Advances in

Steam Cooling

"Although this technology has advanced significantly in recent years, it has received far less attention than the predominant alternative — gas-powered cooling."

By Ian Spanswick, Member ASHRAE

Steam-powered cooling is a proven technology that offers an often-overlooked alternative to electric cooling. Although this technology has advanced significantly in recent years, it has received far less attention than the predominant alternative — gas-powered cooling. To better understand steam-powered cooling, this article presents some its basic precepts and compares the most common types of chillers for large-capacity plants.

Chiller Type	IPLV[a] (COP Basis)	Capital Cost Δ[b]
Electric, Constant-Speed Centrifugal	7.0	Base
Electric, Variable-Speed Centrifugal	9.9	+25%
Electric Screw	7.5	+0%
Steam/Hot-Water, Single-Stage Absorption	0.8	+35%
Steam, Two-Stage Absorption	1.3	+220%
Steam-Turbine Centrifugal	1.8	+210%

a. IPLV values are calculated according to Air-Conditioning and Refrigeration Institute Standards 560-2000 and 550/590-1998.
b. Capital Cost Δ includes the chiller, pumps and tower, but not the boiler.

Table 1: Typical water-cooled chiller efficiencies and costs.

Comparing Electric & Steam Chillers

Traditionally, chiller plants in large facilities consist of electric centrifugal chillers because they have comparatively low capital cost and high efficiency. In the last few years, high demand charges and real-time pricing (RTP) of electricity have provided a strong incentive to manage electrical loads, especially peak usage. Since peak usage generally coincides with peak demand for air conditioning, HVAC designers are considering how to apply non-electric chillers to reduce consumption of on-peak, high-cost electricity.

Choices of electric and steam chillers are summarized in *Table 1,* which compares overall efficiency (integrated part-load value [IPLV]) and capital cost. Because we are comparing chillers powered by different energy sources, the IPLVs are stated as coefficient-of-performance (COP) values. All the figures are based on industry averages.

As *Table 1* indicates, all of the steam chillers carry a higher capital cost than the electric chillers, as well as lower IPLVs. So, when would it make sense to use a steam chiller?

Energy Costs

The simple answer is this: if the cost of electricity is sufficiently high relative to the cost of steam, a steam chiller could offer a lower life-cycle cost, despite its higher capital cost and lower IPLV. Such

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a scenario is not infrequent. As noted, demand charges — possibly coupled with ratcheted rates — or an RTP rate structure will result in high electricity costs. Conversely, low-cost steam could be one of the outputs of an on-site power generation plant, which also may have been installed as a means of lowering peak demand.

All chiller energy sources have seen rising costs, as well as questions about the stability of supply in some regions. This is leading many engineers to evaluate combinations of electric and non-electric chillers to capture the most advantageous energy pricing, and provide a hedge against future uncertainty with energy prices and supplies.

Hybrid Chiller Plants

Depending on local energy costs and rate structures, a combination of electric and non-electric chillers (i.e., a hybrid chiller plant) can provide lowest life-cycle cost.[1] Of course, no two chiller plants are identical, nor are their energy costs, so determining the optimum chiller combination and best operating strategy involves complex calculations. Fortunately, cost analysis software programs can analyze multiple variables quickly and help narrow equipment selections. These programs can perform a sensitivity analysis to show the effect of fluctuating energy costs and help determine, for example, the crossover points to switch from electric chillers to steam chillers.

Steam Supplies

This article intentionally omits a detailed discussion of single-stage absorption chillers, which are powered by low-pressure steam (or hot water). This chiller technology is stable and best suited to heat-recovery applications rather than using steam as a primary energy source. Instead, the focus here is on chillers applied in medium-pressure steam systems, commonly in the range of 100 to 200 psi (690 to 1380 kPa). These chillers have higher capital costs, but offer better IPLVs than low-pressure steam chillers. In addition, this technology has been improved so that medium-pressure steam chillers are easier to install and operate than in the past.

Medium-pressure steam typically is provided in one of three ways:

1. A utility steam system, found in certain metropolitan areas (e.g., New York, Philadelphia, or Minneapolis/St. Paul);
2. A non-utility steam plant that serves its owner's own distributed system, usually including cogeneration of electricity via gas turbine, with heat from the gas turbine exhaust used to produce steam as an integral part of the cycle efficiency (found in large institutional applications, e.g., college campuses); and
3. A boiler that is used for power generation or process/heating duties in a facility; or one that is dedicated solely to a steam chiller.

Cogeneration systems and boilers often operate year-round to meet site demand but function inefficiently when producing steam at low loads in summer. In some cases, it is most economical to maintain higher firing rates through the summer and produce steam for cooling. Additional savings can come from demand-side management strategies that avoid peak electric rates, competitive rates for interruptible supplies, or even from utility rebates. Industry organizations such as the International District Energy Association advocate the economic and environmental benefits of operating such district steam heating/cooling systems.[2]

Medium-Pressure Steam Chillers

The two most common types of medium-pressure steam chillers are two-stage absorption chillers and steam-turbine centrifugal chillers. Basically, an absorption chiller uses a boiling refrigerant (usually water) to extract heat from the chilled liquid, and uses an absorbent solution (usually lithium bromide) to regenerate the refrigerant. With the steam-turbine centrifugal, steam drives the turbine, which operates the compressor to drive the mechanical vapor-compression cycle. For more detailed discussion, see the ASHRAE Handbook.[3] Let's compare these two system types on a number of important parameters.

Capacity

Two-stage absorption chillers are available over a wide capacity range: from about 100 to more than 1,500 tons (350 to 5300 kW). Steam-turbine centrifugal chillers are available from a few hundred to as high as 5,000 tons (17 600 kW). So, an overlap exists in the range of these chiller types, which is an area requiring consideration in each potential application.

The cost of steam turbines is relatively fixed due to their significant machining content. On the other hand, the cost of a two-stage absorption chiller is generally proportional to the capacity of the chiller. Broadly speaking, these characteristics mean that the absorption chillers generally are more cost-effective at capacities less than 1,000 tons (3500 kW), while the steam-turbine centrifugal chillers are generally more cost-effective at capacities above 1,000 tons (3500 kW).

Efficiency

With both chiller types, energy usage is measured in the same way: enthalpy of supply steam minus the enthalpy of the condensate returned to the steam-generating source. For the two-stage absorption chiller, the steam is fully condensed but the cycle efficiency is low. For a steam-turbine centrifugal chiller, the steam leaving the turbine is only partially condensed. At less than 115°F (46°C), the steam enthalpy is usually not sufficient to be used as a further energy source, but it must be fully condensed in a steam condenser so that it may be returned to the steam-generating source. This is, thermodynamically, an unavoidable energy expense. In spite of this loss, the steam-turbine chiller's IPLV is higher: 1.8 vs. 1.3. The reason is more efficient performance at off-design conditions, as explained later.

One factor that has a significant effect on off-design per-

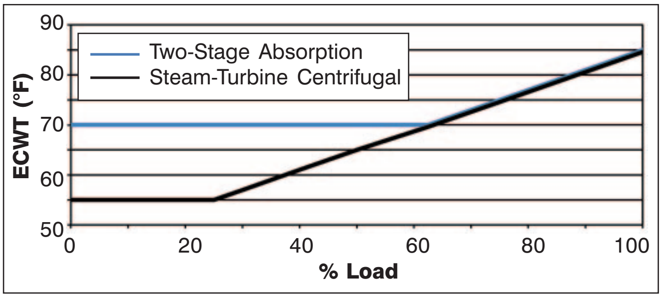

Figure 1: ECWT operating envelope.

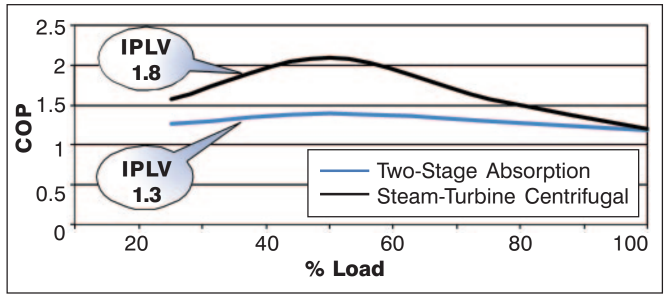

Figure 2: Coefficient of performance comparison.

formance is entering condenser water temperature (ECWT). It is a rule of thumb that lower ECWT means less energy input to the chiller for a given cooling load. Steam-turbine centrifugal chillers can operate with ECWTs as low as 55°F (13°C), while two-stage absorption chillers have a minimum ECWT of 70°F (21°C). *Figure 1* shows a typical ECWT vs. cooling-load profile, and highlights the requirement for maintaining the ECWT above minimum levels at low loads. All other factors being equal, the steam-turbine centrifugal chiller uses less energy when the ECWT is between 70°F and 55°F (21°C and 13°C).

The second factor that has a significant effect on off-design performance is variable-speed drive. The most efficient means of controlling a centrifugal compressor is with a variable-speed drive. On electric chillers, the drive is an add-on component. On the other hand, steam turbines have the inherent capability to change speeds. So, at reduced cooling loads and reduced ECWT, the steam-turbine centrifugal chiller becomes very efficient.

At design conditions, both steam chiller types have a similar COP. However, the steam-turbine centrifugal chiller offers superior performance at off-design conditions. As a result, it has a higher IPLV (*Figure 2*).

Floor Space

Enhanced surface tubes in the refrigerant evaporator and condenser significantly improve heat transfer rates for halocarbon refrigerants, but offer little benefit where water is the refrigerant. Because the steam-turbine centrifugal chiller uses a halocarbon refrigerant, enhanced surface tubes allow compact heat-exchanger shells. In the absorption chiller, which uses water as its refrigerant, the shells tend to be larger for a chiller of equal capacity. For example, the footprint of a 1,500 ton (3500 kW) two-stage absorption chiller is about 310 ft^2 (28.8 m^2), while a steam-turbine centrifugal chiller of the same capacity has a footprint of only 170 ft^2 (15.8 m^2), an 80% savings.

Current centrifugal models also use factory packaging of components to reduce the floor space required by their predecessors. The steam condenser can be mounted on top of the refrigerant condenser — an option only recently available.

Installation

Compared to electric chillers, both steam chiller types require a little more consideration during installation. The use of steam involves more piping connections (steam supply, condensate return, air supply) in addition to the usual chilled and condenser-water piping. If the absorption chiller capacity is large, it may require a two-piece shipment that requires assembly at the site. The steam-turbine centrifugal chiller requires installation of the steam condenser (usually shipped separately from the chiller), and installation of the steam piping from the outlet of the turbine to the inlet of the steam condenser. On the other hand, when compared to earlier steam-turbine centrifugal chillers, the amount of field installation required for current generation chillers is much less, due to an increased level of factory packaging.

Controls

Microcomputer control centers have become standard features on both chiller types, permitting sophisticated control capabilities. On the two-stage absorption chiller, a "pulldown demand" feature permits ramp loading of the input steam flow on startup. Programmable inputs include initial pulldown valve position and duration of pulldown demand period. This effectively prevents the chiller from drawing more steam on startup than the steam system can provide. As a result, the chiller avoids sudden steam system pressure loss and associated problems, such as boiler water carryover.

Remote steam-limiting control permits steam limiting based on a remote signal generated from the building automation system (BAS). Consequently, the BAS can prioritize steam usage between the chiller and other processes without operator intervention.

On steam-turbine centrifugal chillers, the introduction of microprocessor controls allows all the system components to operate together in the most efficient manner — a task that was not possible with older control technologies. Traditionally, an amalgam of various component controls had been applied to steam-turbine chillers. More integration of components results in more integration of controls. Although new, microprocessor-based, graphical control centers present more data, they are more intuitive and simpler to use (*Figure 3*).

Perhaps the area where microprocessor controls have had the biggest impact on steam-turbine centrifugal chillers is in the area of chiller startup. With older style chillers, operators had to be specially trained for the manual startup process. Hot steam entering a cool turbine resulted in some condensed water, which had to be drained before the turbine could be started. The steam could also create temperature gradients within the turbine, which would cause damage on startup if not equalized. So, the turbine had to be slowly rolled to warm all portions to proper temperature.

By contrast, today's control centers can "prompt" an operator through the entire startup process, which reduces the training required. Also available is an option for a "fully automatic start" capability. This can make the chiller as easy to operate as an electric chiller.

Summary

High electric costs (caused by demand charges or RTP rate structures) and/or low steam costs can make a hybrid electric/steam plant financially attractive. Medium-pressure, two-stage absorption and steam-turbine centrifugal chillers offer the best IPLVs and latest technical developments. Thus, if medium-pressure steam is available to the chiller plant, and energy rates are favorable, the latest steam-chiller technology is worth considering in new and retrofit plant designs.

References

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3. *2002 ASHRAE Handbook — Refrigeration,* Chapter 41: Absorption Chillers; *2000 ASHRAE Handbook — HVAC Systems and Equipment,* Chapter 7: Steam Turbines.

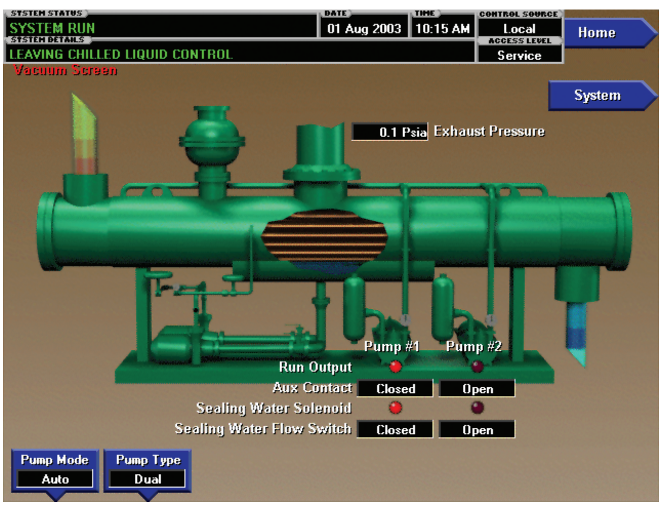

Figure 3: Example of graphic interface.

Real-Life Application

Steam for Arena

The Comcast Center, University of Maryland's new 470,000 ft² (43 700 m²) basketball arena, includes a 2,100 ton (7400 kW) chiller plant with one electric-drive centrifugal chiller and one steam-turbine drive centrifugal chiller, each using R-134a refrigerant and each sized at 1,050 tons (3700 kW). The Center houses the 18,000-seat main arena, athletics administration offices, an academic support center, a 1,500-seat gym, and a multipurpose room for social events. Major events, including basketball games, occur in the arena about 100 times a year, mostly from September through May.

Engineers had to consider this variable, diversified load when designing the HVAC system. The projected life-cycle operating cost of a hybrid plant vs. an all-electric plant showed that the hybrid plant could save almost $70,000 annually in energy costs.

The university buys its energy from a utility company that provides electricity, gas, and steam as well as cogeneration capability. Electricity from the cogeneration plant is used to base load the campus's power requirement (18 to 19 MW) and reduce the purchase of supplemental power during times of high demand (the campus's peak load is 35 MW).

In keeping the cogeneration plant operating at peak efficiency, the campus produced excess steam (not needed for heating during warm weather months). Because this steam is available to the Comcast Center plant, the plan is to operate the steam-turbine chiller as the base-load machine through hot weather, then use the electric chiller to meet cooling loads occurring in the shoulder months. However, that operating strategy could shift as energy prices and rate structures evolve.

The hybrid plant is designed in a conventional fixed primary/variable secondary flow arrangement, with 100% variable-flow pumping. The steam-turbine chiller uses steam at 110 to 120 psi (760 to 830 kPa) supplied from the onsite cogeneration system.

Chilled water is supplied at 44°F (7°C) to 29 air-handling units equipped with electronic variable-speed drives. Eight main AHUs serve the basketball arena, each with a capacity of 45,000 cfm (21 200 L/s). The arena was designed to maintain ventilation airflow at 7.5 cfm (3.5 L/s) per person per hour. This complies with ASHRAE guidelines because of the short duration (up to three hours) of a basketball game. Overriding this, the ventilation system can supply as much as 100% outdoor air if CO_2 levels reach 1,200 ppm in the arena.