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Ceramic, Microchannel Heat Exchangers for Supercritical Carbon Dioxide Power Cycles

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Dr. Charles Lewinsohn has extensive experience in design and fabrication of ceramic, microchannel components. He has transferred ceramic, microchannel products from lab to pilot line to manufacturing plant and has a background in reliability and mechanical behavior of ceramics. Dr. Lewinsohn has an S.B. in Materials Science and Engineering from The Massachusetts Institute of Technology and M.S. and Ph.D. degrees in Ceramic Science from The Pennsylvania State University. He has published over 75 peer reviewed papers and proceedings and has given several invited talks on ceramic microchannel devices, including heat exchangers. From 2005 to 2015, he was Project Manager for The ITM Oxygen project at Ceramatec, aimed at commercializing ceramic membrane technology for gasification and carbon capture in combustion-based power production. Currently he is Director of Research at Ceramatec with the charter to develop new, commercial technologies at Ceramatec.

Introduction

Power cycles using supercritical carbon dioxide (SCCO2) offer high efficiency for power generation systems using fossil, nuclear, concentrated solar, geothermal, and recovered waste heat[i,ii]. The high efficiency is a result of the reduced penalties in the work of compression associated with the use of a supercritical fluid relative to the benefits gained by high pressure recuperation[iii]. Recuperation is key to obtaining high thermal efficiency and reducing carbon emissions. The relatively high pressure associated with SCCO2 cycles may cause excessive creep or buckling in conventional heat exchangers. Compact heat exchangers are subject to significantly lower stresses than metallic heat exchangers under the same external load, due to the small scale of the structures. Ceramic materials, such as silicon carbide (SiC), can be used at significantly higher temperatures due to the nature of the covalent bonds in their crystalline structures providing greater creep resistance than the nickel-based alloys, further extending the maximum pressure limit of compact heat exchangers.

Ceramatec has developed innovative microchannel designs and manufacturing methods to produce scalable, cost- effective ceramic recuperators with high reliability, high heat transfer efficiency, and low pressure-drop suitable for deployment in large-scale power cycle applications. In addition to high effectiveness, excellent creep resistance, and ease of manufacturing, ceramic heat exchangers can be fabricated from materials with significantly lower cost, per kilogram, than nickel-based alloys. Ceramatec uses a modular approach to assembling ceramic heat exchangers that scales easily for both a wide variation in size, capacity and temperature. The Colorado School of Mines has analyzed specific requirements for high temperature recuperation in microturbine systems and the effect of microchannel design parameters on performance. This paper will discuss the principles of fabrication of Ceramatec's, ceramic, compact heat exchangers, some results from heat transfer testing, and the development tasks required for application of these heat exchangers in supercritical carbon dioxide power cycles.

Fabrication Methods

Ceramatec's ceramic, compact, heat exchanger is based on a shell and plate design (Figure 1) consisting of modular stacks of identical plates containing microchannels. Fabrication consists of producing microchannel plates and, subsequently, bonding them into stacks. Stacks are then connected by manifolds to each other or to external piping. The design is such that the temperature of the ceramic to metal joints will be relatively low. Therefore, standard ceramic to metal joining methods, such as brazing, can be used. By utilising well-established commercial manufacturing techniques, the production costs of ceramic heat exchangers becomes extremely competitive. When the temperature and performance capabilities are considered, compact, ceramic heat exchangers compared very favourably with heat exchangers made from expensive superalloy materials. Although exact costs will vary with specifications and assumptions such as the annual volume of production, the heat exchangers described in this paper are estimated to perform thermal duty for roughly $50-100/kW[iv]. These costs are competitive with compact heat exchangers made from superalloys, yet ceramic heat exchangers can operate at temperatures as much as 150°C higher and at higher pressures due to the superior creep and oxidation behaviour of ceramic materials relative to that of superalloys.

Production of the microchannel plates involves six primary operations: powder processing, slip mixing, tape casting, tape featuring, lamination, and sintering. In some cases, powder can be procured with the appropriate characteristics for downstream processing. In other cases, raw materials must be prepared using appropriate combinations of blending, calcining, and milling. Typically, specific surface area, particle size distribution, and phase distribution are specified to meet production requirements. For a silicon carbide heat exchanger, commercially available powder (UF-15, H.C. Starck) with a high specific surface area was used to promote densification. Mixtures of organic binder, plasticiser, and solvent were prepared and the powder was subsequently added and mixed on a roller mill to produce the slip used for tape casting. Tape was cast by the doctor blade method. Tape was then cut into sheets or punched, or both, and cut using flying-optics style laser cutters, see Figure 2. The laser cutters cut the appropriate design for each layer of the microchannel plates. The material removed created the space for the microchannels, whereas the remaining material formed the channel walls. The top and bottom of channels was formed by the surfaces of adjoining layers. Examples of features that can be fabricated using this approach, including those incorporating porous layers, are shown in Figure 3. The plates are

Figure 1 Modular stack design of a ceramic, compact heat exchanger.

Figure 2 Typical laser featuring equipment (a), and (b) their operation, used to produce microchannel layers.

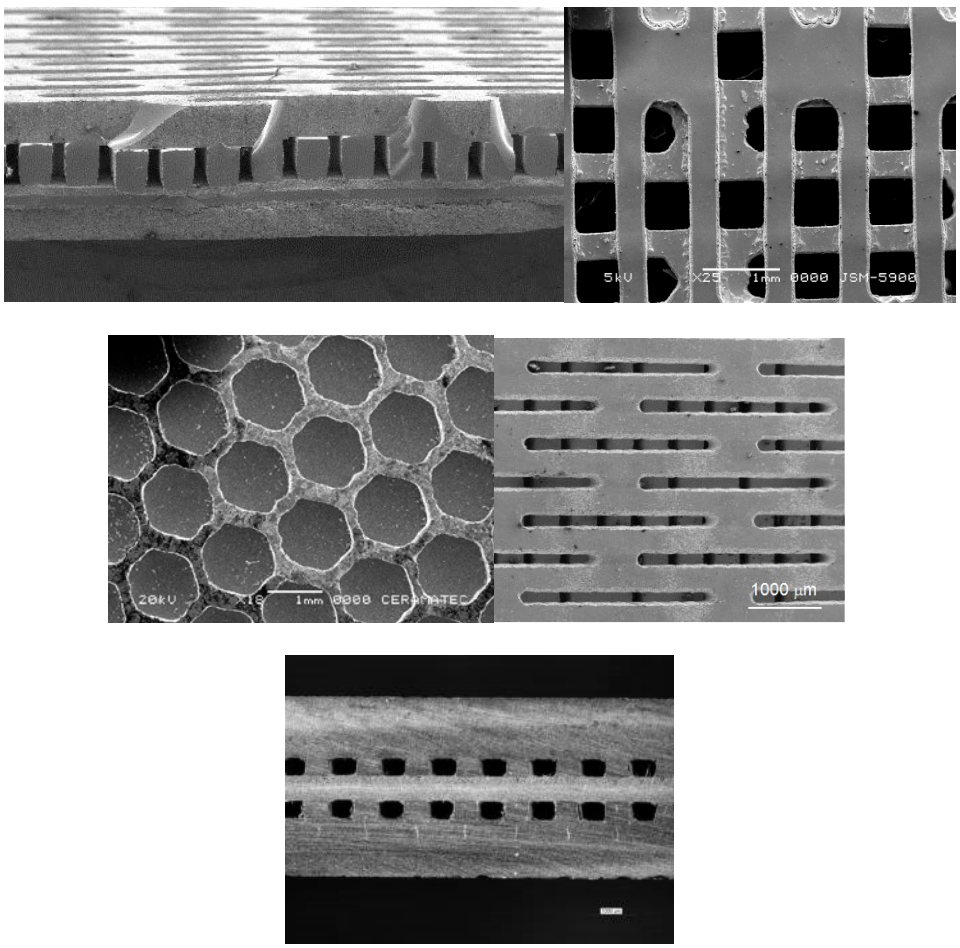

Figure 3 Examples of microchannel features produced by laser featuring.

formed by laminating the featured or unfeatured layers together using combinations of heat and pressure. Plates are subject to a thermal cycle that removes the organic binders and plasticisers and then densifies the components via sintering, resulting in components that can be joined together to form the modular stacks described earlier, see Figure 3. As an example of the compact size of these stacks, the external dimensions of a heat exchanger stack for 5 MW power system would be about 0.15 m^3.

Experimental Results

Numerical modeling, performed at The Colorado School of Mines, was used to determine the optimum channel dimensions and flow conditions for air-to-air heat exchange in conditions expected in commercial microturbine systems. The results, shown in Figure 4 indicate that maintaining the Reynolds number in the channels below 600 and using channels with a width/height ratio around 1.2 leads to the lowest pressure drop. The box in Figure 4 outlines the design window for best performance. Computational fluid dynamics calculations show that ceramic, compact heat exchangers exhibit the expected relationships amongst effectiveness, temperature and pressure drop (Figure 5). These relationships are anticipated to follow similar trends for systems on the scale of SCCO2 power cycle turbines. The effectiveness increases with pressure drop for a fixed approach temperature. The effectiveness decreases with increasing approach temperature for a fixed pressure drop. To achieve values of effectiveness greater than 0.85, low approach temperatures, i.e. < 70°C, are required.

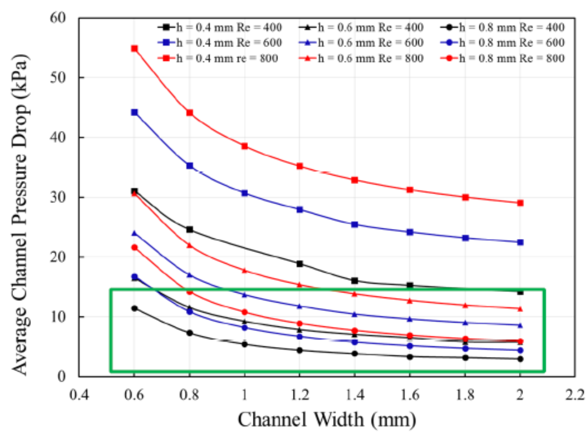

Figure 4 Channel pressure drop versus width for several Reynolds numbers and channel heights.

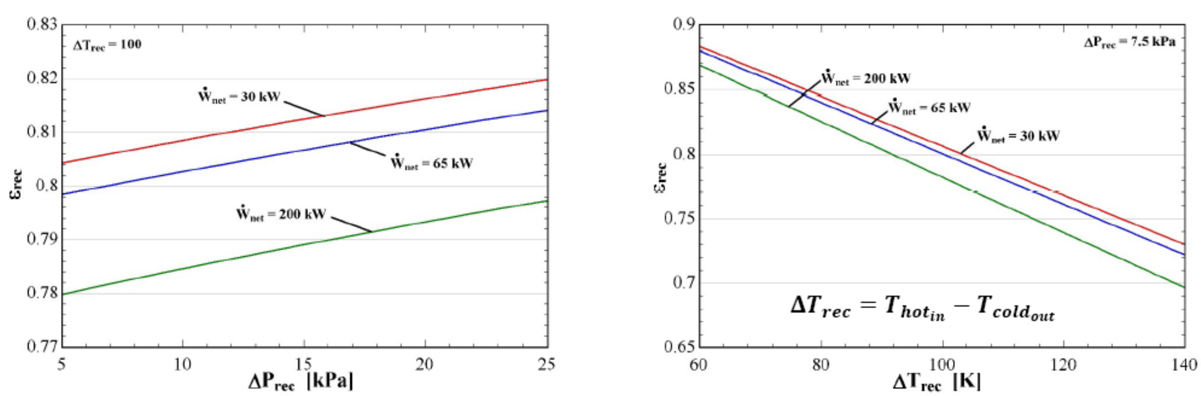

Figure 5 Heat exchanger plate effectiveness as a function of pressure drop (left) or approach temperature (right).

The effect of the microchannel geometry on heat transfer has been evaluated by testing individual heat exchanger plates at Ceramatec. Ceramic tubes are bonded to single plates that are subsequently lowered into a high temperature furnace. The ceramic tubes are inserted through holes in the bottom of the furnace so that they can be connected, via compression fittings, to metallic supply and exhaust lines. The furnace is heated up while air flows continuously, at 5 slpm, through the microchannels of the plate. When the furnace reaches temperature, the furnace temperature and the temperature of the inlet and outlet to the microchannels is measured. The plate inlet and outlet pressures are measured so that the pressure drop through the microchannels can be quantified. Figure 6 shows an experiment where the flow through the microchannels was adjusted while the furnace temperature was held at either 400°C or 800°C. The results, from this unsophisticated test, indicate effective heat transfer through the plate into the microchannels due to the low approach temperatures measured.

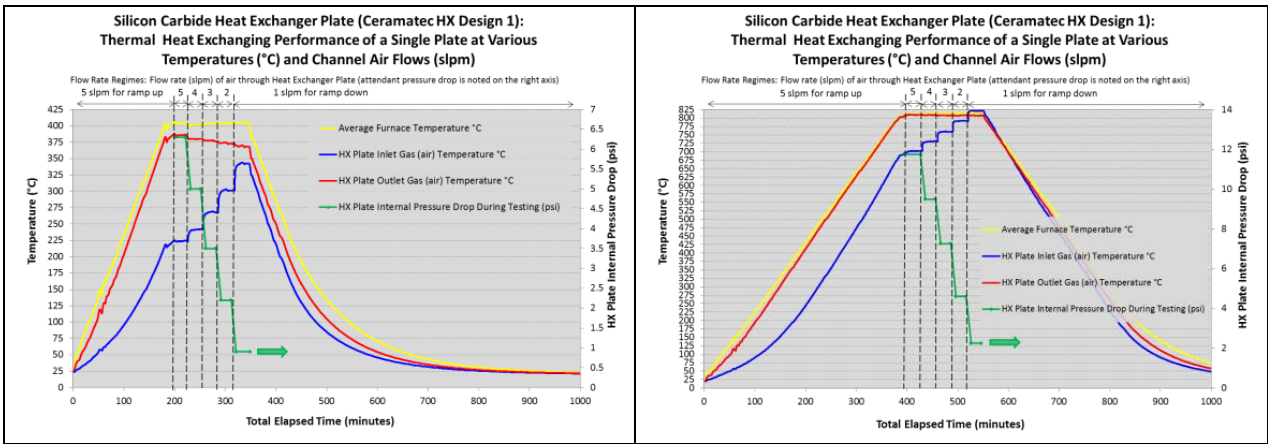

Figure 6 Initial results from single-plate testing at 400°C and 800°C in stagnant air.

Future Challenges

Although Ceramatec's fabrication method is capable of producing scalable, modular heat exchanger stacks in high volume at relatively low cost, additional development is required prior to commercialization. Design and performance models need to be verified on a statistically significant basis. Heat exchanger reliability and durability needs to be demonstrated on a meaningful population for representative duty cycles. For use in SCCO2 power cycles, designs need to be developed and tested, analysis of reliability needs to be performed, environmental effects of supercritical carbon dioxide on relevant materials needs to be investigated, and viable means of integrating modular heat exchangers into the balance of plant need to be verified.

Conclusions

Ceramic, compact heat exchangers can offer high effectiveness at elevated temperatures and pressures at competitive cost. Although this technology is in development, it is very attractive for power cycles using supercritical carbon dioxide and high temperature cycles where recuperation is the key to obtaining high efficiency. Ceramatec has developed methods for fabricating scalable, modular heat exchangers using cost effective, conventional processing methods. Additional testing to verify performance and reliability are required.

i D.J. Mollot, “Power Cycles Based on Supercritical CO2 – Applications, Challenges and Benefits,” Proceedings 4th International Symposium on SCO2 Cycles, Pittsburgh, PA, September, 2014.

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iii C.M. Invernizzi, Closed Power Cycles: Thermodynamic Fundamentals and Applications, Springer-Verlag, London, 2013.

iv M.A. Wilson, C.A. Lewinsohn, J. Cutts, V. Ponyavin, “Design of a Ceramic Heat Exchanger for Sulfuric Acid Decomposition,”IMECE2006-16044, ASME International Conference & Exhibition, Nov. 2006, Chicago, IL, USA.