5th Thermal and Fluids Engineering Conference (TFEC)
April 5–8, 2020
New Orleans, LA, USA

TFEC-2020-32367

EXPERIMENTAL PERFORMANCE OF A TURBO-COMPRESSION COOLING SYSTEM OPERATING UNDER POWER PLANT CONDITIONS

Shane D. Garland[1*], **Todd M. Bandhauer**[1]

[1]Interdisciplinary Thermal Science Laboratory, Colorado State University, Fort Collins, CO 80524, USA

ABSTRACT

Power generation assets consume tremendous amounts of water in the United States, using 40% of all freshwater withdrawals. Although most of this water is recycled within the plants, approximately 4% leaves the site via evaporative cooling towers. This evaporating water represents a strong opportunity to provide substantial water savings, especially for water constrained regions such as the desert southwest. A common water reduction option is to replace the evaporative cooling towers with air coupled condensers, but the size and cost of the air-coupled heat exchangers often makes this option prohibitive. One method to enable air-coupled heat exchange is to offset a portion of the condenser cooling load with a waste heat activated cooling system. The team at Colorado State University has recently developed an experimental Turbo-Compression Cooling System (TCCS) at 250 kW_{th} cooling scale which can operate under unique power plant operating conditions (i.e., $\underline{T}_{waste}$=106°C, T_{amb}=15°C, and T_{cool}=17.2°C). The present study provides experimental results for the TCCS over a range of cooling water temperatures and ambient temperatures to fully characterize system performance. The highest COP obtained for the system was 2.07 and occurred with ambient temperature of 21.4°C and ambient to cooling water temperature difference of 1.4°C.

KEY WORDS: Waste heat recovery, Heat activated cooling, COP, Turbo-compression cooling

1. INTRODUCTION

Waste heat recovery (WHR) technologies are one method of improving the energy utilization of thermodynamic processes. The technologies typically convert low-grade thermal energy into some useful form of mechanical work, cooling, or higher temperature thermal energy. Power plants in particular are one thermodynamic cycle which have large quantities of waste heat and potentially co-located benefits from waste heat recovery. However, although power plants generate waste heat, the temperatures are often so low (less than 120°C) that the efficiency of transfer to mechanical work is poor due to Carnot limitations. Many studies have shown that the efficiencies of organic Rankine cycles typically lie within 12-18 % [1, 2]. One option which can mitigate the low efficiency of mechanical work generation is to use a waste heat recovery system which can generate cooling. Such a system would extract heat from the power plant exhaust stack and generate cooling that could offset a portion of the power plant condenser cooling load. One power plant configuration which could benefit from such a configuration is a NETL Case 13 power plant which has flue gas exhaust, cooling water, and ambient temperatures of 106°C, 17.2°C, and 15°C, respectively [3]. The Colorado State University team has been developing a turbo-compression cooling system (TCCS) which could be used in a power plant application due to its operational advantages and similar performance compared with traditional heat activated cooling such as absorption, adsorption, and ejector cycles [4-8]. The TCCS is a type of organic-Rankine vapor compression (ORVC) system which directly couples a Rankine power cycle with a typical vapor compression system via a magnetically coupled centrifugal turbo-compressor. The magnetic coupling of the turbo-compressor creates a hermetic seal between the cycles which allows for operation with two separate fluids. Using two fluids is critical toward optimizing turbo-

*Corresponding Author: garland@rams.colostate.edu

compressor and overall cycle efficiency. There have been several previous studies which have analyzed theoretical or economic performance of the TCCS [7, 8], but experimental studies for the system have been limited to a small range [4, 5]. The present study seeks to add experimental data for the TCCS operating over a larger range of ambient and cooling water temperatures. The data presented provides useful insights into overall system performance and will allow for future comparison with theoretical modeling approaches.

2. TEST FACILITY DESCRIPTION

The TCCS test facility was designed to simulate waste heat recovery in a NETL case 13 natural gas fired power plant [3]. As shown in Figure 1 and 2, the facility has one flue gas simulation loop, four condenser cooling towers, and one cooling water simulation loop which are each coupled to the turbo-compression cooling system. The flue gas simulation loop replicates the hot power plant exhaust (106°C) by circulating air over an electrical resistance heater which can supply 160 kW of heat input. The hot air is then passed over a custom tube-fin style boiler which transfers heat into the TCCS. The condenser cooling tower fans pull air through the tube-fin condensers of the turbo-compression cooling system to cool the power and cooling cycle working fluids. There is one cooling tower for the power cycle and three for the cooling cycle and, in normal operation, the air flow rates are 37,000 m^3 hr^{-1} and 96,000 m^3 hr^{-1}, respectively. The cooling water simulation loop provides the chilling load for the cooling cycle evaporators and operates with a 30:70 mixture of propylene-gylol:water. The loop is coupled with one plate frame and one custom bar-plate chiller and the flow rates of refrigerant and chilled water are fully adjustable. The TCCS is composed of power and cooling cycles which are connected by a magnetically coupled turbo-compressor. The magnetic coupling provides a hermetic seal between the two cycles which allows for operation with different fluids, HFE-7000 (power cycle) and R134a (cooling cycle). Several instruments including T-type thermocouples and pressure transducers were installed to quantify the enthalpy at the inlet and outlet of heat exchangers and the turbo-compressor to determine heat duties, efficiencies, and effectiveness's. These values were then used to calculate the overall COP by dividing the chiller cooling duty by the sum of the boiler heat duty, fan power, and pump power as shown in Figure 2.

3. TESTING RESULTS AND DISCUSSION

The TCCS test facility was successfully operated over multiple test days with the goal of simulating power plant operating conditions. The target test conditions for the NETL case 13 combined cycle natural gas power plant were flue gas exhaust, cooling water, and ambient temperatures of 106°C, 17.2°C, and 15°C, respectively [3]. The target heat exchanger heat duties were 251 kW_{th} of cooling at the chiller and 100 kW_{th} of heat input at the boiler. The overall COP target was 2.1 with an auxiliary power (pumps and fans) target of 19.3 kW. In addition to testing at power plant conditions, the facility was operated over a variety of exhaust, cooling water, and ambient temperatures to observe overall system performance impacts. The exhaust temperature varied from 103°C to 115°C, the ambient temperature from 8.2°C to 22.4°C, and the cooling water temperature from 8.8°C to 23.6°C. The secondary side mass flow rates are another parameter which can affect overall system performance. During testing, the exhaust air, cooling water, and power cycle condenser air flow rates were held

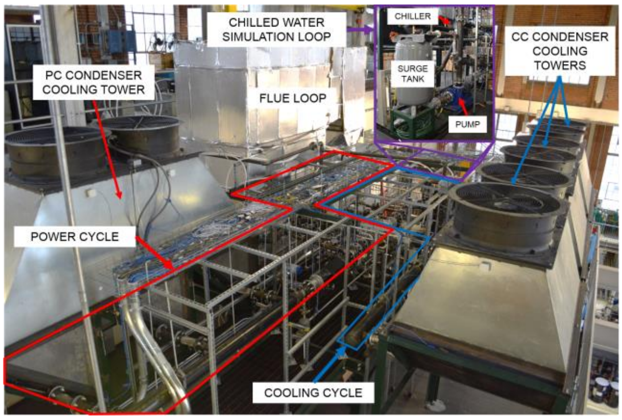


Fig. 1 Overview of the TCCS facility.

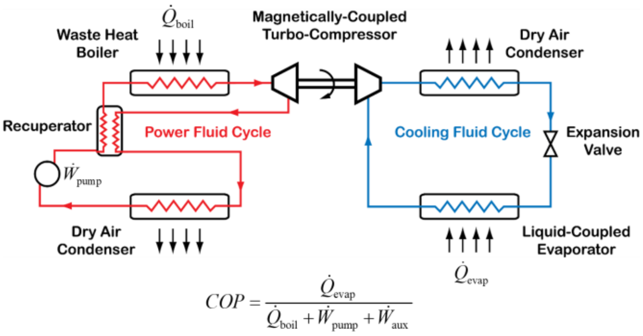
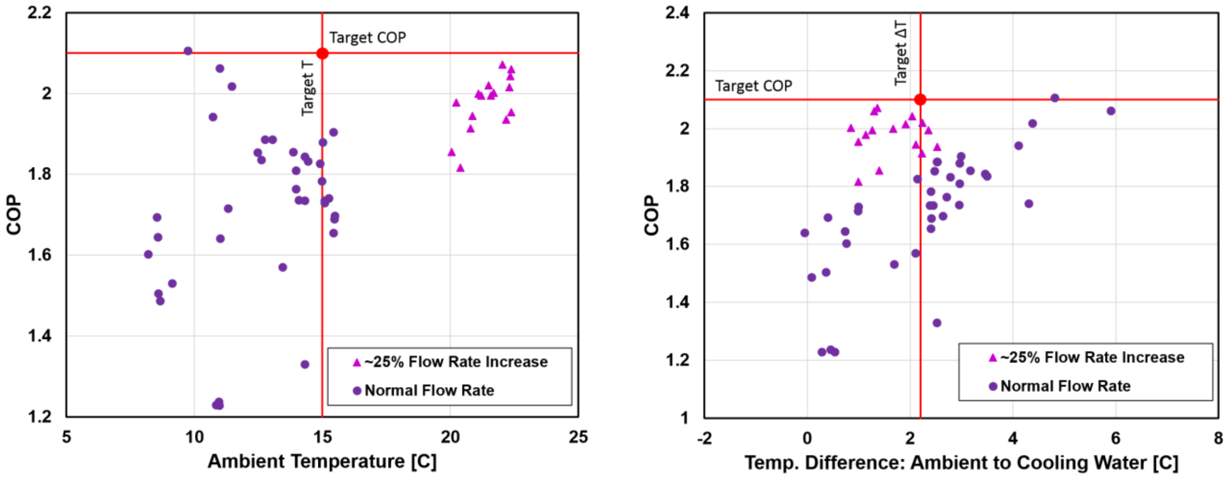


Fig. 2 TCCS Process Flow Diagram

constant at 32,500 m^3 hr^{-1}, 680 gal min^{-1}, and 37,350 m^3 hr^{-1}, respectively, while the cooling cycle condensers were operated at two conditions, 96,000 m^3 hr^{-1} and 130,000 m^3 hr^{-1}. The variance in cooling cycle condenser air flow rate proved critical toward achieving high system COPs.

The ambient temperature is generally a key parameter toward determining system performance of thermodynamic systems. Fig. 3(a) shows a sampling of data over a range of ambient temperatures. It is clear from the figure that there is no overall performance trend for increasing ambient temperatures. This result can be explained by the power plant operating conditions which were applied during testing. As the ambient temperature was increased, the cooling water temperature was also increased to maintain the desired ambient to cooling water temperature difference. This increase in cooling water temperature effectively removed the COP decreases which occur at high ambient conditions [6]. Instead, the temperature difference between cooling water and ambient became the dominant driver for system performance. Fig. 3(b) shows the variance in COP as a function of ambient to cooling water temperature difference. The figure shows that as the temperature difference increases, the overall system performance generally increases. The boost in performance is caused by the increased heat transfer in the chiller due to high temperature differences and the decreased cooling cycle pressure ratio. This performance boost is best exemplified by the data point at a temperature difference of 4.8°C which achieves a COP of 2.11. Although the design COP was met, the performance was inflated and is not indicative of true design point performance.

As noted in Section 2, the TCCS test facility has air coupled heat exchangers which are located indoors. Temperature control can be challenging within the building because large quantities of heat are exhausted into the room via the condensers, which increases the ambient temperature. Therefore, in normal operation, the condenser outlet air was ducted outdoors which provides building temperature control, but increases the pressure drop for the condenser fans which reduces air side flow rate and degrades overall performance. The highest COP obtained for the system while operating with the normal condenser air flow rate of 96,000 m^3 hr^{-1} at ambient to cooling water temperature differences below 2.2°C was 1.83. This result is significantly below the 2.1 target and is likely caused by the increased cooling cycle pressure ratio at low air side flow rates. Due to the fixed power across the compressor, increases in pressure ratio result in decreases in refrigerant mass flow rate. The decrease in refrigerant mass flow rate limits the chiller heat duty which in turn decreases system COP. Therefore, increasing air side flow rate is critical toward increasing overall system performance. The duct work was removed from the cooling cycle which resulted in a condenser air flow rate increase to 130,000 m^3 hr^{-1}. As shown in Fig. 3(b), the 25% increase in flow rate provided an approximate 12% increase in overall system COP. The highest COP recorded with the increased flow rate was 2.07 at an ambient temperature of 21.4°C and ambient to cooling water temperature difference of 1.4°C. Table 1 shows a sampling of the highest performing test points. The removal of the duct work came at a consequence of increased ambient temperature due to lack of building control. However, as shown above, ambient temperature has minimal effect on system performance, indicating the system could achieve similar



(a) **(b)**

Figure 3. The ambient to cooling water temperature difference was the most important factor toward optimizing overall system COP.

performance if tested at 15°C with a low ambient to cooling water temperature difference. Future tests will validate this prediction by testing at ambient temperatures of 15°C.

Table 1. Sampling data for the highest performing TCCS test points.

Test	Ambient Temp. [°C]	Cooling Water Temp. [°C]	ΔT Ambient to Cooling Water [°C]	Boiler Heat Duty [kW]	Chiller Heat Duty [kW]	Auxiliary Power [kW]	Turbo-machine Power [kW]	System COP
Design	15	17.2	2.2	99.5	250.8	19.3	12.4	2.1
1	20.2	22.4	2.2	93.6	238.4	24.5	8.3	2.02
2	21.3	23.3	2.0	102.2	259.1	24.7	9.6	2.04
3	21.4	22.7	1.4	102.3	256.1	21.3	9.5	2.07

4. CONCLUSIONS AND FUTURE RESEARCH

The primary focus of this research was to operate tests at power plant design conditions as well as a range of exhaust, cooling water, and ambient temperature to determine overall system performance. The results showed the most important factors which effected system performance were the ambient to cooling water temperature difference and the cooling cycle air side flow rate. These two factors will be critical toward designing future turbo-compression cooling systems in a variety of applications. The highest COP of 2.07 was obtained at an ambient temperature of 21.4°C and temperature difference of 1.4°C with an elevated cooling cycle condenser air side flow rate. Although the ambient temperature is higher than power plant design conditions, it indicates that the system could meet design targets at lower ambient temperatures. Future work will include testing at high cooling cycle condenser air side flow rates and low ambient conditions to verify system performance at the design point. In addition, the team plans to validate the experimental data with analytical modeling techniques. A turbo-compression cooling system which meets these specific design criteria could be installed at a power plant to improve overall performance.

ACKNOWLEDGMENT

The authors acknowledge the Department of Energy Advanced Research Project Agency-Energy (ARPA-e) for their support. The authors also thank Robert Fuller and Kevin Eisemann from Barber-Nichols Inc. and Ranga Sami and Michael Reinke from Modine Manufacturing Co. for their helpful insights and discussions.

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