High-efficiency, ceramic microchannel heat exchangers

Microchannel structures in ceramic heat exchangers effectively improve efficiency of energy-intensive processes.

By Charles Lewinsohn

This article explains how ceramic, microchannel heat exchangers can improve the efficiency, lower the cost, and reduce emissions of a large number of energy-intensive applications. It also discusses the need to use ceramics to obtain higher efficiencies than that of existing heat exchangers; how microchannel designs enable the use of ceramics in reliable and highly efficient heat exchangers; and how ceramic microchannel heat exchangers can be fabricated for use on an industrial scale at economical costs.

There are many technologies for harvesting thermal energy, and heat exchangers are one of the most efficient and economical. Because much of the primary energy used to power modern lifestyles is lost as waste heat,[1] significant improvements in thermal efficiency will provide significant reductions to cost and carbon dioxide emissions associated with using energy. The concentration of carbon dioxide in the earth's atmosphere is increasing at rates higher than any previously known timeframe.[2] Therefore, prudence would seem to dictate reducing and capturing carbon dioxide emissions as well as mitigating their potential impact. Low-cost, high-efficiency heat exchangers are a key to improving efficiency and reducing emissions in a variety of industrial applications in a highly economical manner.

Heat exchangers transfer heat from a hot medium to a cooler one, typically through a solid wall. They are widely used in chemical engineering practice to transfer heat energy from one process stream to another. The heat transferred may be latent heat accompanying a phase change (vaporization or condensation) or sensible heat from increasing or decreasing the temperature of a fluid without phase change—or both. The Carnot cycle describes the idealized efficiency of these processes. By recovering thermal energy rejected during a process, a heat exchanger reduces energy that must be added to the system to achieve the same net change in entropy, thereby increasing efficiency. Heat exchangers also can be used for cooling, in which case they improve efficiency in the same manner. Early

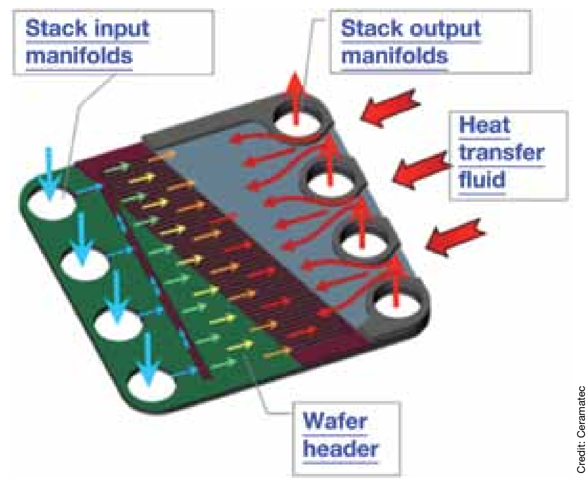


Figure 1. Schematic design of a microchannel plate for a ceramic heat exchanger.

trials of ceramic recuperators installed on industrial furnaces for metals and ceramic materials processing and component production measured fuel savings ranging from 12% to 61%, depending on operating conditions.[3]

Heat exchangers also convey heat to or from materials that may react with the source of the heat or the heat transport medium. For example, heat exchangers can be used for indirect heating to prevent unwanted combustion products from reacting with fuel cell materials or materials in melt furnaces. Therefore, heat exchangers are useful over a broad range of temperatures, for an equally broad range of applications.

High-temperature heat exchangers that increase efficiency across a broad spectrum of applications and economic sectors can be obtained by combining ceramic materials with intrinsically reliable, low-cost microchannel designs. Ceramic microchannel heat exchangers can increase efficiency for recuperators in existing turbines powered by fossil fuels; allow heat from high-temperature nuclear reactors to provide a transitional, low-carbon energy source; and, ultimately, ensure viability of renewable energy, such as thermal solar systems, to reduce energy-related and greenhouse gas emissions and eliminate imports of energy. In the immediate future, compact ceramic heat exchangers can be used to recover waste heat from gas-fired furnace flue gases, recirculating air in kilns, glassmelting and metalmelting furnaces, and numerous industrial processes in the chemical and petrochemical industry. Durable, low-cost ceramic heat exchangers also have application in automotive intercooling, point-of-use water heaters, and power electronics cooling. Microchannel

Capsule summary

IMPROVEMENT OPPORTUNITY

Waste heat is a result of inefficient processes, which also cause higher unwanted emissions.

HEAT RECOVERY

Low thermal conductivity ceramics with microchannel structures recover and transfer waste heat in high-temperature and corrosive environments.

APPLICATIONS

Heat exchangers reduce energy needed to raise temperatures of process liquids and gases and thereby improve efficiency of energy-intensive applications, such as electricity generation and gas-to-liquid conversion.

heat exchangers provide the foundation for numerous applications in process intensification, especially when combined with functional membranes and catalysts, which is an additional pathway to reduced energy consumption.

Ceramic materials offer many benefits for use in heat exchangers, including high-temperature capabilities and corrosion resistance. Although pioneering work was done in the 1980s on ceramic heat exchangers,[4] manufacturing costs and reliability proved barriers to widescale commercial use. More recently Ceramatec[5] (Salt Lake City, Utah), in collaboration with its parent company, CoorsTek (Golden, Colo.), and others,[6–9] has developed designs and fabrication methods capable of producing highly efficient microchannel reactors and heat exchangers at low cost. Furthermore, the fabrication cost of these high-efficiency, ceramic microchannel heat exchangers with complex designs is likely competitive with those of metal components made by stamping, brazing, and welding of select, and often expensive, alloys.

Figure 1 shows a typical microchannel design for a ceramic heat exchanger. Table 1 compares the performance and cost of compact, ceramic heat exchangers with other designs and materials.

These unique ceramic microchannel heat exchangers offer high effectiveness at temperatures far above existing technology, offering step changes in system efficiencies and concomitant reductions in emissions. Microchannel designs couple multiscale physical behavior of enhanced transport at the microscale with macroscale heat and mass flows. Advanced ceramic materials allow operation at temperatures currently unobtainable by conventional materials.

Ceramatec has developed an innovative approach to fabricate microchannel components using advanced ceramic materials to produce systems capable of high efficiency under conditions

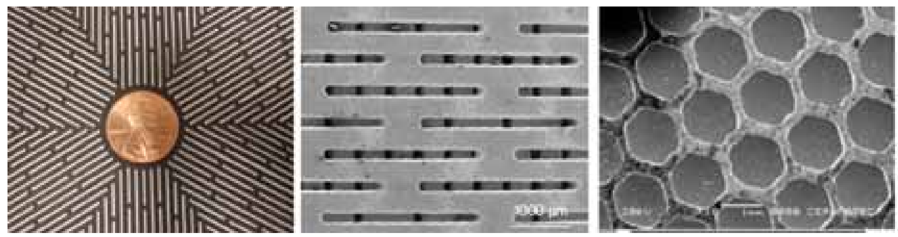


Figure 2. Examples of ceramic microchannel designs fabricated by Ceramatec showing a green layer (far left) and sintered layers (middle and right).

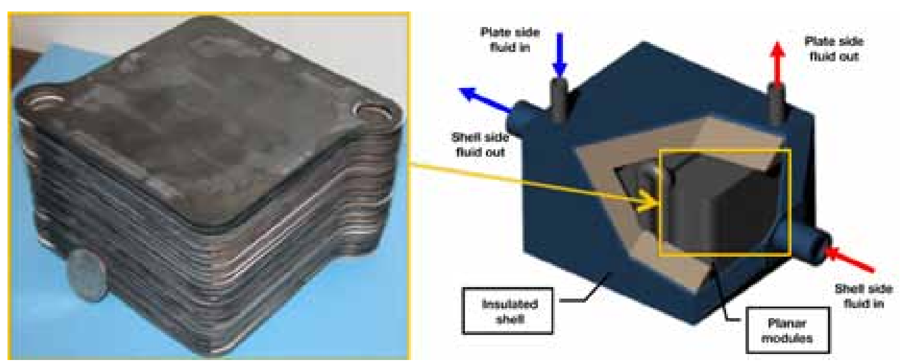


Figure 3. A stack of silicon carbide heat exchanger plates (left) and a conceptual design of modular, microchannel plate heat exchanger for a macroscale process (right).

beyond the regime of existing technology. Ceramatec's modular design allows industrial scale systems to be built from identical, engineered microchannel components (Figure 2) assembled in arrays of modules (Figure 3) for numerous applications.

Design and reliability

Designs and fabrication methods for heat exchangers have been relatively constant for almost 100 years. Incremental advances in performance have occurred through improved alloys or superalloys. More significant advances were made with the introduction of microchannel heat exchangers, now beginning to enter commercial use. These remain costly and limited to a small set of materials for construction.

In conventional heat exchangers, thermal conductivity of the transfer layer governs resistance to heat transfer and, hence, efficiency. In microchannel heat exchangers, on the other hand, convective transport terms related to the flow rates and geometries govern resistance, not thermal conductivity of

Table I. Comparison of calculated performance and cost targets for heat exchanger designs and materials

Technology	Status	Upper use temperature (°C)	Effectiveness†	Lifetime (years)	Cost ($/kW)
Superalloy, conventional designs	Existing	700	0.6–0.9	5	20–50 (Ref 12)
Metallic microchannel	Existing/emerging	700	0.8–0.9	5	175–300 (Ref 12)
Ceramic microchannel	Target*	800–1300	>0.9	5 to >10	100

†Effectiveness is the ratio of actual heat transfer rate to maximum possible heat transfer rate.
*Values have yet to be verified.

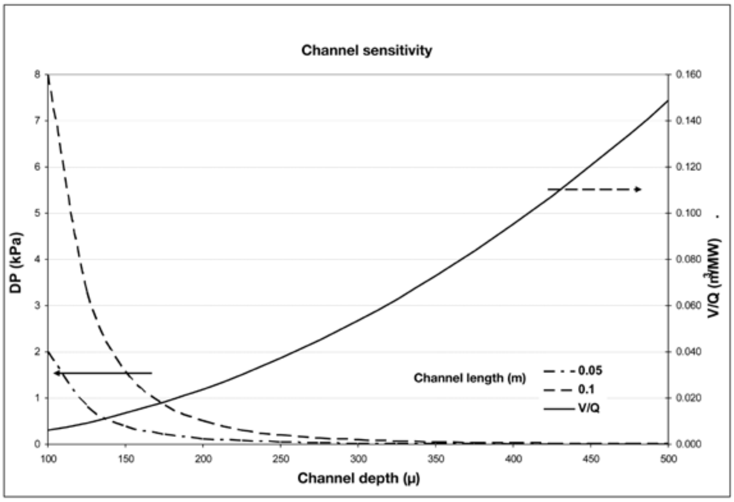


Figure 4. Competing effect of channel depth and device performance, *V/Q*, on pressure drop.

the heat transfer layer. Materials with high thermal conductivity promote axial conduction along microchannel walls, which reduces the temperature gradient and driving force for heat transfer. Therefore, high effectiveness is obtained using materials with moderate thermal conductivities, such as ceramics. Another benefit of using ceramics with high melting temperatures is that heat exchangers are capable of operating at temperatures well above the limits of existing designs.

As described above, increasing the operating temperature increases system efficiency, resulting in reduced operating costs and emissions.

The high effectiveness of microchannel and other compact heat exchanger designs results from extremely high surface-area-to-volume ratios. Ratio of the volume, V, of a compact heat exchanger to the heat flux through it, Q, can be a figure of merit for performance. A low value is desired, because this represents a large amount of heat transfer in a small volume. To maximize performance, one would minimize microchannel depth, d. However, to reduce pressure drop, which requires external work and reduces the efficiency of the overall system, one would maximize hydraulic diameter ($D_h \approx 2d$), as shown in Figure 4.

The small heat and mass transport distances associated with compact designs ensure adequate heat transfer, even under laminar flow conditions. Therefore, pressure drop is reduced by maintaining laminar flow inside microchannels. Typically, channel dimensions are selected such that Reynold's numbers are less than 1,000 and, ideally, in the range of 500–600. (Reynold's number, Re, is the dimensionless ratio of inertial forces and viscous forces. It helps describe fluid flow in a tube or around an object.) Ceramatec's designs often have greater than 300 m^2 of heat transfer surface per cubic meter of total heat exchanger volume. Pressure measurements at various locations along exposed channels of microchannel plates have been used to confirm computational fluid dynamics methods used to design the plates (Figure 5).

Calculated reliability of these designs is significantly greater than shell and tube designs for the same thermal duty, because microchannel structure mechanically reinforces the heat transfer layer.[10] Weibull analyses performed during the design stage of Ceramatec's components help guide iterations and aid comparison with conventional shell and tube heat exchangers. Laboratory testing, such as four-point flexural strength tests, provides Weibull parameters for the materials of construction. Stress states over the microchannels, or other areas of interest, are calculated using finite-element methods.

Component and system analysis often is simplified using local models that use input from global analysis (Figure 6). As an approximation, the probability of failure, P_f, for a single heat transfer layer spanning a microchannel (Figure 7) can be calculated using closed-form solutions for a simply sup-

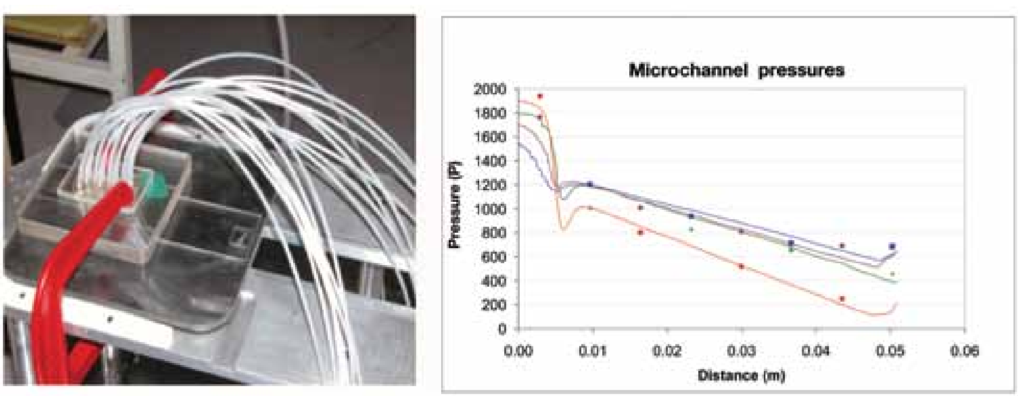


Figure 5. Apparatus for measuring pressure in microchannel components (left), and comparison between measured (points) and computed (lines) pressure in a microchannel heat exchanger plate as a function of position (right).

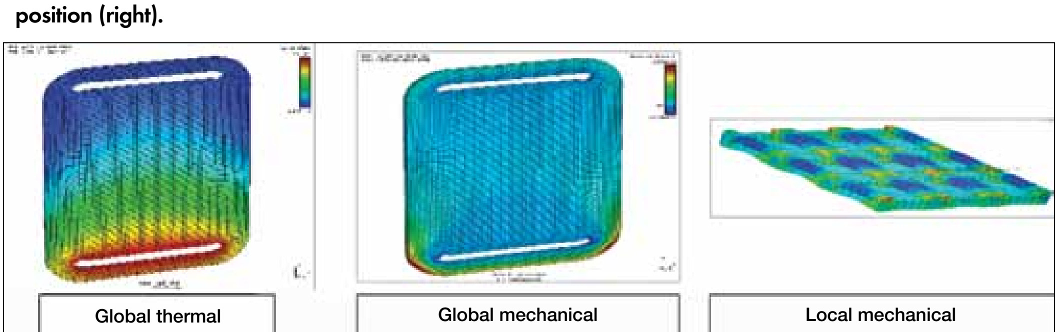


Figure 6. Finite-element modeling of local stress state over microchannels.

ported plate under uniform pressure. Effective pressure can be determined from a local finite-element analysis. For design, P_f is calculated as a function of the dimensions of microchannel components. Figure 8 shows how calculated reliability of a single microchannel of a gas-to-gas heat exchanger depends on its dimensions and Weibull properties of the microchannel material. Figure 8 also shows that the design is more than an order of magnitude more reliable than design requirements. Required P_f determines the allowable stack size for a single module in a given application. The results shown in Figure 8 imply that heat exchanger stacks could have thousands of microchannels and continue to maintain P_f below one in a million.

Fabrication

Ceramatec uses a laminated-object-manufacturing (LOM) approach based on laminating tape-cast material to produce plates that function as the basic repeat unit for modular designs. A wide range of channel sizes and orientations is possible (Figure 2). This method of producing plates is similar to that used for making multilayer capacitors, which is capable of producing high volumes of material at low cost. Using these methods, Ceramatec has made components from silicon carbide, mullite, alumina, zirconia, and several specialty oxide compositions. Ceramatec has produced thousands of parts per year on its pilot line facility and demonstrated transfer of the process to a full-sized manufacturing facility. CoorsTek (Golden, Colo.), in conjunction with the Colorado School of Mines (Golden, Colo.),[8] also has developed methods for dry-pressing channels into green parts that are subsequently cosintered to make microchannel plates (Figure 9). This approach is low cost and suitable for designs where slightly lower surface-area-to-volume ratios are acceptable. Other fabrication approaches exist, including several additive manufacturing methods. These approaches have yet to prove competitive for production of ceramic microchannel components at high volume. Sommers[9] reviewed a number of ways to fabricate ceramic microchannel heat exchangers. Each processing method has unique costs and capabilities. Therefore, users need to

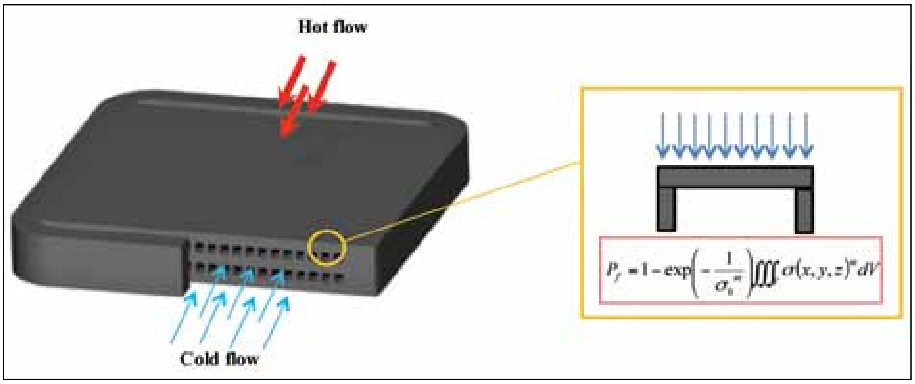


Figure 7. Simple model demonstrating reliability of microchannel heat exchangers.

be aware of the role of key design features on performance.

Ceramatec makes its microchannel plates by blending powders of desired compositions with binders, plasticizers, and solvent to make a suspension. Tape casting produces tapes of varying thickness from 10 μm to 1,000 μm, depending on design requirements. Features are added to resulting tapes using methods, such as mechanical punching, laser cutting, water-jet cutting, or embossing. The "featured" tapes are laminated together to form microchannel components and then sintered. Figure 10 shows examples of processing equipment used at Ceramatec's processing facility.

Heat exchanger devices are fabricated

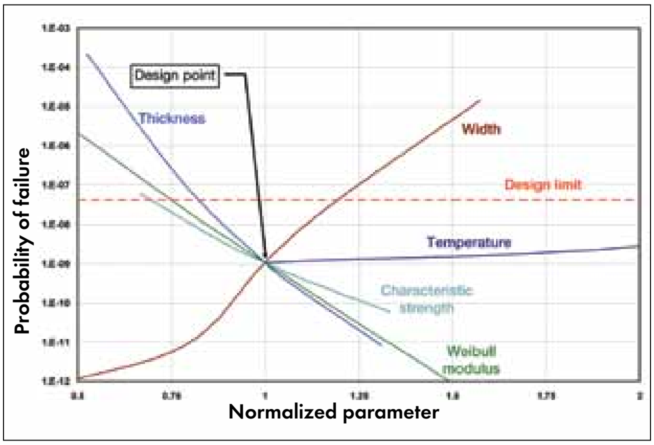


Figure 8. Sensitivity of microchannel reliability to design parameters.

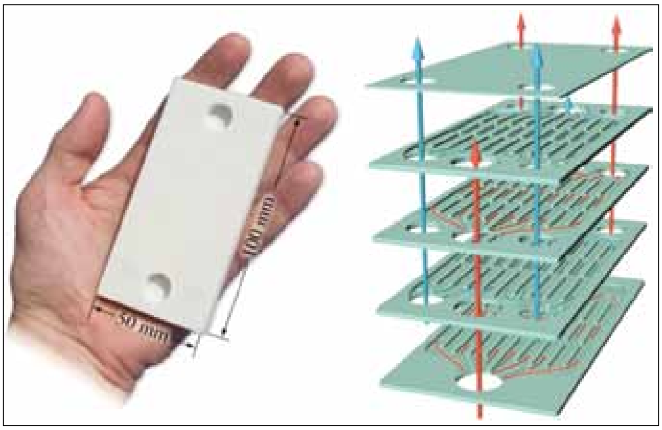


Figure 9. Alumina microchannel component made by dry-pressing and green-joining.

Figure 10. Processing equipment used at Ceramatec. Clockwise, from top left, tape caster, laser cutters, mechanical punch, sintering furnace, and lamination press.

Credit: Ceramatec

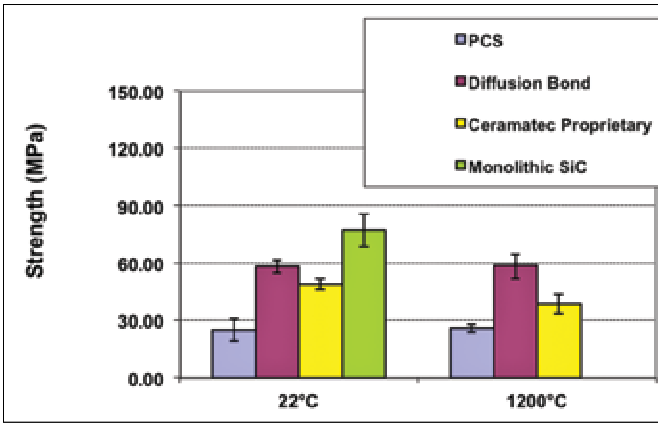
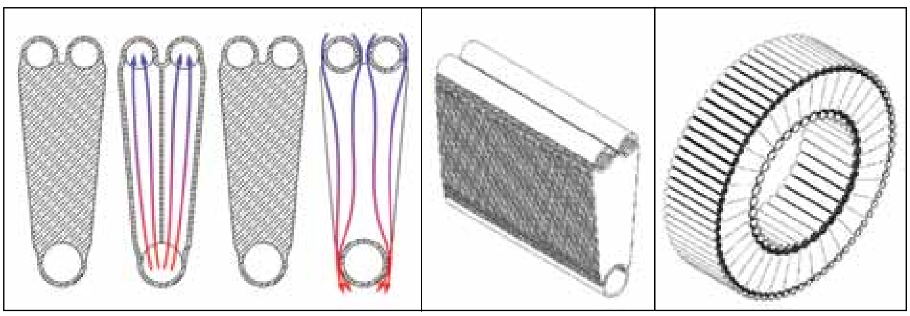


Figure 11. Shear strength of joints as a function of test temperature for three bonding approaches.

Credit: Ceramatec



Credit: M. Vick, U.S. Naval Research Laboratory

Figure 12. Design of a microchannel recuperator for a microturbine showing the microchannel architecture (left), a modular segment (middle), and the complete assembly.

Credit: Ceramatec

Figure 13. Segment of mullite microturbine recuperator fabricated at Ceramatec.

by joining individual microchannel plates. A variety of methods—such as diffusion bonding, brazing, glass bonding, ceramic cements, and polymer-derived ceramic adhesives—can join plates. Joints must have sufficient mechanical properties to withstand service conditions reliably; they must have sufficiently low leak rates to prevent undesired mixing of fluids; and they must be able to be manufactured in a manner that does not reduce performance of the completed assembly.

Therefore, Ceramatec has developed methods for joining heat exchanger plates at temperatures far below those at which individual plates exhibit creep. For example, preceramic precursors, such as polycarbosilane (PCS), convert to covalently bonded ceramic material after pyrolysis and thermal treatment at temperatures around 1,000°C to form polymer-derived ceramic joints. Ceramatec also has developed a proprietary braze that enables bonding silicon carbide below 1,200°C. Details of these materials and their evaluation are given elsewhere.[11] Figure 11 compares the shear strength, at room temperature and 1,200°C, of joints made by these methods between silicon carbide substrates compared with that of a diffusion bond.

Application—High-temperature microturbines

Microturbines, referring to combustion-driven turbomachinery producing power in the 50–250 kW range, are attractive for highly efficient distributed power applications and in primary or load-levelling capacities. Although centralized power stations can take advantage of economies of scale in controlling emissions, it is likely that distributed power systems with efficiencies of 35%–40% or greater will have similar emissions profiles and facilitate the transition to cleaner fuels. Obtaining efficiencies of 35%–40%, however, requires higher turbine inlet temperatures and recuperation of heat from exhaust gas.[12] In fact, the major contributor to improved efficiency is not increased turbine inlet temperature, but reduced heat required to raise turbine inlet temperature, thanks to heat exchange from the exhaust gas.[13]

In conjunction with the U.S. Naval Research Laboratory (Washington, D.C.), Ceramatec fabricated sections of a prototype radial recuperator for a high-efficiency, 3-kW engine. The design, shown in Figure 12, consisted of modular segments surrounding the combustion chamber and turbine sections of an engine, with one inlet port and two outlet ports for exhaust gas, flowing through microchannels. Gaps between heat exchanger plates allow inlet air to flow. To meet design requirements, plates were made from mullite. Individual plates were fabricated using methods described above and bonded after sintering to make leak-tight segments (Figure 13). Additionally, several sections were made successfully in a one-step firing that sintered plates and bonded them together. Testing at the Naval Research Laboratory confirmed that the design provided 87% effectiveness with very low pressure drop: < 1% for air flow, and about 9% for exhaust gas.

Application—Gas-to-liquids conversion

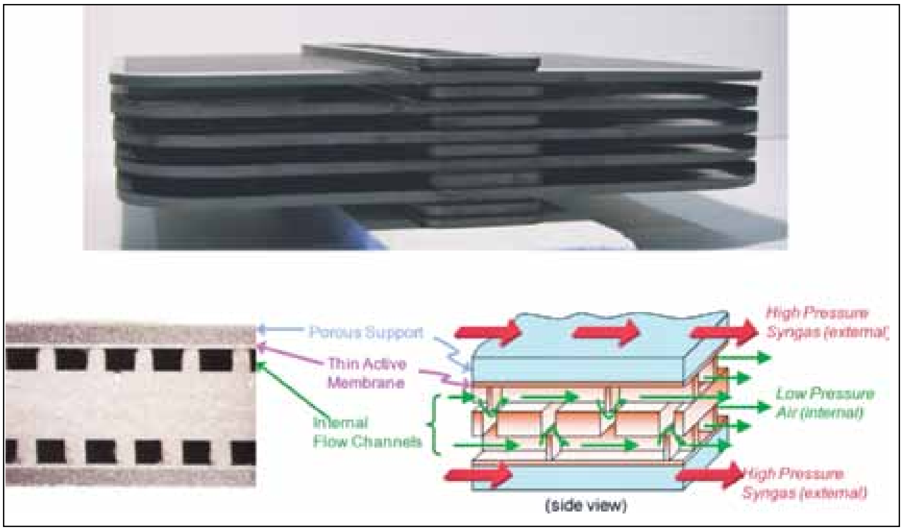
Ceramatec is developing advanced technologies for gas-to-liquid fuel conversion. A Fischer-Tropsch synthesis system—demonstrated at lab scale—utilizes plasma reforming and catalysts developed at Ceramatec to convert natural gas to liquid fuel. An engineering prototype reactor system under construction at Ceramatec will produce roughly 0.1 bbl/day of liquid fuel.

A prototype microchannel heat exchanger incorporated into the apparatus to recover heat from reformed gas will evaluate performance of ceramic microchannel heat exchangers in a chemical reactor environment. Heat will transfer to incoming gas to reduce energy required to heat it to reforming temperatures. Tests will run for several hundred hours to demonstrate long-term performance in combination with gas compositions and conditions relevant to industrial processes. Pressure, flow, and temperature will be monitored continually, and the heat exchanger will be subject to any planned or unplanned transients that occur. Further, testing will provide verification of ceramic-to-ceramic and ceramic-to-metal joining methods.

Application—Integrated heat exchange microreactors for process intensification

As microchannel heat exchangers gain acceptance and the benefits of ceramics are utilized in more and more applications, additional benefits of incorporating catalysts, membrane layers, and more complex microchannel designs to control multiple flow paths simultaneously are likely to be realized. Figure 14 shows catalytic membrane reactor components with porous catalyst support layers and a membrane to control reactions. Ceramatec, in collaboration with Air Products and Chemicals Inc. (Allentown, Pa.), and the U.S. Department of Energy, has developed a novel microreactor system incorporating an oxygen-ion-conducting membrane and catalysts that converts methane to synthesis gas (H_2 and CO_2) that can reduce CO_2 emissions when using natural gas to produce hydrogen, or as a precursor for chemical or fuels processing.

Likewise, others have demonstrated use of ceramic microreactors combined with catalysts coated on internal microchannel walls for autothermal reforming of methane, which requires deliberate thermal management to prevent runaway exothermic reactions.[14] Numerous applications for catalytic membrane reactors using dense, ceramic membranes have been reviewed by Dong et al.[15] and include methods for CO_2 recycling, water splitting to generate hydrogen, and NO_x control. These examples illustrate the enormous potential that ceramic microchannel devices have for process intensification,[16] with subsequent reduced capital and energy costs, in numerous applications in energy production and chemical processing.



Credit: Ceramatec

Figure 14. Clockwise from bottom right: Conceptual design for ceramic catalytic membrane reactor for process intensification; cosintered microchannel structure detail; and a modular component for prototype testing.

Summary

Significant amounts of energy are lost to waste heat, especially in electricity generation and transportation. Heat exchangers can improve significantly the efficiency of thermal processes. Ceramic materials enable heat exchangers to be used at higher temperatures, or in extreme environments where other materials degrade. Microchannel designs enable ceramic materials, with low thermal conductivities, to be used in heat exchangers with high effectiveness. Additional benefits of microchannel heat exchanger designs using ceramic materials are their compactness, enhanced reliability relative to other designs, and comparatively low manufacturing cost based on established, ceramic-processing methods. Ceramatec has demonstrated these benefits in the laboratory scale and is rapidly building prototype systems to facilitate commercial production.

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