HVAC&R ENGINEERING
update

Chiller Efficiency: Recips Better Than Most Screws

For many years, the selection of small-tonnage chillers (80 to 400 TR [280 to 1,400 kWR]) was simple: reciprocating compressors were the only available choice. The development of the screw compressor changed that, and promised to end the need for costly, routine maintenance required by reciprocating chillers.

However, the savings made possible by reduced maintenance demands must be balanced against the increased energy usage that's typical of most screw chillers. For air-conditioning or heat-pump duty, the energy-cost savings of reciprocating chillers can exceed the maintenance-cost savings of screw chillers by 100 to 300%!

YORK manufactures both types of chillers, and understands that each type has its benefits. This Update will explain why reciprocating chillers use less energy than most screw chillers. It will also show that while the chillers may be "small", the cost savings are not.

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Background

In the small-tonnage chiller market, reciprocating compressors are the long-time favorites. Like automobile engines, they use multiple pistons and valves to control refrigerant compression and flow. They have been used in refrigeration systems since the 1800s. As a result, reciprocating compressors have the largest installed base of any compressor type.

Screw compressors are the relative newcomers. Introduced to the HVAC industry in the 1930s, they use interlocking screw-shaped rotors to compress the refrigerant. Because there is only one set of rotors, and because the inlet and exhaust ports are fixed, there are fewer moving parts to maintain than in a reciprocating compressor.

Many of the maintenance costs for a reciprocating chiller are similar to those for a screw chiller: for instance, the cost of maintaining the heat exchangers and controls. There is one major difference, though. Valve assemblies on reciprocating compressors must be replaced periodically. Based on the experience of the YORK Service organization, the lifetime labor and material costs for replacing the valve assemblies on a 150-TR (528-kWR) reciprocating chiller would be about $16,000, assuming a 20-year life and a modest 3% cost escalation.

The screw compressor, with its fixed inlet and exhaust ports, completely eliminates these maintenance costs. It should be noted that if screw-compressor maintenance is required, it usually cannot be done in the field. Because the screw assembly is exceptionally precise, screw compressors must be removed from service and returned to the factory for maintenance. This is a costly process, and one that requires availability of a backup compressor or chiller. However, because screw compressors don't fail very often, this is usually not a burden.

While the maintenance-cost savings have driven the popularity of the screw chiller, energy costs have largely been forgotten. However, energy costs can far exceed the maintenance-cost savings.

To understand the differences in energy costs, it's necessary to understand how reciprocating and screw compressors operate.

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Compressor operation

In a reciprocating compressor, the refrigerant gas is drawn through the intake valve into a cylinder, where the piston compresses the gas during its upstroke. The compressed gas is then expelled through the discharge valve to the condenser. During the downstroke, uncompressed gas is drawn again into the cylinder and the cycle repeats.

The discharge valve on a reciprocating compressor begins to open when the pressure inside the cylinder exceeds the condenser pressure. If a chiller is charged with HCFC-22 refrigerant and is operating at full load with an outdoor ambient temperature of 95°F (35°C), this will occur at approximately 260 psig (1793 kPa). (Fig.1).

Reciprocating Discharge at Design Conditions

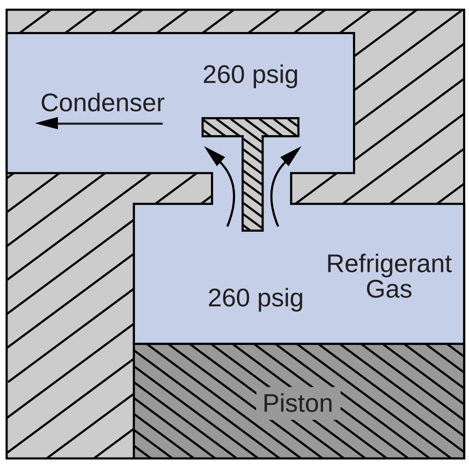


Fig.1: At design conditions, the discharge valve begins to open when the cylinder pressure exceeds the condenser pressure. As the piston completes its cycle, the refrigerant flows smoothly and efficiently through the valve and to the condenser.

If the condenser pressure is higher, the piston will travel farther before the discharge valve begins to open, and if the pressure is lower, the piston will not have to travel as far. Because of their ability to vary how much compression takes place, reciprocating compressors can be said to have a variable volume-ratio.

On the other hand, most screw compressors used in water chillers are designed with a fixed volume-ratio. The discharge pressures are determined by compressor geometry and are matched to the anticipated condenser pressures at design conditions (Fig. 2).

Screw Discharge at Design Conditions

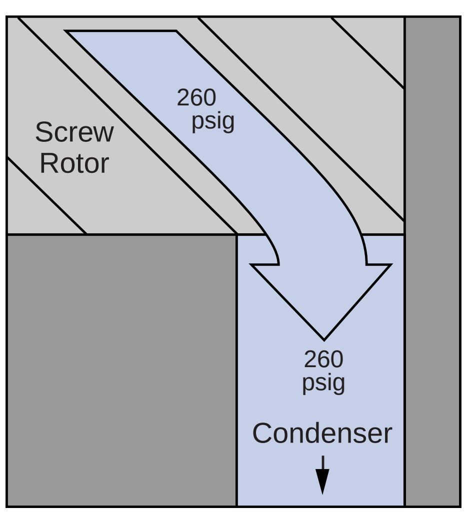


Fig. 2: At design conditions, the discharge pressure for a screw compressor matches the condenser design pressure. Refrigerant flows smoothly and efficiently through the discharge port to the condenser.

Once the screw compressor design is finalized, the discharge pressure will remain relatively constant. And as long as the chiller is operating at design conditions, the refrigerant gas will flow smoothly and efficiently to the condenser.

HVAC operators are well aware, however, that chillers seldom operate at design conditions.

Energy at off-design conditions

Most chillers operate at off-design conditions more than 99% of the time. Lower outdoor-ambient temperatures and lower heat loads result in reduced condenser pressures, which affects the chiller's efficiency.

The Air-conditioning and Refrigeration Institute (ARI) has developed a rating system to better predict chiller energy performance by accounting for operation at off-design conditions, rather than relying solely on energy consumption at design conditions. The Integrated Part-Load Value (IPLV) uses weighted national weather averages, weighted averages of building operation, and a blending of the kW/TR (or EER) at four rating points: 100%, 75%, 50%, and 25%. Using the equations specified by the ARI, manufacturers and users can determine the IPLV of different chillers to allow more accurate comparisons. For small-tonnage chillers, the IPLV is a function of EER, so higher numbers are better.

A survey of manufacturers' catalogs indicates that reciprocating chillers often attain an IPLV rating 10 to 15% higher than similar-sized screw chillers (Fig. 3).

Typical IPLV at ARI Standard Conditions

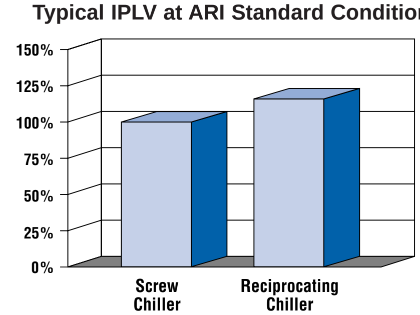


Fig. 3: At ARI Standard Conditions, the Integrated Part-Load Value of reciprocating chillers is 10-15% better than screw chillers.

That difference in efficiency can result in significantly higher operating costs for screw chillers—as much as $67,000 over the life of a 150-TR (528-kWR) air-cooled chiller.

Energy use for reciprocating vs. screw chillers

Let's examine the calculations used to arrive at that dollar figure. We compared two 150-TR (528-kWR) air-cooled chillers, with similar kW consumption at design conditions, operating 12 hours each day, six days each week, over a seven-month cooling season. That yielded a total operating time of about 2,500 hours each year, or 50,000 hours over the chiller's 20-year life.

The reciprocating chiller (based on an average of chillers from several manufacturers) has an IPLV of 13.1 EER, which equates to a power consumption of 137 kW. The screw chiller (again, an average of several manufacturers' models) has an IPLV of 11.6 EER, or 155 kW, a difference of 18 kW.

Assuming an electricity cost of $0.07 per kilowatt-hour, the reciprocating chiller saves its owner about $3,100 in energy the first year. Assuming a modest 3% cost escalation each year of the chillers' 20-year lives, energy savings for the reciprocating chiller total out at approximately $83,000! Even accounting for the higher maintenance costs, the reciprocating unit would save its owner about $67,000.

Why this happens

This dramatic difference in energy efficiency is a result of how the two compressor types respond to the reduced condenser pressures experienced at off-design conditions. For example, let's examine an off-design condition where the condenser pressure is only 200 psig (1379 kPa).

In the reciprocating compressor, the discharge valve will begin to open as soon as the pressure within the cylinders exceeds 200 psig (1379 kPa). The refrigerant flows efficiently to the condenser, and the additional stroke of the piston simply serves to push more refrigerant to the condenser at the same pressure (Fig. 4).

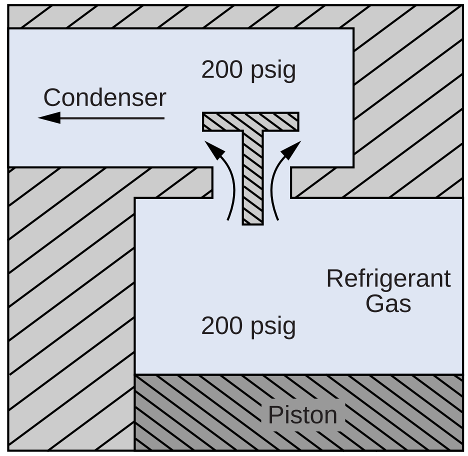
In a screw compressor, however, the fixed volume-ratio means that the refrigerant discharge is constantly maintained at the design pressure of 260 psig (1793 kPa). When the over-compressed gas exits the compressor, it equalizes to the condenser pressure of 200 psig (1379 kPa) (Fig. 5). The work expended to raise the refrigerant from 200 psig (1379 kPa) to 260 psig (1793 kPa) is effectively wasted. This wasted work accounts for the 10-15% difference in IPLV between reciprocating and screw chillers.

In summary, even though the energy consumption of both chillers at design conditions is the same, the off-design performance of the reciprocating chiller results in significant energy savings.

Energy at high-ambient temperatures

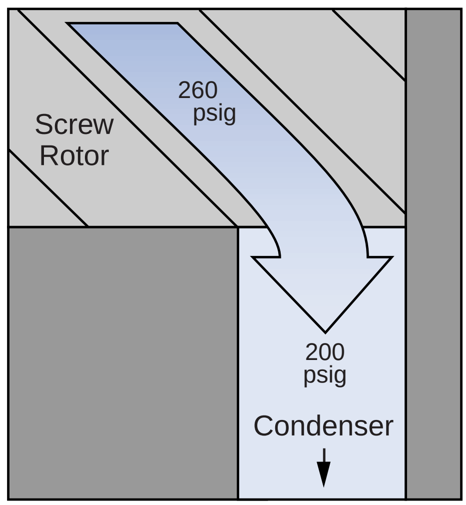
Now, imagine the impact if the reciprocating chiller started with *lower* energy consumption at design conditions. This is what happens at high-ambient conditions.

Air-cooled chillers—both screw and reciprocating—are typically designed for ambient temperatures in the 95 to 100°F (35 to 37.8°C) range. Under these conditions, the design efficiency of the two chillers is very similar. When the ambient temperature climbs, however, the design efficiency of screw chillers drops off faster than that of reciprocating chillers (Fig. 6). Again, this is a direct result of compressor design.



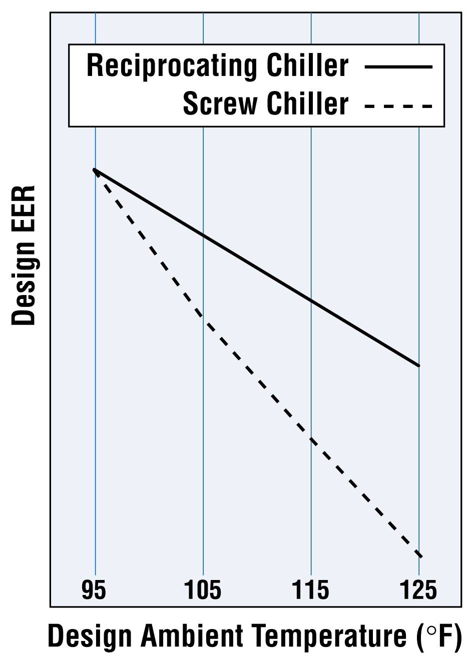
Reciprocating Discharge at Off-Design Conditions

Fig. 4: At off-design conditions, the condenser pressure is lower: i.e., 200 psig. The discharge valve opens earlier in the cycle, again allowing the refrigerant to flow smoothly to the condenser.



Screw Discharge at Off-Design Conditions

Fig. 5: In a screw compressor, the discharge pressure is fixed: i.e., at 260 psig. At off-design conditions, the condenser pressure will be lower, and the screw compressor will over-compress the refrigerant, wasting energy.



Design EER at Higher Ambients

Fig. 6: At higher ambient temperatures, reciprocating chillers have a better design EER than screw chillers.

As the ambient temperature increases, so does the condenser pressure. Reciprocating compressors, with their variable volume-ratios, continue to compress the refrigerant gas until the discharge pressure exceeds the condenser pressure. When the pressure is high (for example, 350 psig [2413 kPa]), the piston will travel further in the cylinder before the cylinder pressure exceeds the condenser pressure and the discharge valve begins to open. When the valve opens, further travel of the piston simply moves the refrigerant out of the cylinder, and the refrigerant flows smoothly and efficiently to the condenser (Fig. 7).

Reciprocating Discharge at High-Ambient Conditions

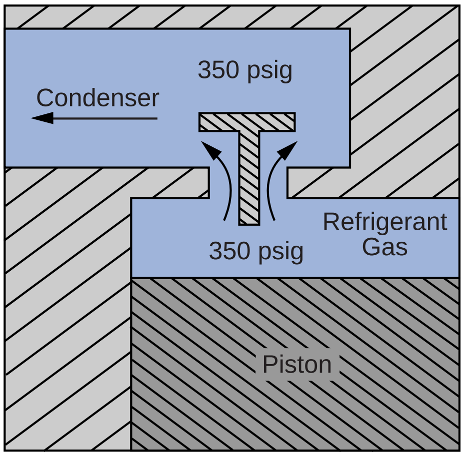


Fig. 7: As the condenser pressure climbs under high-ambient conditions, the discharge valve opens later. The compressed refrigerant enters the discharge line at the same pressure as the condenser.

Screw Discharge at High-Ambient Conditions

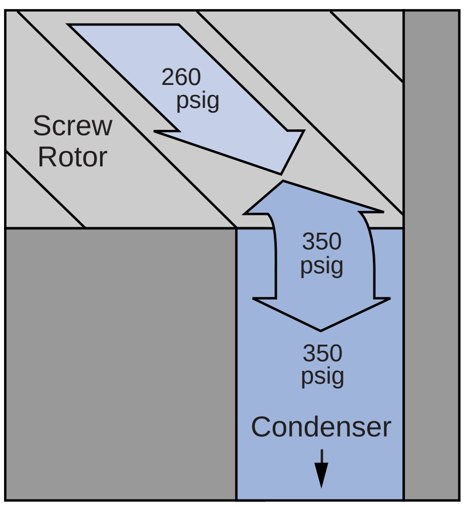


Fig. 8: At high-ambient conditions, the condenser pressure will exceed the pressure within the rotors. When the rotors open to the discharge, higher-pressure refrigerant from the condenser will rush back into the compression cavity. While the compressor eventually compresses the refrigerant to the higher condenser pressure, the fluctuating gas flow adversely affects system efficiency.

Screw compressors, with their fixed volume-ratios, initially compress the refrigerant to the output pressure designed in by the manufacturer: in our example, 260 psig (1793 kPa). Thus, when the rotors open to the exhaust port, the discharge pressure is lower than the condenser pressure. Higher-pressure refrigerant from the condenser quickly rushes back into the compression cavity (Fig. 8). While the compressor eventually compresses the refrigerant up to the higher condenser pressure, the fluctuating gas flow is thermodynamically inefficient and adversely affects system efficiency.

ARI's rating program does not encompass ambient temperatures above 95°F (35°C), so there is no convenient way to directly compare different designs or models from different manufacturers under these operating conditions. However, a conservative estimate is that reciprocating chillers are 15 to 25% more efficient than screw chillers at high-ambient conditions! The results are similar if the chillers are operated as heat pumps, because of high condenser pressures.

Conclusion

In the small-tonnage chiller market (80 to 400 TR [280 to 1,400 kWR]), screw chillers are often specified because of lower maintenance costs. In our example, a 150-TR (528-kWR) air-cooled screw chiller would cost $16,000 less than a reciprocating chiller to maintain over its 20-year life.

However, because chillers operate at off-design conditions more than 99% of the time, reciprocating chillers — which are more efficient at off-design conditions — can provide significant savings in energy consumption that offset their higher maintenance costs. In our example, energy savings reached approximately $83,000. Even with the increased maintenance costs, choosing a reciprocating chiller instead of a screw chiller resulted in net lifetime savings of about $67,000.

Therefore, any evaluation of small-tonnage chillers should include energy costs, as well as maintenance costs. Additional factors, such as the need for off-site maintenance for screw compressors and high-ambient operating conditions should also be considered.

YORK understands that our customers have varying needs. We are committed to allowing our customers to choose the technology that best meets their needs. Whether they need the energy efficiency of reciprocating chillers or the lower maintenance of screw chillers, YORK offers both.

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