Saving Energy

Improving the Performance of Steam Turbine Chiller Plants

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Retrofitting older multi-stage steam turbines with state-of-the-art controls, single-stage compressors and other technologies can improve the performance of existing steam turbines, often at a fraction of new chiller installation costs. As home to the largest higher-pressure district steam system in the world,[1] New York City's Borough of Manhattan system provides an ideal test case for upgrading the performance of steam turbines. While different optimization options exist for steam turbine chillers, this article will focus on advanced controls, replacement drives and other upgrades that improve chiller operation.

Many buildings, large industrial sites, public and private campuses, and cities use distributed high-pressure (HP) steam systems for heating and cooling. The Manhattan underground system distributes HP steam at ±175 psi, from cogeneration and boiler systems to supply a significant amount of the Borough's steam requirements. Over 50% of the summer district steam largely used for cooling in steam turbine or absorption chillers is now cogenerated. Cogeneration uses the by-product heat from electric generation to significantly improve fuel usage, reducing both pollutant emissions and carbon footprint. A fossil fuel cogeneration plant can be up to 75% efficient in generating electricity, as compared to 35% +/- for a typical, remote, fossil fuel electrical generating station, when one includes the plant and transmission losses.[2] Significant incentives and good practice avoid the use of limited electricity at peak demand. Until the electric grid becomes largely supported by renewable wind and solar energy, which may not happen for decades, other strategies to reduce our fossil fuel use must be employed.

For cooling, HP steam turbine chillers are a technology used in many commercial buildings and large campuses since the 1950s. Other steam chillers, like two-stage lithium bromide absorption chillers, in my experience, have a much shorter lifespan, often less than 20 years. Steam turbine chillers are typically robust, sometimes lasting in excess of 50 years and frequently requiring

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only upgrades to their controls, drives, and related moving parts as well as normal maintenance. Their industrial-grade evaporator, condenser and surface condenser shells often require only replacement of their tubes, while the shells remain in excellent condition. From an overall energy perspective, maintaining existing equipment—and improving its efficiency close to the performance of new equipment—retains the embedded energy and reduces energy needed to build new units.

TABLE 1 Steam turbine upgrades summary.

ENERGY						
			ACTUAL AND ESTIMATED SAVINGS			
BUILDING (LOAD TONS)	SCOPE	FLOOR AREA (FT^2)	STEAM USE (MLBS)	ELECTRIC (KWH)	OVERALL (MMBTU)	CO_2 REDUCTION (T CO_2E)
A (3,200)	Turbine/Chiller Controls Single-Stage Compressor	928,000	8,411	0	10,043	377,927
B (4,600)	Turbine/Chiller Controls Pump Control Upgrades	2,690,000	1,180	465,198	2,996	53,144
C* (3,000)	Turbine/Chiller Controls Single-Stage Compressor	1,270,000	44,177	0	52,747	1,985,084
D* (2,250)	Turbine/Chiller Controls Pump Control Upgrades	1,321,000	3,718	232,759	5,233	167,128
E (1,475)	Turbine/Chiller Pump Control Upgrades	866,000	1,872	410,808	2,235	84,118
F (3,000)	Two Turbine/Chiller Controls	1,899,000	12,420	0	14,829	558,090
G (3,200)	Two Turbine/Chiller Controls	1,272,119	5,237	0	6,253	235,323
H* (1,200)	Turbine/Chiller Controls Side-Mounted Electric Driveline	535,720	16,029	–319,345	18,049	720,177

COST EFFECTIVENESS					
BUILDING	PROJECT	INSTALL COST	INCENTIVE AWARDED	COST SAVINGS	SIMPLE PAYBACK (YEARS)
A	Turbine/Chiller Controls Single-Stage Compressor	$430,200	$150,000	$152,000	1.8
B	Turbine/Chiller Controls Pump Control Upgrades	$900,000	$425,000	$109,000	4.4
C	Turbine/Chiller Controls Single-Stage Compressor	$350,200	$164,160	$815,000	0.2
D	Turbine/Chiller Controls Pump Control Upgrades	$897,200	$419,500	$111,000	4.3
E	Turbine/Chiller Controls Pump Control Upgrades	$765,100	$382,500	$110,600	3.5
F	Two Turbine/Chiller Controls	$1,312,600	$656,300	$273,000	2.4
G	Two Turbine/Chiller Controls	$845,600	$591,900	$78,000	3.3
H	Turbine/Chiller Controls Side-Mounted Electric Driveline	$651,300	$261,000	$200,000	2

Conversion Factors: 2.1625 MMBtu/metric ton of delivered steam, 95.0535 kgCO_2e/metric ton, 981 Kbtu/Mlbs, 260.0656 kg CO_2e/MWH3; Typical Utility Costs: $0.18/kWh, $20/Mlb steam

*Actual savings per utility and interval analysis

Energy and CO_2 Savings

Table 1 shows some steam turbine retrofit energy savings and CO_2 reductions in several existing installations. Some are based on annual savings according to bills, while others are estimates of declines in steam consumption. Understandably, many of these plants have not had significant upgrades over the years, only replacement of worn-out or failed components. In some cases, tenants installed separate plants, and, along with new code requirements on tenant retrofits, cooling loads were reduced still further, making optimization control panels more beneficial. Costs in some cases have been significantly incentivized by the local utility.

FIGURE 1 Typical steam turbine flow diagram.

Steam Turbine Chiller Operation

For commercial applications, steam turbine-driven chillers use high pressure steam to drive turbines, which in turn power centrifugal compressor chillers. There are two typical types: condensing and non-condensing systems. This article will address only condensing turbine steam chillers, which extract most of the kinetic energy from the steam (*Figure 1*). Residual condensate is typically returned to most steam generation systems; however, in the case of Manhattan's district steam system, there is no formal condensate pipe return system. Good practice is to recapture the waste heat remaining in the condensate at the building for domestic water heating, etc., and to use the resultant cooled condensate as grey water makeup in cooling tower condenser water systems and other uses.

The original steam turbine chiller governor panels, and often the replacement panels, are not generally suited to precise changes in turbine speed or inlet guide vane adjustment and offer only limited system monitoring and feedback. The three options that typically are used to improve performance, along with normal maintenance and upgrades, include:

- Use of an upgraded steam panel and control system;
- Installation of a new single-stage driveline; and
- Hybrid installation with an electric driveline.

Improving the performance of steam turbines allows them to do the following:

- Optimize turbine speed and inlet guide vane operation, while minimizing hot gas bypass;
- Allow varying and colder off-peak condenser water temperature for improved efficiency;
- Reduce condenser water pump operation, especially off-peak;
- More closely approach surge points without use of inefficient methods such as manual hot gas bypass control or other inefficient strategies;
- Enhance performance with the latest single-stage compressors;
- Incorporate automation of the surface condenser and hand valves;
- Increase turbine power management through non-contact torque telemetry; and
- Install a coupled electric drive for off-peak use.

Figure 2 shows the performance of steam consumption in a typical application before and after a controls upgrade. Data is based on hourly steam consumption data as provided by the utility real time meters and building cooling load based on data logged by building staff.

Recommended features incorporated into a control panel and system include the following:

- Measurement of condenser/chilled water temperatures/flow rates and approaches;
- Refrigerant/oil pressures and temperatures;
- Steam pressures/flow rates at various points;
- Steam consumption (lbs/ton);
- Horsepower and torque;
- Automation of surface condenser, including condensate level, alarms, pumps, vacuum, and control valves; and

FIGURE 2 Efficiency comparison before and after controls upgrade.

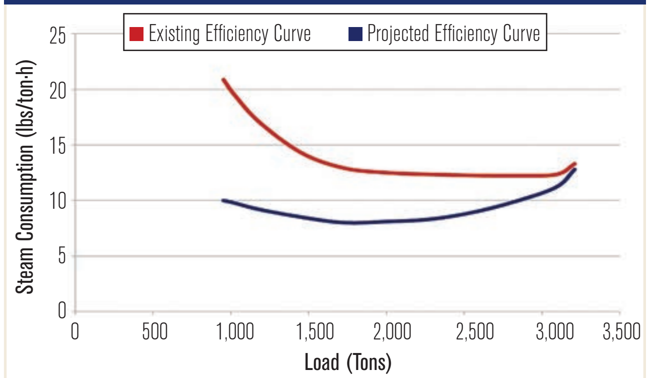
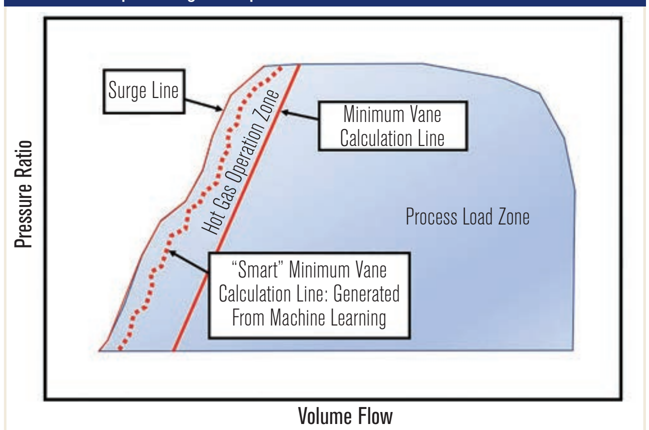


FIGURE 3 Graph of surge line operation.



- Automated and correctly sized hot gas bypass valve.

Upgrading Turbine Control Systems

The challenge of safely operating a steam turbine during off-peak operation involves prudent and careful procedures, since running into a surge condition can cause costly damage to the turbine system. Employing an upgraded control system, control of the turbine speed can be fully integrated into the control system programmable logic controller (PLC). A speed sensor wired directly to the PLC is typically used for speed feedback with the internal proportional integral derivative (PID) control loop regulating the actuation of the turbine governor valve to maintain the desired speed. Control of the turbine speed is maintained by the PLC, including slow roll, ramping to rated speed and over-speed monitoring. The control system adjusts the compressor inlet guide vanes and turbine speed sequentially and ultimately modulates the hot gas bypass valve to maintain the required leaving chilled water temperature. With all the conditions displayed—evaporator (suction) and compressor (discharge) pressures, low suction or high discharge pressure —the turbine speed can be automatically driven down until the pressure setpoint is satisfied, preventing the chiller from tripping.

One feature that deserves more mention is sensing the surge line. As we know, running a chiller operation into the surge zone at low load for a long period can cause significant compressor damage. Often the operators are cautious and open the hot gas bypass early. This can be quite inefficient. A simplified method to approach the surge line, used by some panel control systems, is to create a linear zone (*Figure 3,* Page 24), which limits operation beyond this area without use of inefficient control techniques like the hot gas bypass. A more sophisticated method used in a recent panel is to employ a smart self-learning sequence, which tests the surge line throughout its entire operation and stores it in memory, allowing it to more closely approach the surge line —further improving performance.

Measurement of turbine torque through a non-contact digital telemetry system (*Figure 4*) accurately monitors the turbine's actual loading, thereby calculating the actual shaft horsepower in real time as well as detecting surges.

Combined with steam condensate measurement, overall steam usage (lbs/h) and driveline efficiency (lbs/hp) as well as chilled and condenser water flow, a full energy balance can be achieved.

Features Included in HMI Panels

Provisions in human machine interface (HMI) panels allow for starting and monitoring the chilled water, condensate, vacuum,

FIGURE 4 Measurement of torque telemetry.

and hotwell pumps. If a hotwell pumps fails or the level exceeds a predefined setpoint, the second pump can automatically start. This interface also eliminates chilled water flow during slow roll, thereby minimizing the large chilled water temperature swings during turbine slow roll. Since steam turbines operate at higher temperatures, slow roll minimizes the thermal stress and expansion of components. It also minimizes large chilled water temperature swings by eliminating chilled water flow. Warm chilled water is prevented from diluting the temperature of previously cooled water, allowing the operators to start the unit when required without affecting the building's chilled water supply temperatures. Once the slow roll is completed, the chilled water pumps turn on automatically, and the turbine will ramp to minimum rated speed. In many installations, the original turbine hand valves can be retrofitted with electric actuators for automatic control, thereby sequencing their opening and closing to further improve the chiller efficiency.

Detection of slight rotation of the shaft when the unit is offline due

FIGURE 5 Electric chiller driveline.

to steam leaking can automatically start the turbine and compressor auxiliary oil pumps running for a predetermined amount of time after the rotation has ceased. This prevents damage to the bearings if the shaft is rotated without proper lubrication. Other options include using analog differential pressure sensors in lieu of flow switches for the chilled and condenser water, allowing configuration of low-flow warning alarms prior to the system tripping on low flow. Some HMI panels also include measuring real-time and historical trends, steam consumption from condensate discharge, temperature sensing of fluids and surfaces, pressure transmitters, cutouts and signals.

Interface screen panels can provide users with an intuitive graphical interface to the chiller operation. Screen navigation and control are accomplished with simple point-and-click actions via a touchscreen. Usernames and passwords are required for direct operation of devices or changing of setpoints that are beyond the basic operation of the chiller. These screens include status indication, timers, alarms, capacity control, and real-time and historical trends.

Optimizing Condenser and Chilled Water Flows

Historically, operating engineers have been hesitant to allow condenser water and chilled water flow to vary through steam turbines. However, flows can be reduced to the lower turbulent flow range, based on actual load, with relatively low impact on chiller performance. With many of the large steam turbines supplied by 150 HP or greater chilled and condenser water pumps, speed reduction with variable frequency drives can lead to significant energy savings. With the addition of the sophisticated steam control panels, detailed real-time operational data is available for these turbines. The addition of a complementary panel to control chilled water and condenser water pump speeds can further supplement energy savings at the chiller plant. This panel coordinates with chiller data to determine actual flow requirements through the chiller at any given time, and to vary pump speed to meet these requirements. Condenser water flow, measured by clamp-on ultrasonic flow sensors, is varied based solely on the chiller's requirements, maintaining minimum flow as well as heat rejection requirements for both cooling and auxiliary loads. Chilled water flow is varied first by system differential pressure to assure minimum flow to air handling units, and then to maintain minimum flow through the chiller. In-line magnetic flow meters are also supplied for the condensate discharge and vacuum pump water supply.

Replacing Original Compressors

Replacing the original compressors with modern single-stage units, which most of the latest steam turbines employ, can bring the performance of these chillers up to current steam turbine chiller performance. They allow the efficient compressor unloading from full to part. Typically, they can be powered by the existing steam turbine motor with a fully accessible housing and an operating assembly that is removable from the compressor and scroll housing. Capacity control is also accomplished through pre-rotation vanes and varying turbine speeds to provide modulating control from minimum to maximum load and an improved turn-down ratio. Other features of a modern compressor installation of this type are included, such as a force-fed lubrication system. In some cases, the original compressors have been downsized to replicate the latest cooling loads consistent with reduced interior cooling loads for lighting and equipment.

Electric Drivelines

Another efficient way to improve the operation of steam turbine chillers is to add electric drives to operate the system when electricity is economical, such as off-peak or in the shoulder seasons. The electric driveline is placed near the existing steam turbine (*Figure 5*, Page 26). Suction and discharge lines are inter-connected, and all other controls are integrated, such as common oil returns, hot gas bypass and level controls. New isolation valves and related safety and other controls are all integrated with the existing system and control panel. Typically, the electric driveline has a smaller capacity than the steam drive, in which case the oversized condenser and evaporator surfaces further improve the system's performance, especially during light cooling loads.

Summary

Many existing high-pressure steam turbine chillers are in operation in the US in cities like New York and large campuses. They are generally robust units that perform an important role in using steam efficiently, sometimes as a by-product of electrical generation to stabilize the overall efficiency of steam plants. These chillers can be improved to meet the performance of modern steam chillers with modern controls, single-stage compressors and added electric drivelines, thereby using electricity at off-peak rates and, most importantly, further reducing our carbon footprint.

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