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Natural Refrigerant, Industrial High Temperature Heat Pump

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ABSTRACT

The U.S. DOE identified electrification of industrial process heat as one of the four key pathways to reduce industrial emissions. [1] Industrial thermal energy represents two-thirds of all energy demand in the industrial sector. By shifting heat production away from carbon-intensive fossil fuels to low- or zero-carbon electricity, the opportunity exists to lower costs and decarbonize the industrial sector.

Thar Energy's approach to the development of an industrial high temperature heat pump (iHTHP) system that efficiently transforms waste heat to useful process heat (e.g., air, water, steam), to temperatures up to 200°C, using electricity is discussed.

The iHTHP components, system design and operation are reviewed. The demonstration of a novel high temperature compressor (HTC) using carbon dioxide (CO_2) as a natural refrigerant, R744, is presented. Also highlighted is a CO_2-CO_2 stacked-sheet recuperator that operates at higher pressures/temperatures than commercially available heat exchangers.

INTRODUCTION

Heat pumps are ubiquitous in their use, from supermarket refrigeration to residential heating and cooling. They efficiently provide heating or cooling, not by combustion of fossil fuels, but by transferring energy from one location to another. If the electricity consumed by the heat pump is renewable, the environmental impact is significant.

Heat pumps are composed of four major components, a compressor, an expansion valve and two heat exchangers (HX), a condenser, and an evaporator. Heat pump performance is measured by the coefficient of performance (COP), the ratio of the heating/cooling energy produced divided by the energy consumed. The higher the COP, the more efficient the heat pump.

The properties of the heat pump working fluid, or refrigerant, largely determine heat pump component performance specifications and operation. Thar Energy (Thar) recognized early on that CO_2, also known as R744, is an environmentally exceptional refrigerant that: 1) is non-toxic, non-flammable, and non-corrosive; 2) is ozone layer safe; 3) has a low global warming potential of one; and 4) is low cost (up to 90% less expensive than current synthetic refrigerants). CO_2 also has refrigerant properties that allow for more efficient heat transfer and more compact heat pump components.

Thar has been working with sCO_2 as a natural refrigerant for several decades. The initial work used liquid CO_2 as a heat transfer fluid, using latent heat transfer, for the cooling of computer chips. [2] The findings led to the implementation of a pumped cooling geothermal system and later a direct exchange geothermal system. [3]

Thar was the first to establish a commercial scale, direct exchange, geothermal, heating and cooling, heat pump system using R744. [4-9]. Installed at Thar's headquarters, the system served as a living laboratory, at a TRL 8, demonstrating that the technology can interface with a broad range of heating and cooling systems such as air handling units and radiant heating, cooling, and snow melt systems. System benefits included a simpler design with fewer components, enhanced energy efficiency and a reduced environmental footprint.

Additionally, Thar has designed and installed CO_2 heat pumps to provide simultaneous heating and cooling for modular supercritical fluid extraction/supercritical fluid chromatography purification systems. In this application, the CO_2 heat pump replaces both a natural gas fired boiler and a chiller to provide the required system heating and cooling loads. As an example, one Thar CO_2 heat pump provided ~55 kWt heating and cooling while consuming ~11.5 kW of electricity, yielding a COP of ~4.8, Table 1. This yielded savings over 50% for a publicly traded pharma company.

Table 1. Simultaneous sCO_2 Heat Pump Energy Summary

	Energy Delivered (kW)		**Energy Consumed (kW)**
Heating	23.8	**Compressor**	9.8
Cooling	31.6	**Hot Water Pump**	0.4
Total	55.4	**Chilled Water Pump**	0.8
		Reject Heat Pump	0.2
		Air Blower	0.2
		Controls	0.1
		Total	11.5
COP	**4.81**		

In the last fifteen years, environmentally friendly refrigerants, like CO_2, have moved from the research labs into the commercial marketplace, primarily in providing refrigeration for the food chain. Commercial CO_2 heat pumps are limited in operating temperature range (<90°C), by design, to meet market performance/price metrics, for example, for a commercial hot water system.

The Steam iHTHP**,** being presented**,** is designed as a drop-in replacement for gas fired steam boilers, to lower costs, minimize facility integration barriers and decarbonize industrial process heat. The opportunity is large as 60% of industrial thermal emissions are generated by process heat up to 200ºC in the chemical, refining, and food industries. [10] However, to meet this market opportunity, the technical challenge is to design a reliable steam heat pump that meets economic, performance indicators and non-energy benefits required to overcome the business-as-usual culture.

Compressors are the heart of the heat pump. In general, the harder a compressor works, the more electricity it consumes, and the lower the COP. Compressing a working fluid efficiently and powerfully is challenging. The efficiency of the conventional compressors, like reciprocating piston, screw, and vane compressors is limited because the mechanical methods of compressing and expanding gases suffer from a trade-off between working fluid leakage and high sealing friction [11]. Additionally, the use of lubricants and materials of construction, in state-of-the-art compressors, limit their outlet temperature to those well below proposed in this project. In order to design a CO_2 heat pump that can produce steam, a new approach in compressor design is required.

RESULTS AND DISCUSSION

The iHTHP uses a novel thermodynamic cycle to produce high temperature steam up to 200ºC. This cycle is enabled because the HTC can heat the CO_2 working fluid to temperatures beyond 220ºC. A simple CO_2 steam heat pump process flow diagram for a recuperated cycle is shown in Figure 1.

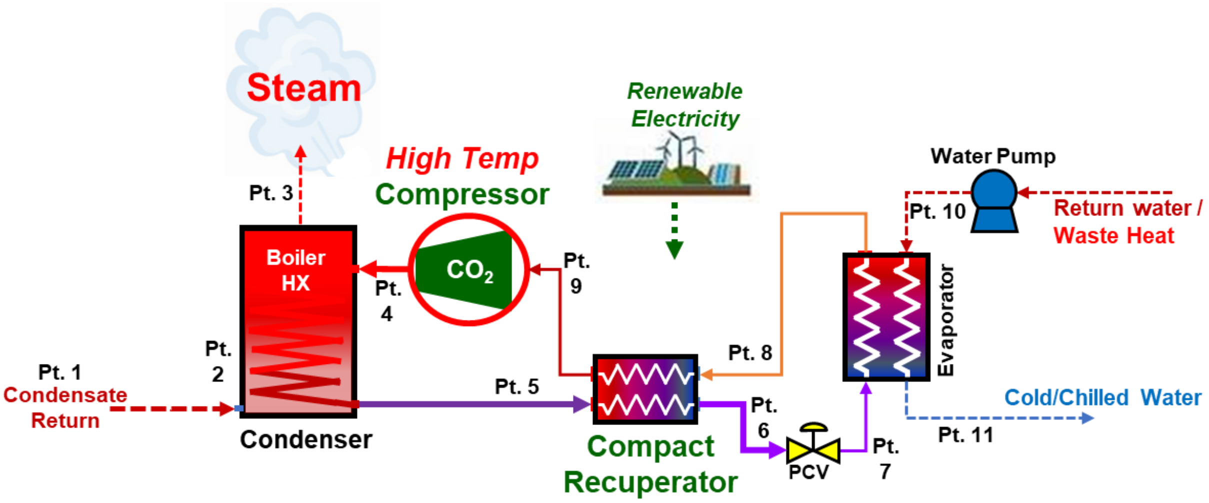


Figure 1. One-Stage Recuperated sCO_2 Steam Heat Pump Process Flow Diagram

Like a natural gas boiler, make-up water or condensate return are the input to the system to produce steam, Pt 1. The condensate return enters the boiler/condenser HX, Pt 2, to be heated and vaporized to produce the process steam, Pt 3. The energy to produce the steam in the heat pump boiler comes from the CO_2 pressurized by the HTC, Pt 4. After transferring its heat to water, CO_2 leaves the boiler and enters the recuperator HX, Pt 5. The recuperator HX, transfers thermal energy from the high temperature CO_2 leaving the boiler to the low temperature CO_2 entering the compressor at Pt 9, reducing compressor work by requiring a smaller pressure increase to reach the target temperature. The CO_2 leaving the recuperator, Pt 6, is depressurized as it passes through the expansion valve and enters the evaporator HX, Pt 7, where it is heated by the heat source fluid, water in this case, and flows to the inlet of the recuperator, Pt 8.

There are several options to heat the CO_2 entering the evaporator based on the specifics of the industrial facility. These options include using the return water, from the process cooling, prior to entering the cooling tower, or preferably from waste heat if available, Pt 10. The question of how cold the fluid stream is chilled depends on the facility. It is preferable to produce chilled water, Pt 11, as simultaneous heating and cooling improves heat pump economics.

One of the major issues with the steam HPs is the compressor's high outlet temperature that exceeds the operational specifications of the available commercial compressors. One way to reduce the required CO_2 temperature at the compressor's outlet is by using a multi-stage system. [12]. A unique 3-stage HP system was designed for this project that utilizes three compressors and three boilers, Figure 2.

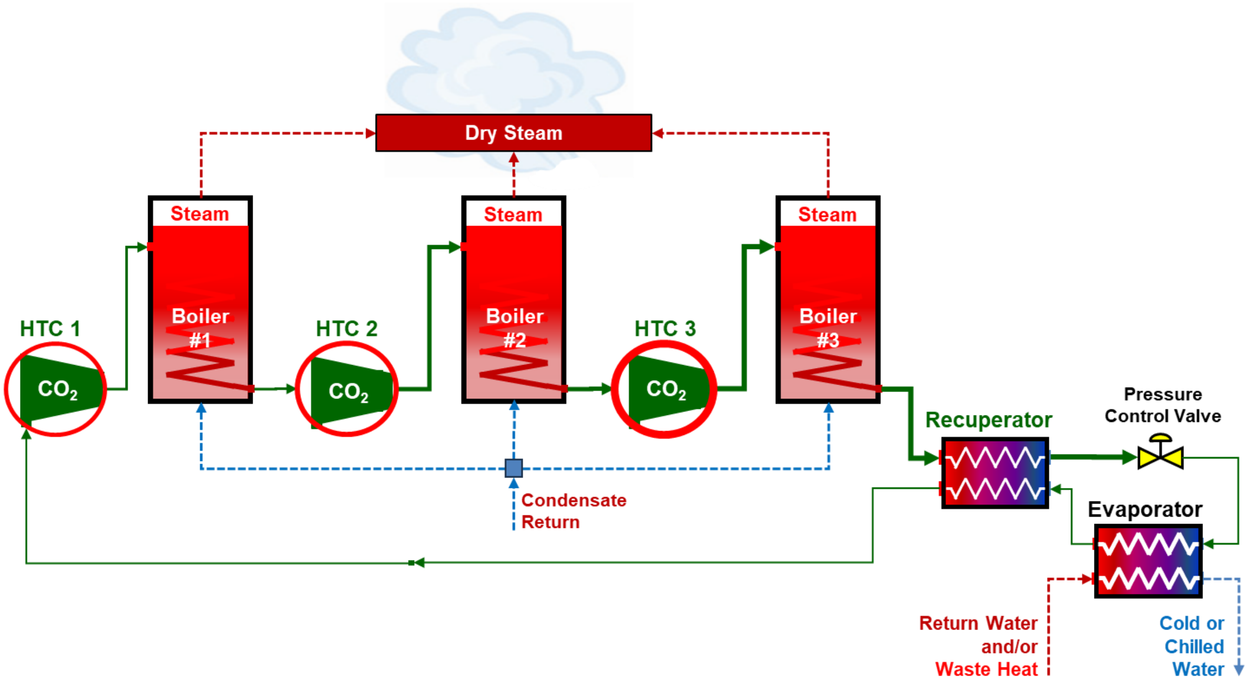


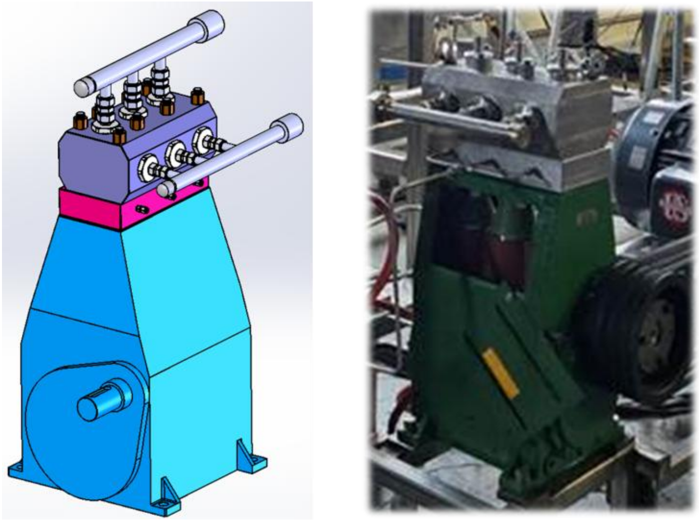
Figure 2. 3-Stage Recuperated Steam Heat Pump Process Flow Diagram

Two key components are highlighted in this Steam heat pump. First is the HTC, Figure 3. The HTC is a modified positive displacement pump that has been designed to compress CO_2 to temperatures, as tested, in excess of 170ºC, at differential pressures from 40 to 140 bar. The design process included evaluating variables such as the number of pistons, piston size, stroke length, RPM, and power-end operation. Designing a pump that can go to outlet temperatures in this range and beyond requires high temperature custom seals that are either actively being cooled, have a thermal barrier, or both. Both approaches are being utilized and investigated for the current and future HTCs.

The second key component is the recuperator HX. The steam heat pump operating pressures exceed the limits for commercially available braze plate heat exchangers, e.g., 150 bar.

A number of HX designs were evaluated utilizing in-house software. The stacked sheet heat exchanger (SSHX) design [13, 14] was selected based on a performance/cost analysis. The SSHX design offers high thermal and hydraulic performance in a compact and light weight recuperator with optimized material usage.

As its name implies, the SSHX core is made up of stacked perforated metal sheets, Figure 4. When sheets are stacked and aligned together, the holes form flow passages for both the high pressure, hot stream, and the low pressure, cold stream. These fluids can then transfer heat through the solid metal that separates them. If the flow passages are circular, the stacked sheets end up forming, in essence, the inner diameter of microtubes.



a) b)

Figure 3. High Temperature Compressor, a) SolidWorks model b) As tested

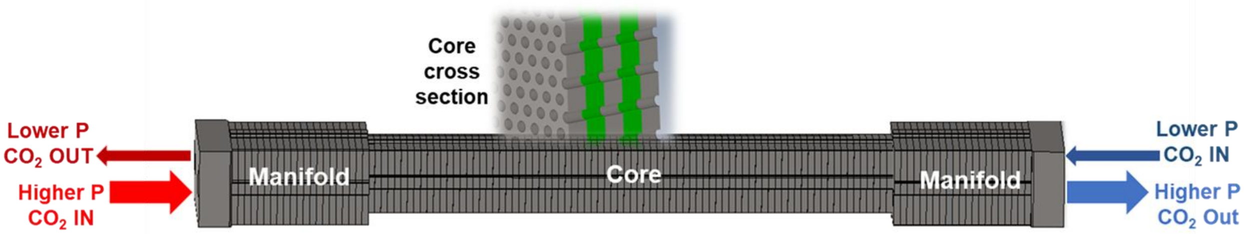


Figure 4. Steam Heat Pump sCO2 – sCO2 Stacked-Sheet Recuperator

Recuperator pressure drop and thermal capacity for each flow stream can be adjusted independently by setting the number of passages, their size and spacing. Like most compact HXs, surface density and the heat transfer coefficient improve as passage size and passage spacing decrease, as does the HX size. However, manufacturing tolerances, for hole size, spacing and sheet alignment ultimately dictate how small and close the passages can be, as does corrosion, fouling allowances, and assumptions of bonding effectiveness per ASME Boiler and Pressure Vessel codes.

The sheets are permanently held together by either brazing or diffusion bonding. In addition to the HX core, manifolds are required. The manifolds are used to separate the hot and cold flows into their respective passages and to connect the separated hot and cold flows to the process piping.

One of the distinctions of the SSHX concept is that the bond between sheets is parallel to the mechanical stresses and perpendicular to the thermal gradient stresses. This improves the structural integrity and thermal compliance of the SSHX recuperator, as compared to the state-of-the-art printed circuit HX, whose bonds are oriented along the HX.

Incorporating a recuperator into the steam heat pump cycle analysis provided significant performance improvements. The addition of the recuperator reduced the flow of CO_2 by more than 50%, the compressor outlet pressure by ~45%, and improved system COP by ~40%.

The first demo sCO_2 steam heat pump system was a 2-stage recuperated heat pump focused on producing 1.3 bar (19 psi), low pressure steam, at 104ºC (219ºF), Figure 5, as a first step to developing the 200ºC steam iHTHP. The practical application of a low-pressure steam heat pump is the replacement and decarbonization of existing natural gas fired boilers used in tall residential and commercial buildings (e.g., 7+ stories) with steam heat distribution systems. [15, 16, 17].

Figure 5. Demo sCO_2 Steam Heat Pump System

The 2-stage recuperated heat pump was operated, successfully producing steam. Figure 6 presents a plot showing the temperatures of the CO_2 refrigerant entering the two boilers and the temperature of the produced steam exiting the boiler, meeting system expectations.

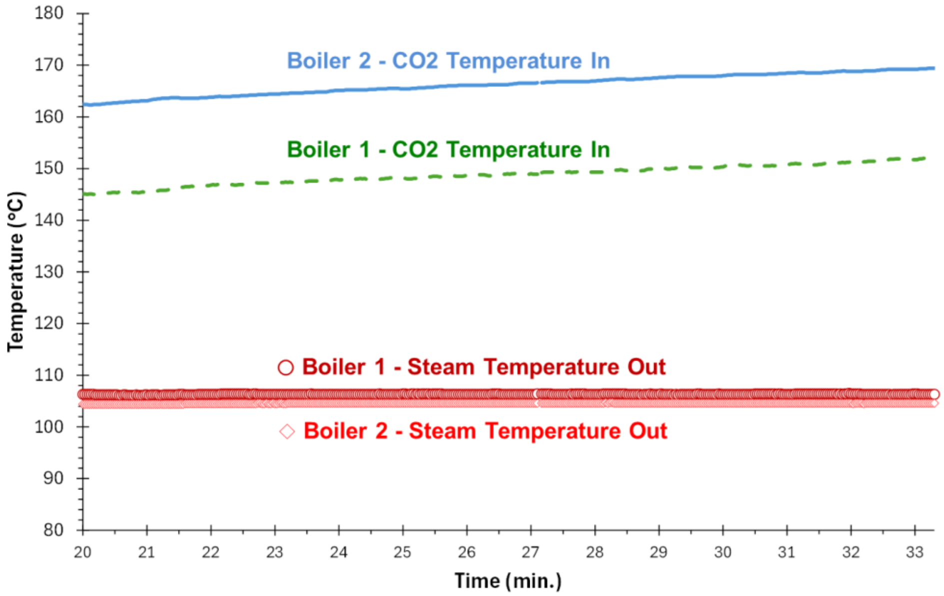


Figure 6. Boiler CO_2 and Steam Temperature Plot

Figure 7 plots how the COP of a 3-stage steam heat pump changes with the temperature of the water entering the evaporator, heat source temperature, according to the thermodynamic cycle analysis. The higher the heat source temperature the higher the COP.

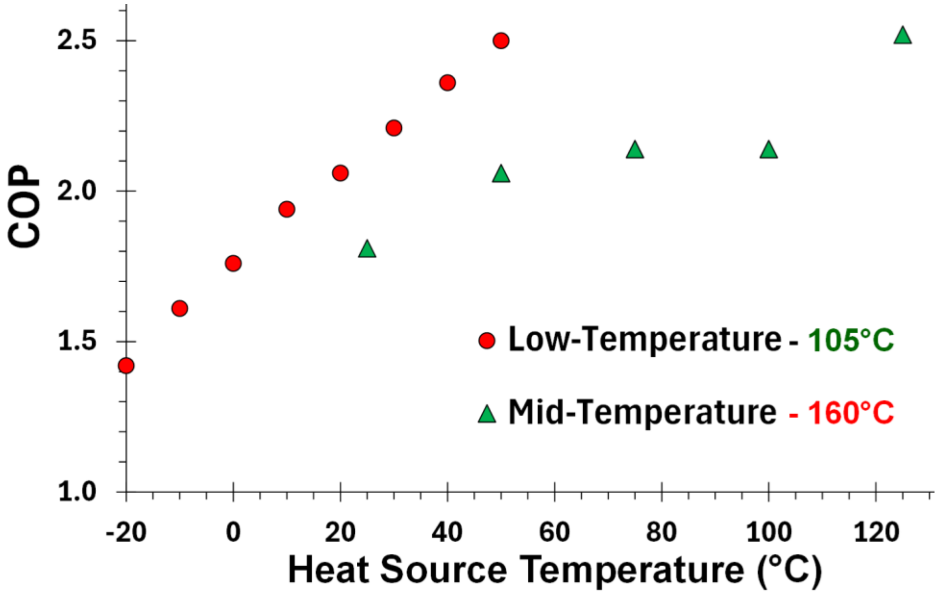


Figure 7. COP vs Heat Source Temperature Plot

The GHG impact of a 100-kW low pressure steam heat pump, with 75% utilization, a COP of 1.9, and a grid emission factor of 0.22258 kg CO2e/kWh (New York State), would be a reduction of 1,400 mT CO2e annually.

Next steps include evaluating and testing additional designs for improved and higher temperature HTC operations.

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