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Pilot Scale Test Facility for Performance Evaluation of Compact Heat Exchangers Using Supercritical CO_2 as Working Fluid

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ABSTRACT

The development of advanced direct and indirect supercritical CO_2 (sCO_2) power cycles is becoming more significant in pursuit of highly efficient power generation systems in today's carbon constrained world. Adoption of these high efficiency power cycles that offer opportunities for carbon capture, reducing emission intensities and water demand, lessens the environmental impact of fossil fuel energy conversion technologies. However, successful uptake by industry depends on addressing current technology and knowledge gaps to improve the economic prospects of these cycles. The successful design and implementation of sCO_2 power cycles depend on a multitude of factors. From a technical point of view, cycle configuration, operating conditions, and selection of suitable materials, components and equipment such as heat exchangers, recuperators, turbomachinery, are among the important factors to consider. With respect to heat exchangers or recuperators, they must be compact, efficient, and reliable, while effectively handling sCO_2 or combustion flue gases at very high temperatures and pressures and, in many cases, under a corrosive environment.

Over the past ten years, CanmetENERGY-Ottawa (CE-O) has been pioneering the research and development of sCO_2 power cycles in Canada, in collaboration with Carleton University. This effort has led to the development of CE-O's patented G2 Technology; an indirectly-fired pressurized oxy-fuel sCO_2 power cycle. Work is ongoing to demonstrate this technology at pilot scale, and developing several test rigs for experimental investigation and model validation of components of sCO_2 power cycles. To this end, a modular pilot-scale test rig was designed and built at CE-O for evaluating the performance of compact heat exchangers using sCO_2 as the working fluid. As the operation of these cycles near the critical point involves steep property changes, it is crucial to study heat transfer properties and transient behavior of these compact heat exchanger unit operations. This also enables validation of heat transfer models against experimental data. The compact heat exchanger test facility at CE-O is equipped with a high-pressure sCO_2 gas supply system. The test rig can accommodate a wide range of temperature pressure combinations, up to 500 °C at 8 MPa, and with a CO_2 mass flow rate capacity of up to 10 kg/hr per each cold and hot streams.

This paper provides an overview of the sCO_2 compact heat exchanger test facility at CE-O and presents preliminary test results for a small printed circuit heat exchanger (PCHE) unit operating near critical point.

INTRODUCTION

sCO_2 power cycles are transformative energy conversion systems for power generation and a broad range of other applications. These cycles have the potential to reach greater efficiencies over traditional Rankine power cycles that utilize steam as the working fluid [1]. This increased conversion efficiency reduces the greenhouse gas (GHG) emission footprint of these cycles. Furthermore, the superior thermodynamic properties of sCO_2 enables very compact designs with small physical footprint compared to incumbent steam cycle power plants. This, in turn, offers potential for significant capital cost reduction [2].

Realization of the full potential of sCO_2 cycles is contingent on overcoming a number of obstacles, including the current engineering and technical gaps in several areas, including materials, turbomachinery, heat exchangers and recuperators, seals, bearings, and so on. Having operating points at high temperatures and pressures within a cycle, as well as near and across the critical point of CO_2, bring about new challenges to both cycle components and turbomachinery design.

As cycle efficiency and optimal heat integration go hand in hand, in particular for the highly recuperated cycles, the compact heat exchangers deployed in these cycles play a critical role in transferring heat and achieving the efficiency targets envisioned for these systems. As compactness is an important feature of these heat exchangers, they must provide high efficiencies at high surface area to volume ratio (with reasonable pressure drop) to be suitable for these applications [4, 5]. These exchangers are also exposed to very high temperature and pressure combinations, which they must be able to withstand for many hours of continuous operation at both design and off-design conditions. However, performance data for these exchangers operating at conditions relevant to sCO_2 power cycles are scarce in the public domain.

CE-O researchers have been leading the R&D efforts in the area of sCO_2 power cycles in Canada, for over a decade now. In collaboration with Carleton University, the research team has developed several test platforms for experimental investigation and model validation of components of sCO_2 power cycles. This includes a recently installed test rig to evaluate the performance of compact heat exchangers for application in sCO_2 power cycles. The development of the latter test rig was carried out in two phases: phase one involved the design and implementation of the test rig using air and CO_2 as the working fluids at subcritical conditions. A computational model has been developed to simulate the performance and validate the heat transfer model of a printed circuit heat exchanger (PCHE) by Heatric, against the data obtained from conducting experiments using this test rig. In the second phase of the work, a new compact heat exchanger test rig was designed and built that utilizes CO_2 as the working fluid, at supercritical state, at both hot and cold sides of the heat exchanger. Test data from this rig will be used to validate performance models of compact heat exchangers at sCO_2 conditions. The test rig is designed in a modular fashion to accommodate various compact heat exchanger designs, within its range of operation.

DESCRIPTION AND SPECIFICATIONS OF THE COMPACT HEAT EXCHANGER TEST RIG

The test rig is comprised of CO_2 and air supply lines, an air-driven booster to increase CO_2 pressure to 8 MPa and three split-tube heaters are used to control the temperature of hot and cold streams. The test unit is instrumented to measure flow rate, pressure, and temperature along the two main process lines. These parameters are continuously recorded through a process control and data acquisition system. A schematic diagram of the process flow for the compact heat exchanger test rig is depicted in Figure 1.

Both the cold and hot streams operate at maximum design pressure of 8 MPa. Maximum operating temperature of the hot stream CO_2 is currently set to 500 °C., while the cold side stream temperature can be set to 150 °C or above. The cold- and hot-side process flow rates are measured using Coriolis flow meters. The pressure drop across the compact heat exchanger is measured using differential pressure transmitters. Moreover, a set of redundant absolute pressure transmitters measure the inlet and outlet pressures of the working fluid on both the cold and hot sides of the heat exchanger. In addition, the inlet and outlet temperatures of the working fluid, along with a few selected points on the heat exchanger's surface used to map the surface temperature profile, are measured and recorded.

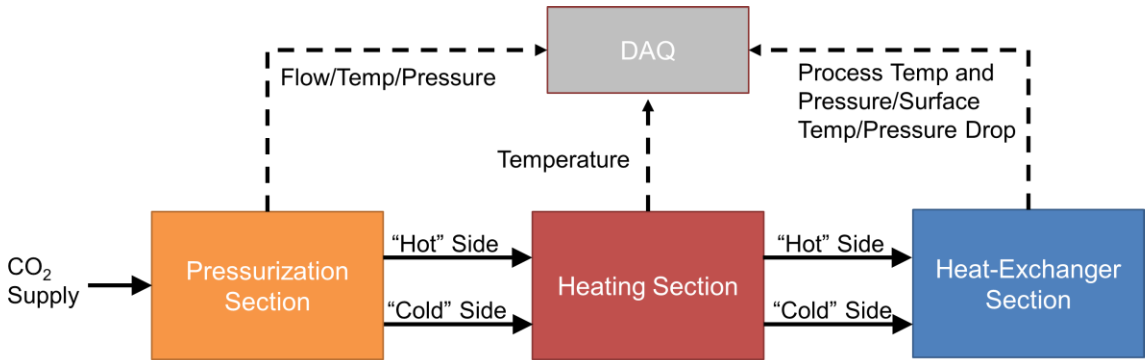

Figure 1: Schematic diagram of the process flow for the compact heat exchanger test rig.

A panoramic image of CE-O's compact heat exchanger test rig is shown in Figure 2. CE-O is currently in the process of commissioning the test rig, which is equipped with a PCHE unit, manufactured by Heatric. The PCHE is made of stainless steel 304H, with core dimensions of 76mm x 996mm x 55 mm and a heat load of about 0.8 kW.

Figure 2: CE-O's sCO_2 compact heat exchanger test rig.

RESULTS AND DISCUSSION

Subcritical CO_2 Results:

A subcritical PCHE model was developed using the COMSOL simulation software package. Tests for the actual subcritical setup were conducted with air and CO_2, in which the air temperature was varied between 70°C to 140°C. The pressure and flow rates of air and CO_2 varied between 0.5 MPa to 1 MPa, and 5 LPM to 10 LPM, respectively. The temperature, pressure, and flow rate data provide insight to off-design and low-flow conditions of the PCHE under study. The temperature results obtained from the COMSOL model showed an average error of 5.6% and 5.7% compared to experimental data obtained for the outlet temperatures of the air and CO_2 streams, respectively (Figure 3).

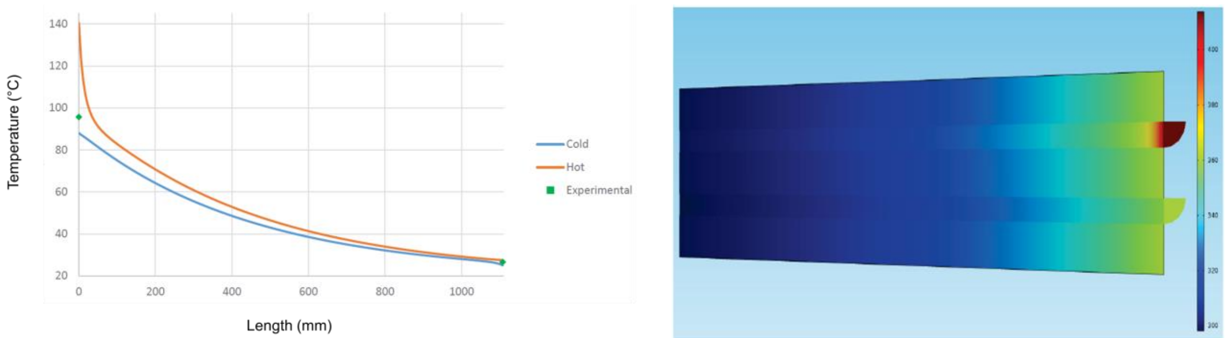

Figure 3: Subcritical test results for the PCHE under study.

Supercritical CO_2 Results:

Commissioning of the supercritical test rig is currently underway. Preliminary test results with CO_2 working fluid, approaching the critical point, is depicted in Figures 4 and 5. The temperature plots represent transient behavior of a compact heat exchanger due to a sudden surge in mass flow rate of the hot stream. The temperature trends depict the response of the system over time, as the system approaches steady-state again.

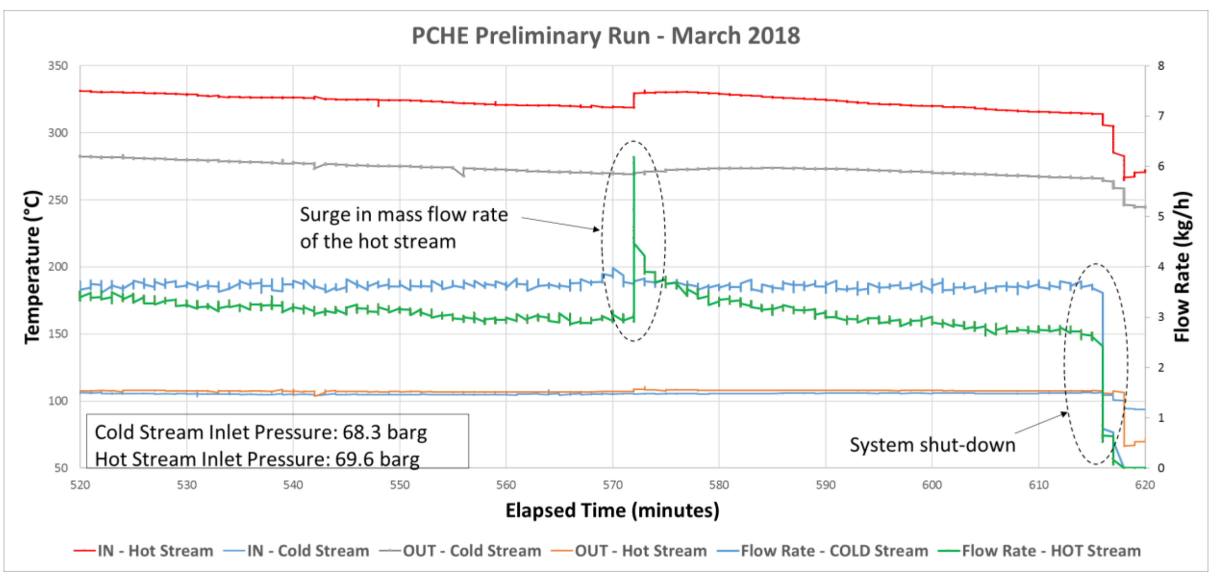

Figure 4: Temperature and mass flow rate plots at near critical point.

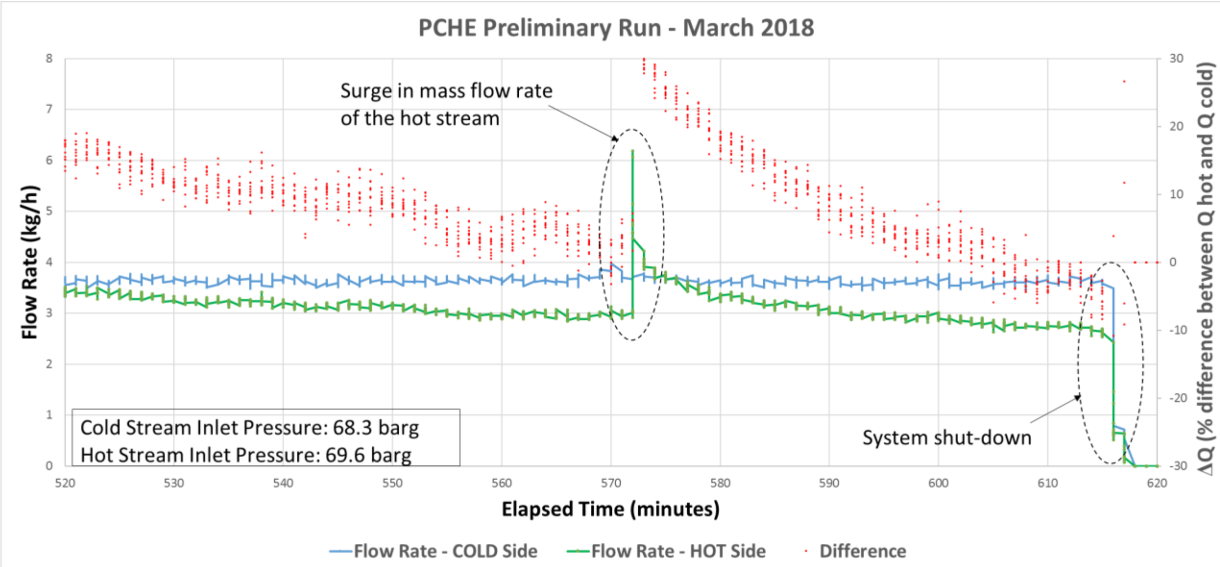

Figure 5: Mass flow rate plots and transient response at near critical point.

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BIOGRAPHIES

Dr. Kourosh Zanganeh 	Dr. Zanganeh is a senior research scientist and group leader of Oxy-combustion/G2 at NRCan/CanmetENERGY-Ottawa. He holds a Ph.D. degree in Mechanical Engineering from McGill University. Since joining NRCan in 1998, he has been involved in research and development of advanced energy conversion systems and processes for control of emissions, including CO_2. He was the Canada's representative to IEA Clean Coal Centre's Executive Committee from 2004-14, managed CanmetENERGY's CO_2 R&D Consortium (a CSLF-recognized project), and served as a member of Technical Group in Canada-Alberta's CCS Task Team, to name but a few. The current focus of his research group is on developing zero-emission and transformational technologies, including Supercritical CO_2 power cycles and pressurized combustion systems, CO_2 capture and utilization (CCU), waste heat recovery, renewable energy integration and energy storage systems.
Dr. Ahmed Shafeen 	Dr. Shafeen is a research scientist at NRCan/CanmetENERGY-Ottawa and holds a Ph.D. degree in Chemical Engineering from University of Waterloo. Since joining NRCan in 2004, he has been involved in various research projects related to supercritical-CO_2 power cycles and pressurized combustion systems, CO_2 capture and utilization, oxy-fuel combustion, and waste heat recovery systems. Prior to joining CanmetENERGY, he did pioneering research work on CO_2 sequestration opportunities in the province of Ontario, Canada. He also has seven years of process/environmental engineering experience in urea fertilizer plants.
Maria Abbassi 	Maria is a research engineer at NRCan/CanmetENERGY-Ottawa. She holds a B.ASc. degree in Chemical Engineering from University of Ottawa. She joined the Oxy-Combustion/G2 Group as a research engineer in 2010. Her research focus includes modelling and development of near-zero emission fossil fuel energy conversion systems and CO_2 capture technologies. Maria has been involved in a number of research projects since 2010. She is currently pursuing her M.ASc. degree in Chemical Engineering at the University of Ottawa.

Ashkan Beigzadeh 	Ashkan is the senior research engineer of the Oxy-combustion/G2 Group at NRCan/CanmetENERGY-Ottawa. He holds a Master's degree in Chemical Engineering and is currently pursuing his Ph.D. at the University of Waterloo. Ashkan has been involved in a number of research projects since he joined CanmetENERGY in 2009. Ashkan's research background and interests include: thermodynamics and detailed kinetics of pressurized energy conversion systems, techno-economic modeling, as well as design of pilot-scale test campaigns. These include clean heat and power generation technologies, CO_2 utilization, and their integration with renewable energy sources, and energy storage systems.
John Nema Najafali 	John is a research engineer in the Oxy-combustion/G2 Group at NRCan/CanmetENERGY-Ottawa. He holds a B.ASc. in Mechanical Engineering from the University of Ottawa. Since joining NRCan in 2015, John has been involved in engineering design, procurement and construction of several R&D projects, including vapour-liquid equilibrium testing of CO_2 mixtures, testing of compact heat exchangers for supercritical CO_2 applications, flue gas pollutant capture and water separation, waste-heat recovery from industrial processes, and supercritical CO_2 power cycles.
Dr. Henry Saari 	Dr. Saari received his Ph.D. in Aerospace Engineering from Carleton University in 2003. His Ph.D. research was part of a collaborative research program between Carleton University, Pratt and Whitney Canada, and the Institute for Aerospace Research, National Research Council Canada on the development and modelling of directionally solidified titanium aluminide alloys. He is currently Associate Professor in the Department of Mechanical and Aerospace Engineering at Carleton University. Dr. Saari's research includes processing, properties, and joining of gas turbine materials, corrosion of materials in supercritical carbon dioxide, and supercritical carbon dioxide Brayton cycle development.
Amr Daouk 	Amr is a research engineer working with Carleton University in the supercritical CO_2 Brayton cycle development team. He received his M.Sc. in Mechanical Engineering from Carleton University in 2016. His Masters research was a collaboration between Carleton University and NRCan/CanmetENERGY-Ottawa on the modelling and testing of a printed circuit heat exchanger using Air and CO_2 as the working fluids. Currently he is working on high temperature material corrosion testing in supercritical CO_2 environment.