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PERFORMANCE OF AN AMBIENT-TEMPERATURE-SOURCE STEAM-GENERATING HEAT PUMP

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1. ABSTRACT

Globally, most electricity is still generated using fossil fuels, however, the share of electricity generated from renewables continues to grow rapidly. As electricity grids across the world decarbonize, electrifying end-uses that are currently fossil fuel fired presents a promising path towards decarbonization. Next generation heat pumps are a viable solution for decarbonizing fossil fuel fired steam boilers. In collaboration with the Colorado State University, AtmosZero has built a prototype ambient-temperature-source, steam-generating heat pump system operating from 15°C heat source and providing steam at temperatures as high as 150°C. Here, we present on the experimental performance of the as-built prototype system.

2. INTRODUCTION

Fossil fuel boilers are ubiquitous across industry and the built environment to produce steam for a wide array of end-uses. High temperature heat pumps have significant potential for decarbonizing steam generation, provided clean electricity is used to power the heat pumps. Most electricity in the United States and across the world is still generated via fossil fuels, but the share of renewables continues to increase [1], with some regional grids even reaching 100% renewables for significant stretches of time [2]. As grids become cleaner, electrifying currently fossil-fired end-uses is a promising path to decarbonization. Most low to medium temperature process heat is steam supplied, which has historically been accomplished through combustion boilers. Steam generation through electrical resistance boilers or heat pumps has recently gained prominence due to the need for decarbonization [3]. Combustion and electrical resistance heating have an efficiency less than one, whereas a heat pump can supply more heat than it requires in electricity input [4]. Because heat pumps have coefficients of performance (COPs) greater than one, they can produce steam at a reduced operating cost compared to electric resistance boilers for a given application, making them a more attractive option. Most current approaches to high temperature heat pumps target waste-heat integrated configurations to lower the required temperature lift [7], thereby increasing the achievable COP. However, due to the significant heterogeneity of waste heat sources across industry, waste-heat integrated heat pumps are deployable only in certain contexts and must be custom designed based on site-specific requirements. Using ambient heat as the low temperature source eliminates the need for a waste heat stream. This enables productization and mass manufacturability for deployment across many potential applications, without requiring bespoke engineering, greatly reducing capital costs and integration costs. AtmosZero, in collaboration with Colorado State University (CSU) has developed a prototype heat pump currently in operation which generates up to 525 kW of steam at up to 150°C using a 15°C heat source. The following sections provide some details on the prototype heat pump and selected results.

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3. SYSTEM DESCRIPTION

The heat pump system configuration is shown in Figure 1. It consists of three cascaded subsystems, starting with the air-source heat exchanger which is coupled with a glycol loop. Heat is extracted from ambient air to warm up a glycol solution which is pumped to an evaporator heat exchanger, which is the source side of the second cascaded subsystem: a low temperature vapor-compression cycle. The low temperature (LT) vapor compression cycle provides a temperature lift from 15°C glycol to ~65°C refrigerant saturation temperature, where heat is then passed to the third cascaded subsystem, a high temperature (HT) vapor compression cycle, via an intermediate heat exchanger. This intermediate heat exchanger serves as the condenser for the LT cycle and the evaporator for the HT cycle. The HT cycle provides a temperature lift from 60°C to ~155°C refrigerant saturation temperature, which is then passed to a condenser heat exchanger where feedwater is boiled to produce saturated steam at 150°C. Both the low temperature and high temperature cycles utilize HFC/HFO refrigerants with multiple stages of centrifugal compression to achieve the required temperature lift.

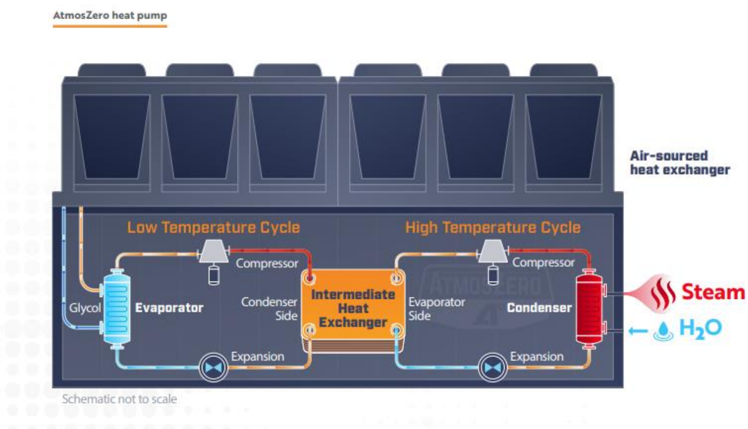

Figure 1: AtmosZero heat pump cycle configuration.

The prototype system does not include the air-source heat exchanger. 15°C glycol is provided directly by CSU into the LT cycle evaporator via a controlled temperature boiler loop. On the heat sink side, CSU receives steam produced by the AtmosZero prototype and condenses it back to saturated feedwater via a condenser loop.

4. RESULTS

The AtmosZero prototype has been in operation since January 2024 and a testing campaign is ongoing, with the primary objectives being characterizing steady-state and transient operation of the heat pump, as well as developing automated controls for system operation. Table 1 presents a summary of one recent steady-state test. Data was averaged over a 14-minute period. During this test, 0.23 kg/s of steam was generated (509 kW_{th}) at a COP of 1.51, which is 48% of the maximum theoretical Carnot limit of 3.15 for heat source and heat sink temperatures of 15°C and 150°C respectively. Boiler feedwater at 145°C was supplied to the condenser. Figure 2 shows a summary of several steady-state test points throughout Spring 2024, including a few data points of the heat pump producing steam at less than 150°C. The steam temperature, capacity, and COP for each of the test points is plotted. The highest COP of 1.85 was achieved for 112°C steam production at 421 kW_{th} of capacity, representing 47% of the Carnot limit. While the highest steam capacity of 525 kW_{th} was achieved at a COP of

Table 1: Performance summary of AtmosZero heat pump prototype during steady-state operation.

Parameter	Average Value
Heat source temperature	15°C
Evaporator heat rate	213 kW
Boiler feedwater temperature	145°C
Steam temperature	150°C
Condenser heat rate	509 kW
Steam flow rate	0.23 kg/s
Total compressor power	338 kW
LT compressor power	91 kW
HT compressor power	247 kW
COP (electrical)	1.51
Percentage of Carnot COP	47.9%

1.49 for production of 151°C steam, representing 48% of the Carnot limit. All data points are for 15°C heat source temperature.

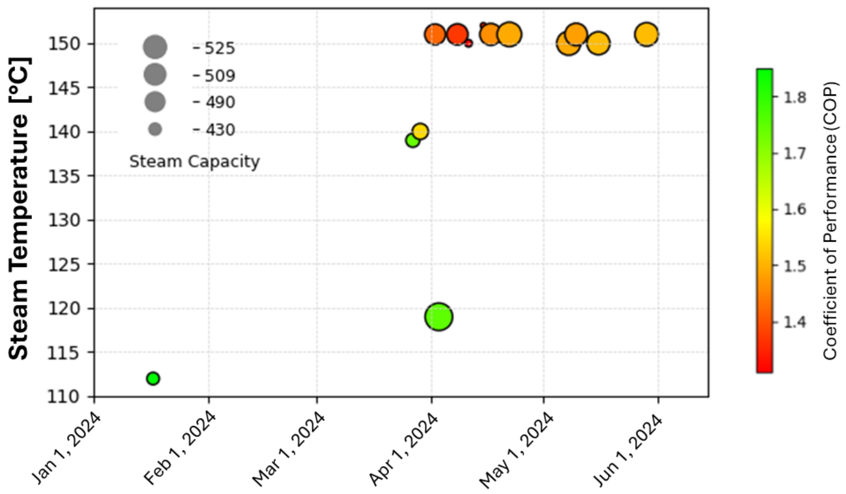

Figure 2: AtmosZero prototype heat pump testing progression.

5. CONCLUSIONS

AtmosZero has built a prototype ambient-temperature-source, steam-generating heat pump system operating from 15°C heat source and providing steam at temperatures as high as 150°C. Testing is ongoing to characterize steady-state and transient operation of the heat pump, as well as develop automated controls for system operation. Of the tests conducted so far, the highest COP of 1.85 was achieved for 112°C steam production at 421 kW of capacity. While the highest steam capacity of 525 kW was achieved at a COP of 1.49 for production of 151°C steam. AtmosZero is currently building a commercial pilot air-source heat pump system which will be deployed with a customer to provide 690 kW of 165°C steam. The pilot is expected to go into service in 2025.

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