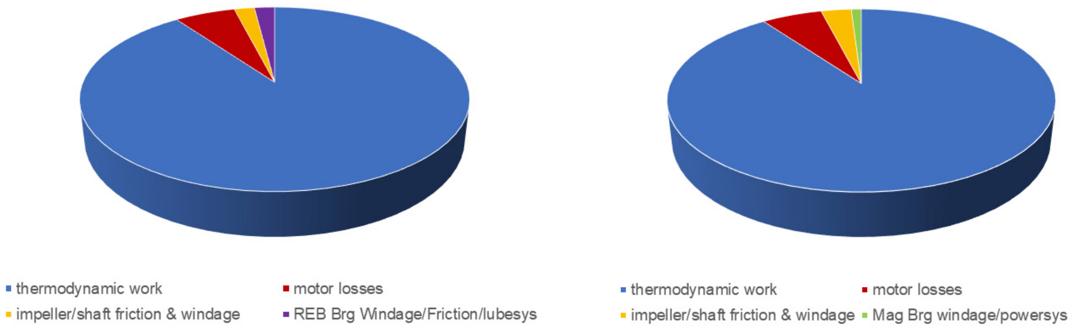
Interestingly enough, the bearing sets themselves contribute very little to the direct efficiency of the chiller. Instead, they simply enable the speed needed based on the other design choices (i.e. aerodynamics, drive train) and for certain tonnages.

Figure 5[5] provides a comparison of how rolling element and magnetic bearing types contribute to the overall efficiency of a chiller. Magnetic bearings use power; whereas roller element bearings have friction. All-in-all, less than 1% of the difference in the total efficiency of the chiller may be attributed to bearing choice. Whether due to frictional, windage, or associated power systems, every bearing choice has some loss component designers must contend with when calculating the overall effect on efficiency.

Refrigerant Cycle Efficiency. As previously mentioned, refrigerant choice significantly contributes to the overall efficiency both directly and indirectly. When considering the direct contribution, Table 8 in the 2017 version of the ASHRAE Handbook of Fundamentals provides insight into how much. Low-pressure refrigerants such as R-123 have higher Coefficient of Performance (COP) values as compared to medium (i.e. R-134a) and high-pressure (i.e. R-410A) refrigerants[6]. Of note, these values are based on a standard cycle and actual efficiencies are a product of the end design and actual operating conditions[6].

Chillers with low-pressure refrigerants tend to have larger footprints as compared to chillers with medium-pressure refrigerants. Because of the lower pressure, larger passageways are required to ensure appropriate mass flow to achieve desired performance.

Figure 5. chiller efficiency based on bearing types



However, if the desired outcome is highest overall efficiency, then low-pressure refrigerants provide the best choice.

Aside from the refrigerant itself, various efficiency-enhancing choices exist to boost overall efficiency as compared to a simple refrigerant cycle. Three to examine more closely are multiple compressor stages, refrigerant economizing, and sub-coolers.

Multiple compressor stages simply means employing multiple impellers instead of one. Multiple stages of compression effectively split the work across multiple impellers. Therefore, instead of one impeller handling all the lift, the multiple impellers each handle a portion resulting in an overall higher COP[7].

An additional benefit of multiple stages is the opportunity to include a refrigerant economizer. One commonly used type of economizer is the flash tank. In a 2-stage centrifugal compressor with this type of economizer, the refrigerant mix enters the economizer where the vapor portion separates and then routes directly to the second stage impeller. This reduces the amount of compressor power needed since the economizer does the work on this portion of refrigerant to raise the pressure. When compared versus a simple cycle (single impeller, no economizer), economizers generate upwards of a 6% efficiency gain.

Sub-coolers are primarily seen in medium-pressure designs, as they are generally needed to get closer to the efficiency of low-pressure designs. Basically an extra tube bundle located in the bottom of the condenser, sub-coolers operate just as the name suggests by further cooling the condenser-side refrigerant prior to the expansion device. When compared to a simple cycle, sub-coolers can achieve upwards of 4% efficiency gains.

Water-to-Refrigerant Heat Transfer Efficiency. In chiller systems, two types of heat exchanger vessels are generally used, shell-and-tube or plate-and-frame. Used predominately in larger tonnages (>100 tons), shell-and-tube heat exchangers are our focus.

Simply put, tubes reside in a larger shell (a.k.a barrel) with water running through the tubes and the refrigerant occupies the space around the tubes.

When considering heat exchanger efficiency, designers determine how tube and overall heat exchange design impacts approach temperatures. Defined as the temperature difference between the leaving fluid and the fluid saturation condition, approach temperatures directly affect compressor lift. For example, if water leaves the evaporator tubes at 40°F and the refrigerant saturated temperature in the shell is 38°F (Figure 1), the approach temperature is 2°F. This temperature contributes to the lift the compressor must provide.

In the condenser, a leaving water temperature of 99°F and saturated refrigerant temperature of 100.5°F yields a 1.5°F approach temperature. Again the approach temperature contributes to compressor lift.

The industry has seen reduced approach temperatures over the past decade decreasing to 1°F or lower. Advances in heat exchanger and tube designs provide improved heat transfer coefficients that result in these better approach temperatures.

With lower approach temperatures, lift subsequently reduces, easing the burden on the compressor while still achieving desired chiller capacities.

Figure 6. impact of design on chiller efficiency

Based on a simple cycle

Efficiency Delivered

Designers have many choices to make throughout the process. Figure 6 provides a summary of the relative impact these various choices have on overall chiller efficiency. As you learned, the combination and interaction of these choices ultimately determines the chiller performance.

It all starts with compressor aerodynamic design. This has the most significant impact of all the design elements. The heat exchanger and drive train both influence and are influenced by compressor aerodynamics design choices. Specifically, these elements must consider refrigerant choice, lift, and specific speed. Control power and starter choice round out the major elements with bearings having a minor impact on the final kW/ton, but indirectly enable other design elements such as higher compressor speeds.

Final Thoughts

All decisions impact efficiency, but not all have equal impact. As we evaluate chillers, understanding the fundamentals of efficiency and how design decisions impact it, help us better select chillers that deliver the efficiency we expect and need. Ultimately, no single feature delivers superior efficiency. The culmination of many design choices throughout the process determines the chillers delivered efficiency.

By Mike Patterson, Trane. To subscribe or view previous issues of the *Engineers Newsletter* visit trane.com/EN. Send comments to ENL@trane.com.

Resources

[1] ASHRAE Handbook – HVAC Systems and Equipment, Atlanta, GA: ASHRAE, 2016: 38.1

[2] Landman, William J., "The Search for Chiller Efficiency" *Heating/Piping/Air Conditioning,* July 1983.

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[5] Texas A&M University, and Turbomachinery Laboratory. 2006."*Proceedings of the thirty-fifth turbomachinery symposium"*, Houston, Texas, September 25-28, pp103-112. College Station, Texas: Turbomachinery Laboratory

[6] ASHRAE Handbook – Fundamentals, Atlanta, GA: ASHRAE, 2017: 29.9

[7] ASHRAE Handbook – HVAC Systems and Equipment, Atlanta, GA: ASHRAE, 2016: 38.30

[8] ME Mechanical Comparison Between Reciprocating and Centrifugal Compressors" me-mechanicalengineering.com. https://me-mechanicalengineering.com/comparison-between-reciprocating-and-centrifugal-compressors/ (accessed April 27, 2016).

[9] Orr, Bryan."Why Compression Ratio Matters." hvacrschool.com. https://hvacrschool.com/compression-ratio-matters/ (accessed March 16, 2018).

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