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Ceramics and ceramic matrix composites for heat exchangers in advanced thermal systems—A review

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ABSTRACT

In air-conditioning and energy-recovery applications, heat exchangers are very important to the overall efficiency, cost, and size of the system. Current heat exchanger designs rely heavily on fin-and-tube or plate heat exchanger designs, often constructed using copper and aluminum. Recent developments in material science—in particular, advances in ceramics and ceramic matrix composites—open opportunities for new heat exchanger designs. Some research directed toward using these materials for heat exchangers in other applications has been reported; however, there has not been a comprehensive study of the use of these emerging materials in both conventional HVAC&R systems and emerging energy technologies. This review reports the current state-of-the-art of ceramic materials for use in a variety of heat transfer systems.

1. Introduction

The overarching objective of this work was the evaluation of current ceramic materials (both monolithic and composite) for use in heat exchangers, and the assessment of their potential benefits and feasibility for application in heat transfer systems. One of the major goals was to identify the most promising concepts of heat exchanger design using ceramics based on the available information from industry, patents, and the technical literature. In doing so, industries and applications where these materials are currently used were identified. The types of heat exchangers that were considered included evaporators, condensers, heat pump systems, gas coolers, tube banks and matrix surfaces.

The key features of ceramics were then investigated in order to target specific usages in heat exchangers. This investigation guided the development of a list of most feasible design alternatives to conventional technologies. The effort behind this work can be divided into three main aspects: replacement of construction materials for existing geometries, major change of configurations by adopting new geometrical concepts, and utilization of advanced fabrication technologies to maximize the benefit from new materials. The feasibility of implementation was also evaluated and addressed manufacturing issues such as bonding, the need for a controlled environment during assembly, manifold construction, and mechanical/structural stability. Unusual manufacturing or implementation techniques were also identified and assessed. The ultimate outcome from these efforts was the evaluation of the relative merits of ceramics to conventional materials in both emerging and traditional heat transfer systems.

2. Potential of ceramics and ceramic matrix composites (CMCs)

Solid materials holding promise for use in heat exchangers can generally be divided into four categories—polymers, metals, ceramics and carbonaceous materials. In many heat exchanger applications, these materials perform satisfactorily in their unmodified or non-reinforced form. However, in some applications advanced structural materials are needed to be stronger, stiffer, lighter in weight, and more resistant to hostile environments. Composite materials offer engineers an ability to create a limitless number of new material systems having unique properties that cannot be obtained using a single monolithic material. This approach to construction holds tremendous promise for future heat exchanger designs—rather than selecting a single material, multiple materials may be selected and then tailored to meet the specific requirements of the application. Composite materials are

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constructed of two or more materials, commonly referred to as *constituents*, and have characteristics derived from the individual constituents. The constituent that is continuous and which is often, but not always, present in the greater quantity in the composite is termed the *matrix*. The second constituent is referred to as the reinforcing phase, or *reinforcement*, as it enhances or reinforces the properties of the matrix [1]. By combining matrices with thermally conductive reinforcements such as special carbon fibers, SiC particles and diamond particles, it is possible to create new materials with high thermal conductivities and a wide range of coefficients of thermal expansion (CTEs). In this work, more detailed information about the properties of both ceramic monolithic materials and their composites - ceramic matrix composites (CMCs) - is provided. The use of these materials in heat exchanger design will also be discussed according to the intended application of the heat exchanger (i.e. liquid—liquid, liquid-gas, gas—gas, etc.).

The American Society for Testing and Materials (ASTM) defines a ceramic material as "*an article [whose] body is produced from essentially inorganic, non-metallic substances and either is formed from a molten mass which solidifies on cooling, or is* formed *and simultaneously or subsequently matured by the action of the heat*." Most ceramic materials are hard, porous and brittle so the use of ceramics in application often requires methods for mitigating the problems associated with these characteristics. Ceramic materials are usually ionic or covalently bonded and may be crystalline or amorphous in structure. Because of this type of electronic bonding, ceramics tend to fracture before undergoing plastic deformation often resulting in fairly low tensile strength and generally poor material toughness. Moreover, because these materials tend to be porous, the microscopic pores can act as stress concentrators further decreasing the toughness and strength of ceramics. These factors can combine, leading to a catastrophic failure of the material instead of the normally more gentle modes of failure associated with metals. Although often neglected, ceramics do exhibit plastic deformation. In crystalline materials, this deformation process occurs very slowly due to the rigid structure of the ceramic and the lack of slip systems for dislocations to move. For non-crystalline ceramic materials, viscous flow is the dominant source of plastic deformation and is also very slow. Table 1 gives a very brief overview of the typical properties of monolithic ceramic materials.

The two main advantages for using ceramic materials in heat exchanger construction over more traditional metallic materials are their temperature resistance and corrosion resistance. First, ceramic materials can withstand operating temperatures (i.e. 1400 °C) that far exceed those of conventional metallic alloys. For example, the bulk material temperature of a heat exchanger made of carbon steel should not exceed 425 °C. Similarly, the bulk material temperature of a heat exchanger manufactured from stainless steel typically should not exceed 650 °C [2]. As a result, the heat exchanger must be protected in some applications. Thermal protection can be accomplished by means of an environmental barrier coating that overlays the metal which has the effect of adding a thermal resistance to the transfer of heat thereby reducing the overall performance of the unit. In other cases, the unit is operated in the parallel flow mode rather than the counterflow mode to maintain a lower overall material temperature. This mode of operation has the effect of increasing the lifetime of the heat exchanger at the expense of lowering the overall thermal efficiency of the unit. Another commonly employed technique is air dilution, where ambient air is added to the hot upstream exhaust gases upstream of the heat exchanger. This technique also has the effect of lowering the overall efficiency of the heat exchanger.

Table 1
Brief property features of monolithic ceramic materials.

	Ceramics
Density	Moderate to high
Thermal conductivity	Low to high
Temperature	High (<1650 °C)
Chemical resistance	Excellent
Mechanical properties	Good
Shape and join	Difficult
Cost	Moderate to high
Main weaknesses	Inherent brittleness

The second major advantage of ceramic-based heat exchangers is their resistance to corrosion and chemical erosion. Corrosion which occurs under normal conditions is exacerbated by elevated operating temperatures. Moreover, corrosion can occur in many different forms in an exhaust gas stream. For example, an exhaust stream rich in oxygen can actually attack a metallic surface. In this case, the diffusion of oxygen into the material causes scaling. Although this scaling initially forms a protective layer, the intermittent use of the heat exchanger and the resulting thermal cycling can cause the scale to flake off, exposing the underlying material to further attack. Other possible gaseous constituents include sulfur and carbon which can also diffuse into the grain boundaries. The migration of sulfur into the grain boundaries forms eutectics that melt at temperatures significantly lower than the material melting temperature. The diffusion of carbon into the metallic surface results in the formation of carbides which can cause residual stresses and embrittlement to occur [2].

The merits and shortcomings of the following ceramic materials will now be discussed: silicon carbide, silicon nitride, alumina, zirconia, aluminum titanate, aluminum nitride, and ceramic matrix composites (CMCs). The thermal-mechanical properties of these materials are shown in Tables 2, 3, and 4. Perhaps the most promising ceramic material, silicon carbide (SiC) has a high temperature of decomposition (approx. 2500 °C). It also displays good thermal shock resistance and maintains its flexural strength at elevated temperatures. Moreover, it is chemically inert and possesses high thermal conductivity (about four times that of steel). Silicon carbide manufactured using silicon powder also maintains its strength well as does reaction bonded Si—SiC. Both, however, are limited to operating temperatures below the melting point of silicon—i.e. ~1425 °C [5].

Silicon nitride (Si_3N_4) exhibits excellent strength and creep resistance at elevated operating temperatures but may be limited by its vulnerability to oxidation at temperatures exceeding 1000 °C [5]. Alumina (Al_2O_3) is very stable and highly resistant to chemical attack under both oxidizing and reducing conditions. Alumina also possesses the advantage of being fairly inexpensive to manufacture. However, alumina suffers from lower thermal shock resistance as compared to silicon carbide and silicon nitride [5].

Zirconia (ZeO_2) cannot withstand large thermal gradients and therefore is susceptible to thermal shock failure. Aluminum titanate (Al_2TiO_5) possesses very low thermal conductivity and therefore is ideally used an insulatory material. Aluminum nitride (AlN) has good oxidation resistance and thermal stability up to 1300 °C. At higher temperatures, however, it is susceptible to attack by oxidation as the Al_2O_3 scale begins to crack exposing the unprotected, underlying AlN [5].

Although the impetus behind the use of ceramics in the manufacturing and design of heat exchangers arises from their excellent corrosive properties, their ability to withstand extremely high operating temperatures, and the economics of their use in heat recovery systems, radiant heating applications, and micro-reactors, major obstacles facing the incorporation and use of ceramics in these systems remain. These obstacles include ceramic-metallic mechanical sealing, manufacturing costs and methods, and their brittleness in tension. Therefore, to help meet the specific

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Table 2
Thermal-mechanical properties of various ceramic materials.

Properties	Ref.	Density, g/cc	Tensile strength, yield, MPa	Young's Modulus, GPa	Rupture Modulus, MPa	Flexural yield strength, MPa	CTE, linear 20 °C, μm/m-K	Thermal conductivity, 20 °C, W/m-K	Thermal conductivity, 100 °C, W/m-K	Thermal conductivity 1000 °C, W/m-K	Max work temp, °C	Melt point, °C	Specific heat Cap, J/g-°C
SiC	[2]	3.21		427			4.8			42			2.54
SiC	[3]	–		410		400	4.6			40	1600		
SiC	[4]	3.10		410		379	–						
SiC	[5]	3.10	186		110		4.6	125			1700	2837	
SiC	[6]	2.2–3.2[a]					2.8–4.2[a]		12.6–200				
Si_3N_4	[5]	3.20			690		3.5	3.0			1900	1900	
Si_3N_4	[6]	1.9–3.0[a]					1.5–3.6[a]		7–43[a]				
Al_2O_3	[7]	–							27.0				
Al_2O_3	[3]	–		340		300	7.5			6	1700		
Al_2O_3	[5]	3.90	55		450		7.1	29			1500	2050	
Al_2O_3	[6]	3.45–3.99[a]					4.5–8.0[a]		13.8–43.2				
Zirconia	[6]	3.5–5.9[a]					7–9[a]		0.9–2.0[a]				

[a] Temperature range not specified.

requirements of the application, ceramic matrix composites (CMCs) were developed to overcome the intrinsic brittleness and lack of reliability of monolithic ceramics.

Ceramic matrix composites (CMCs) combine reinforcing ceramic phases within a ceramic matrix to create materials with improved properties. The desirable characteristics of CMCs include high-temperature stability, high thermal shock resistance, high hardness, high corrosion resistance, non-magnetic and non-conductive properties, and greater versatility in providing unique engineering solutions. The most commonly used CMCs are non-oxide CMCs— namely carbon/carbon (C/C), carbon/silicon carbide (C/SiC), and silicon carbide/silicon carbide (SiC/SiC). The thermal-mechanical properties of these composite materials are shown in Tables 3 and 4.

For their merits, ceramics and CMCs are promising thermo-structural materials for heat exchangers (i.e. liquid–liquid, liquid-gas, gas–gas, etc.) used in severe environments such as rocket and jet engines, gas turbines for power plants, heat shields for space vehicles, fusion reactor walls, aircraft brakes, heat treatment furnaces, etc. In the following sections, the properties of the most promising ceramic and CMC materials will be presented along with identified industrial applications and recently improved manufacturing methods.

3. Applications of ceramics and ceramic matrix composites (CMCs)

The use of ceramic materials in heat exchangers was divided into four categories based on the primary heat transfer mechanisms: (1) liquid-to-liquid heat exchangers; (2) liquid-to-gas heat exchangers; (3) gas-to-gas heat exchangers; and (4) heat sinks. Here, the word “liquid” is taken to include single-phase liquid convection heat transfer or two-phase (liquid-vapor) convection heat transfer in the heat exchangers. The word “gas” represents single-phase gas convection heat transfer in the heat exchangers.

3.1. Liquid-to-liquid heat exchangers

Alm et al. [7] studied the thermal performance of a micro alumina heat exchanger comprised of 26.2 mm × 26.2 mm plates containing channels 250 μm wide and 500 μm tall and 12.25 mm in length (see Fig. 1). The micro-components were fabricated using a rapid prototyping assembly approach. The joining of already sintered micro-components by glass solder was preferred but sometimes resulted in partially blocked (or completely blocked) channel passages. The thermal conductivity of the Al_2O_3 MR52 ceramic was 30.9 W/m-K at 28 °C, 27.0 W/m-K at 100 °C, and 9.1 W/m-K at 750 °C. It should be noted that modular Al_2O_3 HXs may be limited to operating temperatures below 1000 °C. For the experiments performed on these ceramic heat exchangers, the mass flow rates ranged from 12.4 kg/h to 80.6 kg/h. For the first test conducted at 12.4 kg/h, the hot water stream entered at 93.7 °C and exited at 75.8 °C, whereas the cold water stream entered at 11 °C and exited at 26.7 °C at a flow rate of 12.6 kg/h. The system operating pressure for these tests was 8 bar. *FLUENT* was used to guide the initial heat exchanger design parameters although very little discussion of these simulations was provided; moreover, a flow distribution model was used in these simulations to estimate the

Table 3
Thermal-mechanical properties of various ceramic matrix composites (CMCs).

Properties	Ref.	Density, g/cc	Young's Modulus, GPa	Flexural Yield Strength, MPa	CTE, ⊥ orient μm/m-K	CTE, ‖ orient μm/m-K	Thermal Conductivity, ⊥ orient W/m-K	Thermal Conductivity, ‖ orient W/m-K	Specific Heat Cap, J/g-°C	Open porosity %	SiC loading vol %
Schunk FU2952[a]	[8]	2.0	25	65	–	–	14	25	1.25 @ 1000 °C	< 5%	25%
SGL carbon sigrasic[a]	[8]	2.4	30	80	–	1.8–3.0	40	–	0.80–1.20 @ 20–1200 °C	< 1%	70%
Chrysler C-brake[a]	[8]	2.25	30–35	67	4.0–4.7	2.4–2.7	24	30	0.80–1.40	< 2%	–
Brembo CCM[a]	[8]	2.25	–	–	4	–	20	–	1.20	–	–
MS prod. sicom[a]	[8]	1.6–1.9	75	320–370	6.5	0.5	7	27	0.60–2.20 @ 20–1200 °C	–	–
DLR silca SF[a]	[8]	2.0–2.1	50–70	90–140	1.0–4.0	0.5–3.5	25–30	–	1.30 @ 1200 °C	< 3%	48%
Schunk CF226/2 P77[b]	[8]	1.95	55	130	–	–	20	30	–	< 6%	25%
DLR silica XS[b]	[8]	1.8–1.9	63	>160	–	0.4–2.6	15.3	26.3	–	< 3%	30%
DLR silica XG[b]	[8]	2.1–2.3	41	80	–	1.1–2.5	18.9	–	–	< 5%	–
$SiCp/Al_2O_3$	[9]	3.40	341	346	7 @ 1400 °C	7 @ 1400 °C	–	–	–	< 1.0%	0–45%

[a] C/C – SiC composite (short fiber).
[b] C/C – SiC composite (2-D reinforcement).

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Table 4
General properties of ceramic matrix composites (CMCs).

Reinforcement	Matrix	Density g/cm^3	Thermal Conductivity W/m-K		CTE 10^{-6} m/m/°C	Specific Thermal Conductivity W/m-K		Ref.
			In-plane	Thickness	In-plane	In-plane	Thickness	
–	Beryllium oxide	3	260		6			[10]
–	Aluminum nitride	3.3	320		4.5			[10]
–	Silicon carbide	3.3	270		3.7			[10]
Continuous carbon fibers	Silicon carbide	2.2	370	38	2.5	170		[11]
Diamond particles	Silicon	–	525	525	4.5	–		[11]
Diamond particles	Silicon carbide	3.3	600	600	1.8	182		[11]
Silicon carbide particles	Al/SiC	3.0	170–220	170–220	6.2–16.2	57–73		[12]

mass flow through these channels. Reduction of the experimental data was performed using a simple, 1-D planar thermal resistance model. The experimental overall heat transfer coefficient (U) ranged from 7 kW/m^2-K to 15 kW/m^2-K. The associated pressure drop penalty (shown in Fig. 2) ranged from 0.15 bar at 12.4 kg/h to more than 6 bar at 80 kg/h (attributed to problems w/the glass soldering technique for joining the plates).

In a later work [13], water flow rates of up to 120 kg/h were successfully tested for counterflow and cross-flow microchannel heat exchangers made of alumina. Heat transfer coefficients of up to 22 kW/m^{2}K were reached for the cross-flow heat exchanger, and the efficiency was in the range of 0.10–0.22. These experimental results were compared to estimations made using standard heat exchanger correlations, and the heat transfer and pressure loss were found to be larger than predicted using these correlations—a result that the authors attributed to channel blockages arising from the joining process [13].

In a patent by Ishiyama and Maruyama [14], the construction of a ceramic heat exchanger for use in a thermo-chemical plant to produce large quantities of hydrogen and oxygen from feed water using nuclear heat at 950 °C is described. More specifically, the feed water supplied to the Bunsen reactor is decomposed under high temperature, high-pressure conditions in the presence of concentrated sulfuric acid (H_2SO_4) and hydrogen iodide (HI). After reaction, the liquid mixture of H_2SO_4 and HI is fed to the acid separator where it is separated into two layers of H_2SO_4 and HI. The HI solution is then supplied to distillation column; the resulting HI vapor is then decomposed and H_2 is recovered from the condenser. The distillate residue and condensate are finally returned to the reactor. The H_2SO_4 solution is fed to a vaporizer, and the resulting vapor is fed into the H_2SO_4 decomposer where SO_2, H_2O, and O_2 are formed. These species are then fed to a condenser before being returned to the reactor (see Fig. 3).

It appears that because high-pressure ceramic tubes are difficult to manufacture, Ishiyama and Maruyama [14] chose a block core design to allow for easier joining and vacuum sealing (see Fig. 3). This application of ceramics to a heat exchanger is not especially novel, but it represents an important use of ceramics in a corrosive environment.

3.2. Liquid-to-gas heat exchangers

Velasco Gómez et al. [15] describe a ceramic tube bank consisting of 7 columns and 7 rows in a staggered arrangement used to recover heat and precondition the supply air to a room. The tubes were a porous ceramic material primarily composed of Al_2O_3. The

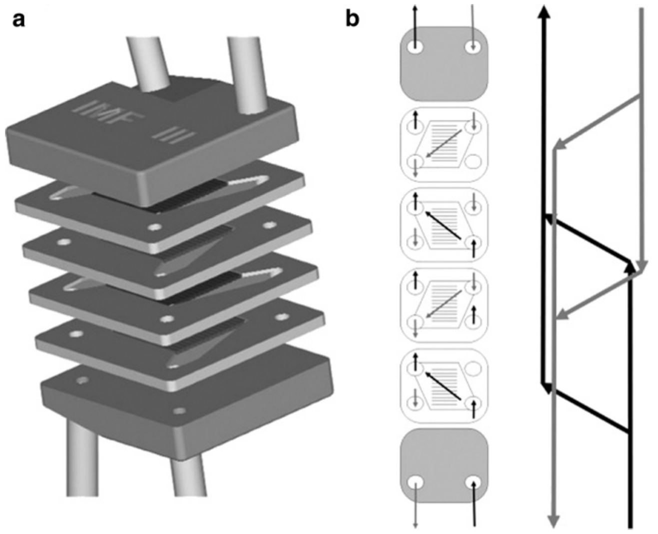

Fig. 1. Ceramic micro heat exchanger construction and cross-flow arrangement [7].

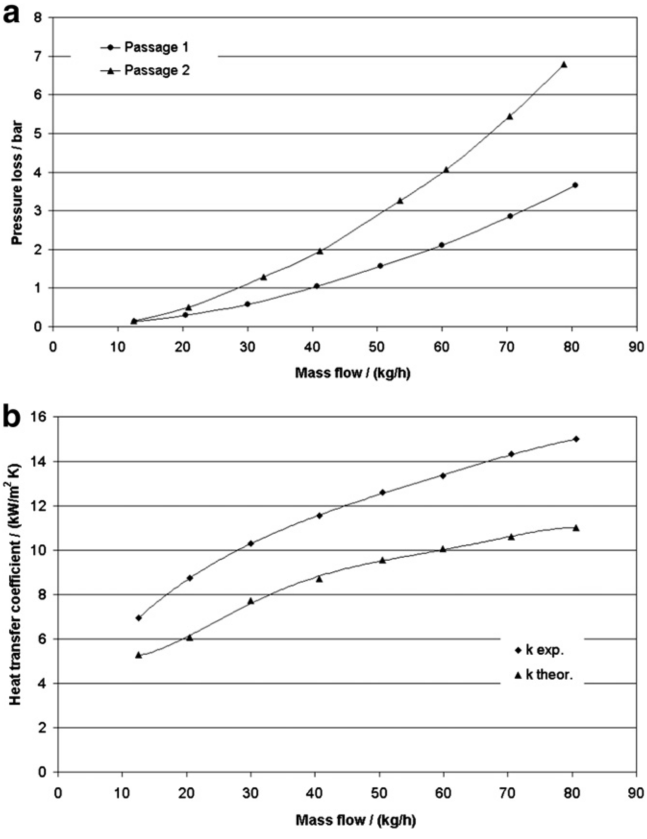

Fig. 2. (a) Pressure drop and (b) heat transfer coefficient data for various water mass flow rates (1-cold stream, 2-warm stream) [7].

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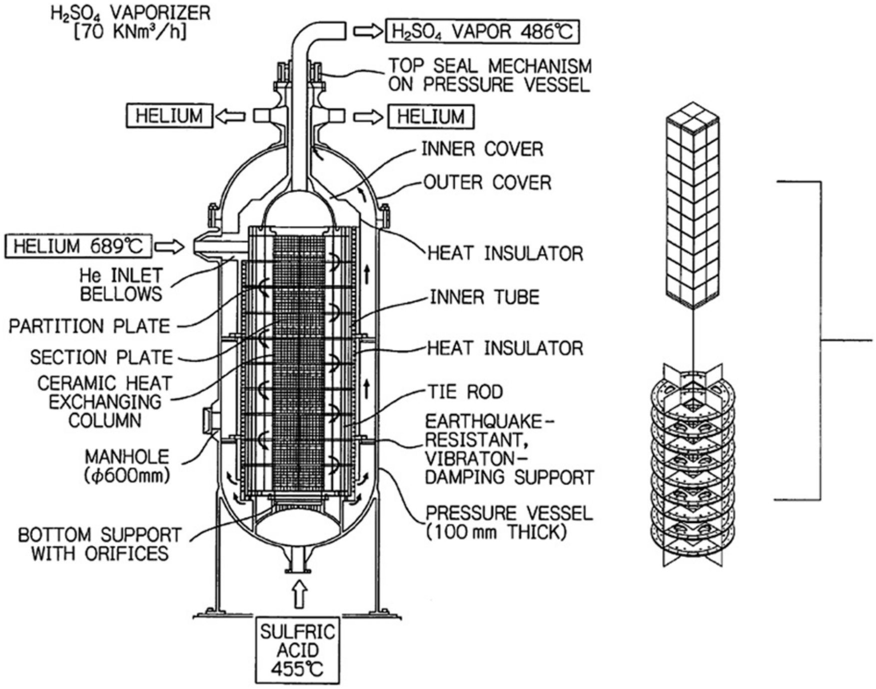

Fig. 3. Schematic of ceramic heat exchanger for use in a high-pressure, high-temperature H_2SO_4 vaporizer unit [14].

density of these tubes was approx. 2.5 g/cm^3. The porosity was 22–25%, and their absorption of water was 9–10%. This "semi-indirect evaporative cooler" shown in Fig. 4 utilized heat and mass transfer in the return air stream, heat transport through the porous wall, and evaporation (or condensation) in the supply air stream to deliver the air to the occupied space at comfort conditions (22 °C, 50% RH). This design was tested for tropical climates as well as continental summer and winter conditions. The intended application is for cooling in subtropical to tropical climates where the temperature and humidity are both high. However, it may also be used in winter conditions to humidify the supply air. The ceramic pipes had an external diameter of 25 mm, thickness of 5 mm, and length of 600 mm. Tested air flow rates were 140–380 m^3/h, and the average water flow rate was 100 L/h. Evaporative recuperators take advantage of the hydrothermal conditions of the indoor air to cool the water in the porous ceramic tubes to a lower temperature than would ordinarily be achieved using the outdoor air, especially when the outdoor air is humid.

Velasco Gómez et al. [15] point out that these porous tubes prevent the exchange of harmful agents such as those causing Legionnaire's disease (the tubes serve as a filter). However, because water can wick through the structure, these recuperators are labeled 'semi-indirect." Velasco Gómez et al. [15] also point to a related work where this recuperator was compared to an indirect system using an aluminum flat-plate HX in cross-flow with everything held the same. The thermal efficiency and overall cooling capacity was found to be higher for the ceramic recuperator. The authors suggest that a similar device could be made from the ceramic materials used in building construction to make the recuperator cheaper. This type of recuperator is limited to non-pressurized applications and probably best suited for warmer, more humid environments limiting its realizable benefit. An earlier study by Rey Martínez et al. [16] compared this semi-indirect ceramic evaporative cooler with an indirect evaporative cooler. The semi-indirect cooler was found to perform better.

Kelly et al. [17] describe potential applications for cross-flow, micro heat exchangers manufactured using a variation of the LIGA process where the liquid stream would be contained within the plane of the heat exchanger and the gas stream would pass through it. Materials being used to make these heat exchangers include

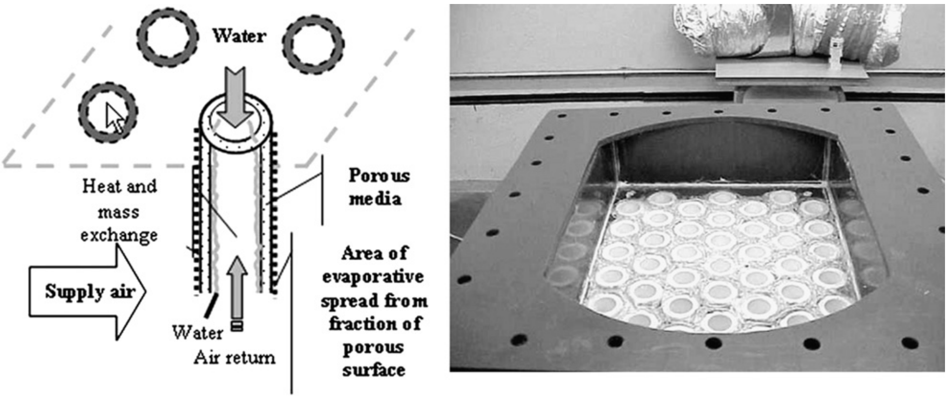

Fig. 4. Ceramic pipe heat exchanger utilizing both heat and mass transfer [15].

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PMMA (polymer), nickel (metal), Si_3N_4 (ceramic), and alumina (ceramic). Preliminary heat transfer and pressure drop data were provided and compared against model predictions but only for the case of the polymer and nickel cross-flow μ-HXs. Possible applications for these simple cross-flow μ-HXs include the surface cooling of gas turbine components and mechanical seals/journal bearings as well as catalytic converters.

To fabricate a silicon nitride μ-HX, a derivative of the LIGA process is used where a PMMA part is bonded to another PMMA part to produce an enclosed PMMA "lost mold." This mold is then injected with silicon nitride precursor which is solidified at relatively low temperatures. The polymer is then dissolved, and the remaining solid is sintered to form a dense ceramic part (see Fig. 5). This unique method of fabrication has also been used to produce complex metal μ-HXs on non-planar surfaces through an electroplating process.

The heat transfer per unit mass (or heat transfer/volume) of μ-HXs has been shown to be superior to conventional cross-flow HXs since the exit temperature of a gas flowing through this type of HX is constant for a given value of L/D_h^2 at fixed velocity and constant fluid/material properties. This means that a reduction in the hydraulic diameter allows for a significant reduction in the required flow depth [17]. The paper elaborates nicely on the manufacturing methods used in making μ-HXs and the theory behind their expected merits, but it provides very little supporting heat transfer data and none for the ceramic μ-HX.

3.3. *Gas-to-gas heat exchangers*

A sintered silicon carbide (SSC) offset strip fin (OSF-) heat exchanger coated with a 100 μm cordierite environmental barrier coating (EBC) was described by Schulte-Fischedick et al. [3] with a focus on the design of the heat exchanger and the thermal-mechanical stresses induced during normal operation and sudden thermo-mechanical loading. The construction consists of 127 flue gas plates and 128 process plates sintered together to produce a counterflow heat exchanger block 2 m × 2 m × 0.5 m in size with a fin spacing of 11 mm (see Fig. 6). The following operating conditions were used: a duty of 10.1 MW, inlet/outlet process gas temperatures of 700/1015 °C, inlet/outlet flue gas temperatures of 1215/900 °C, process/flue gas pressures of 14/1 bar, and process/flue gas pressure drops of 0.7/0.4 bar.

Thermal design of the recuperator was performed using empirical correlations. Stress analysis was performed using FEM. Al_2O_3 was disallowed due to its high CTE and low thermal conductivity, which can create high thermal stresses. A prototype of an actual ceramic SSC HX was designed and constructed. Comparisons with other data were not provided. The HX was designed for a single application under a specific set of operating conditions, thus lacking generality of application. Nonetheless, this HX design might be beneficial for air-to-air heat recovery systems. This construction approach has a distinct advantage, in that all the joints are sintered, so no pressure-tight seals are necessary. The modularity of this approach, however, is limited since damaged plates cannot be isolated for removal from a stack after joint sintering.

A high-temperature heat pipe recuperator, used to preheat combustion air with furnace exhaust gas was described by Strumpf et al. [18] (see Fig. 7). The heat pipes are made from sintered silicon carbide (SiC) and are internally coated with CVD tungsten which serves as a protective layer and a heat pipe wicking material. The working fluid is liquid metal (sodium), and each of the three recuperator designs presented in this paper was based on a flue gas temperature of 2500 °F, and an air preheat temperature of 2000 °F. Pressure drops of 20-inch water and 8-inch water were permitted on the air-side and gas-side, respectively. Feasibility of construction was demonstrated in a laboratory environment.

The paper presents an engineering economic analysis of ceramic heat pipe recuperators, but it does not provide an evaluation of their thermal performance. The simple payback period for these heat pipe recuperators was calculated to be 0.8–1.8 years. Because each heat pipe is essentially an independent heat exchanger, they are easy to replace and individually have a low impact on the overall performance of the recuperator should one fail.

Isamoglu [19] examined the effect of a non-uniform convective heat transfer coefficient on the thermal-induced stresses of a silicon carbide (SiC) ceramic tube heat exchanger using the finite element method (FEM). Substantial increases in both the radial and tangential (hoop) stress field were observed for the non-uniform heat transfer coefficient case versus the uniform heat transfer case. Special design considerations thus might be warranted within the entrance region of a ceramic tube where the thermal boundary layer is still developing and the heat transfer coefficient can vary significantly with axial location.

Smyth [20] proposed a ceramic shell-and-tube heat exchanger for heat recuperation in a gas turbine cycle, where the combustion gases flow through the inside of silicon carbide tubes, and the pressurized working fluid (steam or gases) flows over the tube bundle within the shell (Note: This arrangement is counter to the conventional design where the process fluid flows through the tubes). This arrangement keeps the ceramic tubes in compression, which is desired because ceramic materials are more durable in compression than tension. In support of this proposed system, the paper presents a complete cycle analysis for a combined-cycle gas turbine (CCGT) power plant (similar to the one shown in Fig. 8) that uses two-stage compression with inter-cooling, reheat, and complete exhaust gas heat recuperation. Using the ceramic heat

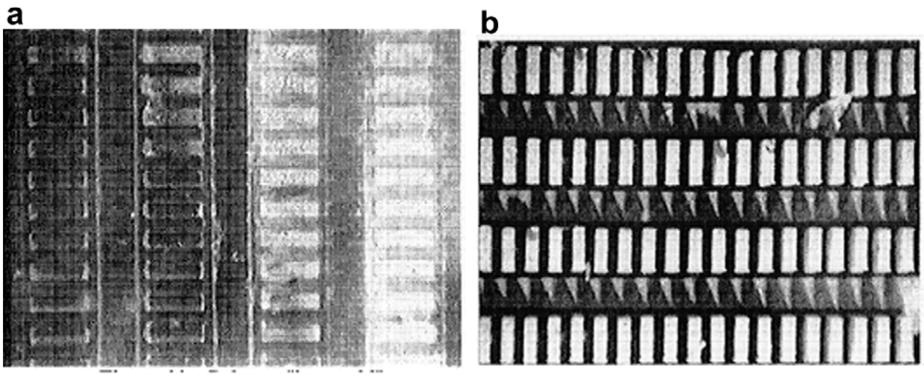

Fig. 5. (a) Polymer "lost mold" and (b) fully-dense silicon nitride sintered part [17].

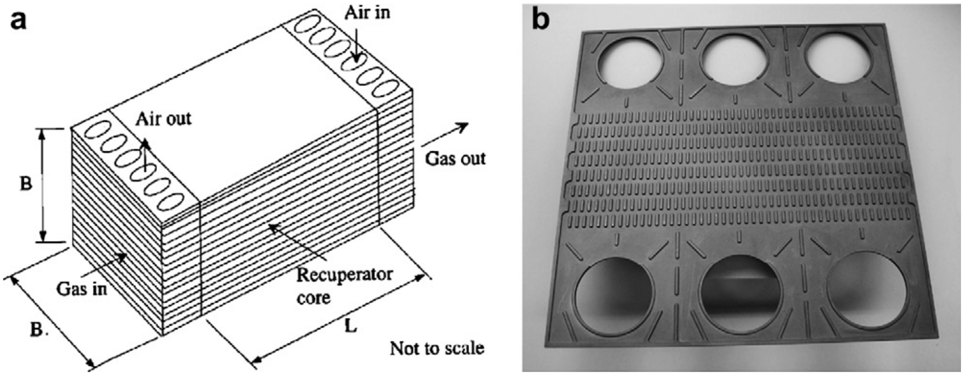

Fig. 6. (a) Schematic of the heat exchanger body showing the flow directions and (b) a sintered SiC process gas plate [3].

exchanger in this system could raise the thermal efficiency of a closed gas turbine power cycle to approximately 65% from 55% for conventional combined-cycle power plant. The cycle studied was a 100 MW unit, with a turbine inlet temperature of 1260 °C. The compression ratio was 14:1 with an air mass flow rate of 150 kg/s.

Smyth [20] also discussed the problem areas associated with ceramic heat exchanger construction. These problematic design areas include: stress prediction and control on structural components, especially joints, fouling and cleaning issues, repairability with the capability to selectively replace parts, endurance to thermal cycling, and gas tight bonding of metallic–ceramic interfaces. The most novel idea, however, in this paper involves maintaining the ceramic components in compression (perhaps by a pressurized process fluid) since ceramic components have much better strength in compression than ceramic components in tension.

In gas turbine applications, ceramics also continue to play a significant role [21,22]. For example, Zhong and Brown [22] report a new integrally-woven ceramic matrix composite (CMC) material that creates the possibility for multi-hole cooling of combustor liners as shown in Fig. 9. In the area of thermal barrier coatings (TBCs), Vaβen et al. [23] report a new class of double-layer coatings in which conventional yttria-stabilized zirconia (YSZ) is used as the bottom layer, and new materials such as pyrochlores or perovskites are used for the topcoat layer. Besides higher temperature capability, these coatings can be tailored to have sensorial properties for improved temperature control and monitoring. A summarizing work on the current state-of-the-art of ceramic thermal barrier coating research in Europe is Vaβen et al. [24]. And in automotive applications, a new flame-sprayed zirconia-based coating developed by ZIRCOTEC has been reported to reduce heat transfer in exhaust manifolds by up to 26.7%, which equates to a surface temperature reduction of 135 °C [25].

3.4. Heat sinks

Bower et al. [26] described six different SiC heat sinks, 3.2 cm × 2.2 cm in platform area of varying thickness, channel diameter, number of channel rows, and number of channels per row (see Fig. 10). These heat sinks were fabricated by co-extruding multiple layers of SiC filaments filled with a water-soluble polymer core (later removed during thermal processing). Water was passed through these heat sinks at 500 mL/min, and the thermal performance was measured using type-K thermocouples and pressure taps and compared to laminar flow theory.

The bulk thermal conductivity of SiC (in this study) was only 15 W/m °C, but because the CTE closely matches silicon, SiC is an ideal candidate for integration into microelectronic applications. Despite the low thermal conductivity value, these SiC heat sinks provided a thermal performance similar to a copper baseline heat sink at the same flow rate. The thermal resistance and Nusselt number data (shown in Fig. 11) suggest that multiple-row SiC heat sinks perform better than single-row designs. However, Bower and co-workers [26] conjecture that an optimum number of rows exist. The authors also assert that air-cooled heat sinks are limited to 100 W/cm^2 heat rejection, but water-cooled, microchannel heat sinks can achieve up to 790 W/cm^2. Friction factor data compare favorably to the Shah and London correlation, and the Nusselt number data compare favorably to the solution by Hausen for thermally developing, hydrodynamically developed flow. These

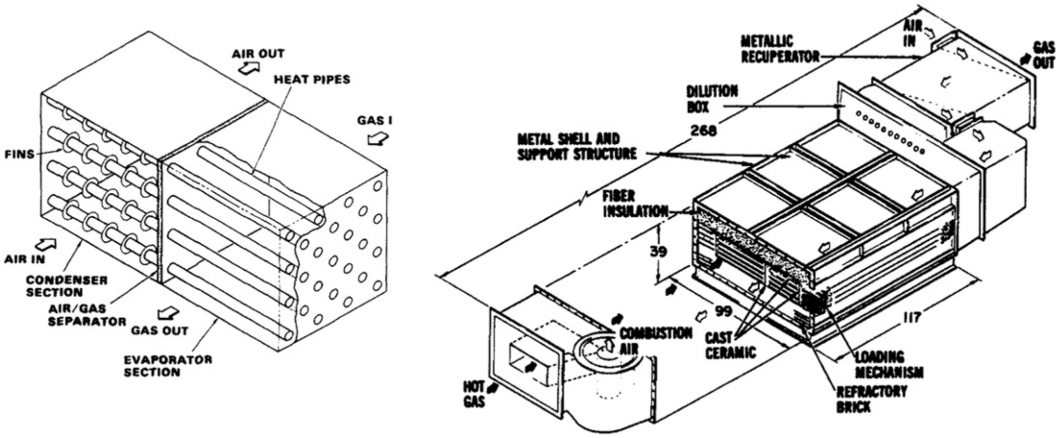

Fig. 7. Schematic of a ceramic heat pipe recuperator [18].

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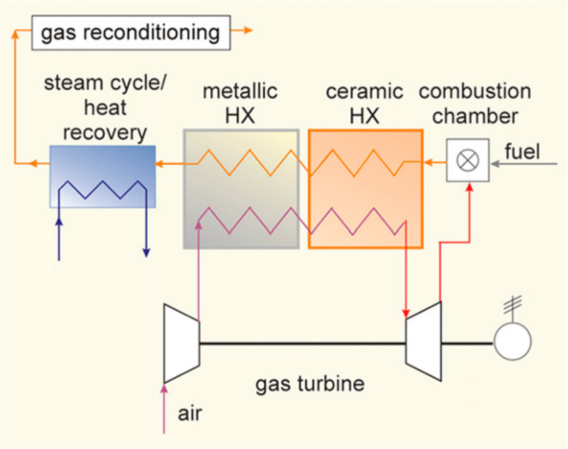

Fig. 8. Combined cycle gas turbine power plant with a high temperature ceramic heat exchanger [3].

experiments were performed with great attention to detail. However, physical irregularities in the channels (size and shape distribution) were observed due to the fabrication method.

The very high cost (up to $10,000/kg) of C–C composites combined with their lengthy (up to 9 month) processing time has hindered their wide-spread commercialization as heat sinks. Kowbel et al. [27,28] developed low cost, high thermal conductivity 2D C–C and 2-D C-SIC composites for Si-based and GaAs-based electronics. Both 2-D C–C and 2-D C-SIC greatly outperformed state-of-the-art Cu–W, AIN and BeO heat spreaders (see Fig. 12). The relatively low through-thickness thermal conductivity of C–C and C-Sic composites does not negatively affect their thermal performance up to 44 W/cm^2. Chips were attached to both C–C and C–SiC via epoxy bonds. Up to 500 thermal cycles were performed satisfactorily. The price of C–C composites has greatly reduced to less than $100/lb. This allowed the fabrication of C–C and C-Sic heat spreaders at a cost comparable to Cu–W ($2/in^2).

4. Manufacturing methods and limitations of ceramics and CMCs

When introducing ceramic and ceramic matrix composite materials in heat exchangers either by replacing the materials of existing designs or by implementing new configurations, it is necessary to consider special needs during manufacturing, handling, and operation processes. For example, the coefficient of thermal expansion varies widely depending on the type of materials (see Fig. 13). When dissimilar materials are interfaced, differential thermal expansion or contraction can have a pathological impact on the long-term durability of the heat exchangers. In this section, the essential aspects of implementing of ceramic materials in heat exchangers are further examined.

Various manufacturing methods available for using ceramic materials to construct heat exchangers are reviewed. Detailed fabrication procedures include forming primary components from raw materials, subsequent machining, joining, bonding, and assembling. While some of the techniques are currently being used for commercial products, further developments of manufacturing methods are needed for a wider use of ceramic materials in heat exchangers in HVAC&R and recovered-energy applications. We believe that the benefits of ceramic heat exchangers could drive the development of novel manufacturing methods as well as the assessment of material compatibility and long-term durability.

The methods used for manufacturing ceramic heat exchangers can be classified as either monolithic assembly or non-monolithic assembly, depending on whether the heat exchanger components are permanently joined or not. Ceramic materials can be further classified depending on their composition and structure. Crystalline ceramic materials, which are more commonly used in the construction of a heat exchanger, are not amenable to a great range of processing options. Typically, the ceramic is made into the desired shape in one of two ways: (a) by reaction *in situ*, or (b) by “forming” the desired object using powders and then sintering it to form a solid body. Ceramic forming techniques include throwing, slip casting, tape casting, injection molding, dry pressing, and various hybrid approaches. Non-crystalline ceramics tend to be formed from melts. The glass is shaped by casting when fully molten or by blowing when highly viscous. If heat-treatments result in a partially crystalline structure, the resulting material is typically referred to as a glass-ceramic. In most cases, however, the method of manufacture is fairly complex involving semi-discontinuous assembly and frequently, a large expenditure of time. However, new manufacturing methods are making these limitations less and less of a concern. In fact, in some cases, the method of manufacture may even become the selling point.

The choice of monolithic versus non-monolithic assembly frequently depends on the chosen configuration of the heat exchanger. In monolithic assembly, the individual heat exchange components are bonded together using slip and then re-fired to create an integral piece. This type of assembly may or may not include the plenum and ductwork; nevertheless, if the core of the heat exchanger is produced in this manner, it is referred to as being

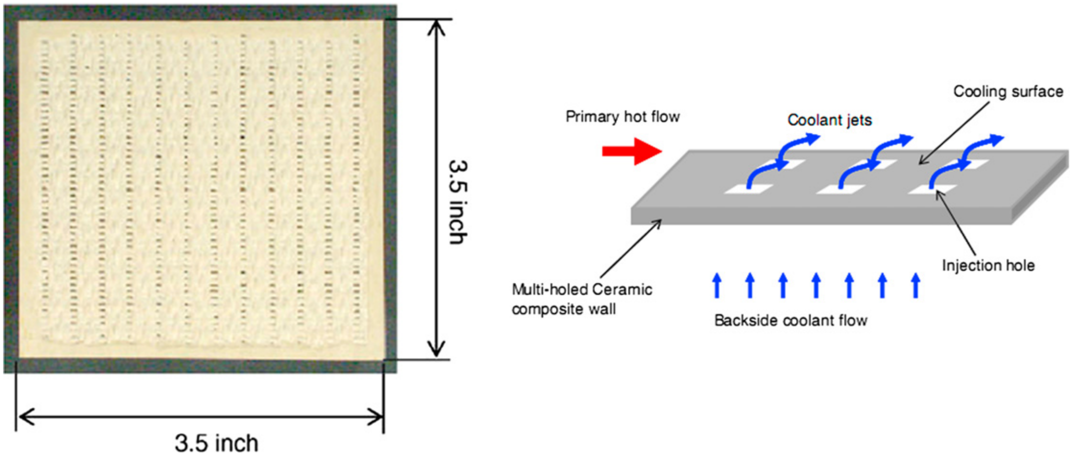

Fig. 9. Integrally-woven SiC/SiC ceramic matrix composite materials for gas turbine applications [22].

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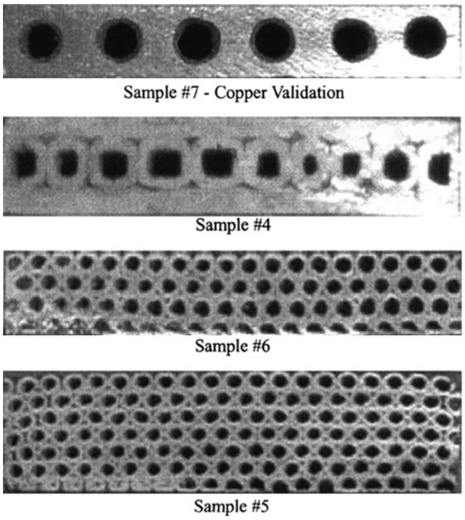

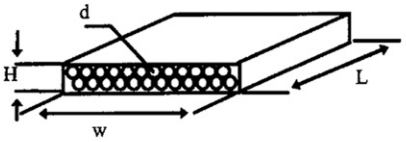

Sample ID	L×w×H $m \cdot 10^{-3}$	d $m \cdot 10^{-6}$	No. of rows	N
1	33×22×11.2	1300	5	42
2	33×22×10.8	335	11	155
3	32×22×11.8	940	7	49
4	30×22×5	1150	1	10
5	33×22×5	510	7	126
6	33×22×2.8	510	4	76
7	32×25.4×3.8	2030	1	6

Fig. 10. Photographs and schematic of representative SiC heat sink samples [26].

monolithic. This method of assembly is desirable for one major reason. There are no internal joints and therefore no attendant problems with sealing. The major drawback of this method is tied up in the advantage—the entire heat exchanger must be replaced after failure. Individual parts and components cannot be swapped and exchanged. Also, the monolithic assembly method can cause stress concentrations under extreme operating conditions that may shorten the life of the heat exchanger resulting in more frequent servicing and/or replacement.

In non-monolithic assembly, the heat exchanger is constructed from individual components and therefore can be disassembled and repaired. This is its major advantage. Accompanying this choice of assembly, however, is the need for mechanical joints and seals—historically, a problem area for ceramics due to their brittleness and the difficulties of forming a resilient metal-ceramic or ceramic–ceramic joint. The joining of two dissimilar materials poses a problem because stresses can arise at the interface due to differences in the coefficient of thermal expansion (CTE) of the two materials. To prevent leakage through the seal, advanced surface machining techniques are often necessary. In order to work around these difficulties, a compliant material is often used in ceramic–ceramic joints that allows for the release of these stresses while still providing good sealing. This material can be: (1) a cement, (2) a packing, or (3) a glass. Cements have the advantage of conforming to the surfaces being bonded; however, its strength must be tailored in such a way that permits it to yield at lower stresses than the surrounding ceramic materials. Packing is more commonly used because of its high fiber density which makes it a highly compliant, amorphous sealing material. However, at very high operating temperatures, this type of sealing becomes crystalline and loses some of its resilience. This type of seal is also not well-suited for high-pressure applications. The glass joint design similar to the cement joint design also requires a careful tailoring of the material properties. In particular, the viscosity must be tailored to ensure that the glass does not flow out of the joint at high temperature.

In one study, packing material was used to provide a ceramic-to-metal seal in an application with a high-pressure differential (>10 bar). Siliconized silicon carbide (Si–SiC) tubes were utilized, and the seal was shown to slip under very low axial forces and prevent the tubes from being put in tension. A floating head design type was not considered since a complex pattern of compression and tension was expected to occur in regions of temperature discontinuity [29].

Another novel bonding option is laser supported brazing which can be used to join ceramic materials with other ceramic materials and even with metals. In Rohde et al. [30], Al_2O_3-ceramics were brazed to steel using a CO_2-laser and an active braze filler material. The microstructural characteristics of the interface were examined as well as the mechanical strength of the brazed joint using bending tests. The bending strength was found to vary between 40 and 80 MPa. In Lippmann et al. [31], an innovative laser joining process is described that permits tight binding between ceramic bodies of any shape (see Fig. 14). The method is based on a solder that is specially made from Al_2O_3, Y_2O_3 and SiO_2 and melted locally by use of laser radiation. The soldering process can be carried out in

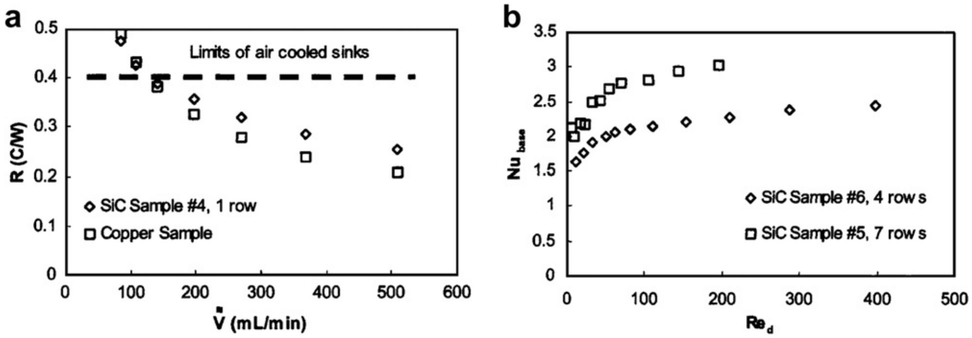

Fig. 11. (a) The thermal resistance of water-cooled heat sinks is significantly lower that air-cooled sinks for modest flow rates, and (b) the Nusselt number based on base area was observed to increase as the number of rows increased [26].

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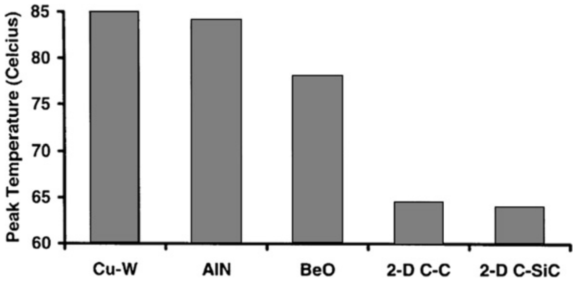

Fig. 12. Thermal Spreader Results [27,28].

the free atmosphere (i.e. no vacuum, no inert gas), and the surfaces do not require preparing. The resulting joints are temperature resistant at 1600 °C and above. The mechanical strength of the joined material was also evaluated using a 4-point bending test, and the bonded specimens were found to have a strength of 236 MPa in comparison to the reference specimens which had a strength of 341 MPa.

A few different monolithic manufacturing methods will now be discussed in greater detail. Schmitt et al. [32] described the construction of a catalytic, ceramic micro-structured plate microreactor. The manufacturing process begins with the casting of the ceramic "green" tape from a slip made from a particular form of α-alumina. The raw α-alumina tape is then cut into sheets using a laser, stacked into the desired arrangement, and laminated before being sintered together. This porous ceramic structure is then externally and internally sealed, and finally the reaction chamber is coated with catalyst. This process is illustrated below in Fig. 15. The actual tape casting was performed using the so-called "doctor blade process" illustrated in Fig. 16 where a casting substrate of polyethylene film is drawn at constant speed under a slip reservoir. The slip is then formed using two doctor blades whose height is adjusted to provide a uniform film on the casting substrate. Tape thicknesses between 0.1 and 1.2 mm were manufactured using this method. The connections to external equipment were accomplished using perfluorinated rubber O-rings which can withstand temperatures up to approx. 320 °C. This, of course, places a significant limitation on the maximum operating temperature of the heat exchanger. Complete sealing of the internal porous partition plates which separate the reaction and cooling chambers was also difficult to obtain. However, using chemical vapor deposition (CVD) reductions in permeability from 29,500 nano-Perm to 270 nano-Perm after 40 h of reaction time were achieved.

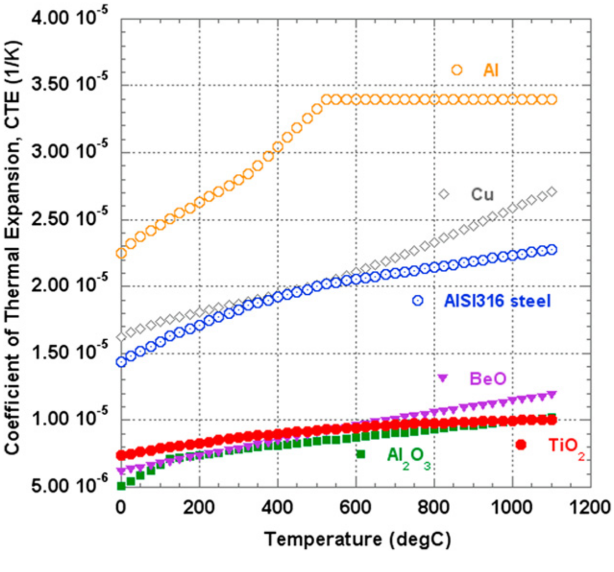

Fig. 13. The difference in linear thermal expansion between metals and ceramics can be significant.

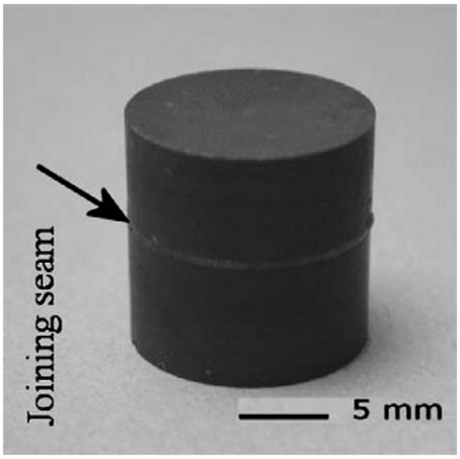

Fig. 14. Laser bonded hollow SiC capsule showing the applicability of the laser induced soldering technique [31].

In a paper by Alm et al. [7], the thermal performance of an alumina micro ceramic heat exchanger comprised of 26.25 mm × 26.25 mm plates containing channels 250 μm wide and 500 μm tall and 12.25 mm in length is described. The micro-components were fabricated using the rapid prototyping assembly approach shown in Fig. 17. First, a polymer master model was made of the original using stereolithography, and then a silicon mold was made. Next, "green bodies" were produced from an alumina/binder (MR52) dispersion through a low-pressure, injection molding process. Finally, the green bodies undergo a debinding step at 500 °C and a sintering step at 1700 °C. The joining of ceramic components was performed two ways—(1) by the hot joining of green bodies followed by group debinding/sintering, or (2) by the joining of already sintered micro-components by glass solder. It was found that the hot joining of green bodies was less reproducible at higher pressures. Therefore, joining by glass solder was preferred but sometimes resulted in partially blocked (or completely blocked) channel passages. Other germane studies concerned with issues related to the manufacture of ceramic materials for heat exchange applications include Payne and Evans [33] and Meschke et al. [34].

5. Exploitation of the novel properties of ceramics and ceramic matrix composites (CMCs)

The key features of ceramics and ceramic matrix composites (CMCs) were also investigated in this study to identify specific uses in heat exchangers. These efforts can be divided into three main areas: *(1) replacement of construction materials for existing geometries, (2) major configurational changes resulting from the adoption of* new geometrical concepts, and (3) utilization of advanced fabrication technologies to maximize the benefit from new materials. The possibility of improving conventional heat exchangers through ceramic materials was primarily explored via the replacing of parts of heat exchangers (*e.g.* fins or tubes) with new parts with minor geometrical modifications. Good performance evaluation criteria were needed to facilitate an even-handed comparison between the most competitive conventional materials (copper, aluminum, stainless steel, etc.) and possible ceramic alternatives and to help identify suitable geometric ranges and operating conditions. Because the merits of materials may rely on multiple factors,

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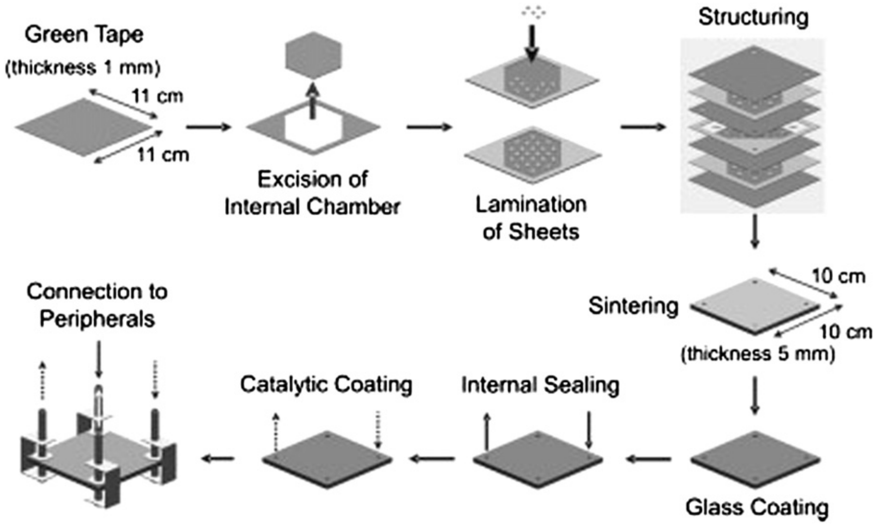

Fig. 15. Manufacturing process for the construction of a ceramic plate heat exchanger from green tape [32].

including enhanced convective heat transfer, higher thermal conductivity, low flow friction and size reduction, suitable comparison methods were divided into target applications differentiating the types of heat transfer systems and the fluids involved.

In order to find alternative materials for a part of a heat exchanger with a specific configuration, it is necessary to consider the desirable characteristics of the candidate changes. For example, air-side fins for some compact heat exchangers may benefit more from high thermal conductivity than from high structural strength. On the other hand, structural strength may be more important when considering a refrigerant tube. While some of these characteristics are directly linked to the figures of merit, other factors, especially those related to reliability or application compatibility, may not be easily converted to a single figure of merit. An applicable performance evaluation method, which combines the thermal-hydraulic performance and qualitative properties, was developed by employing a Pugh Matrix for each target application.

Based on the property features of ceramics, a few of the promising ceramic materials (SiC and SiC/SiC composites) were selected for further evaluation as candidate materials. Table 5 gives the definitions of these rating grades for each criterion, and Table 6 gives the rating grades for these candidate materials.

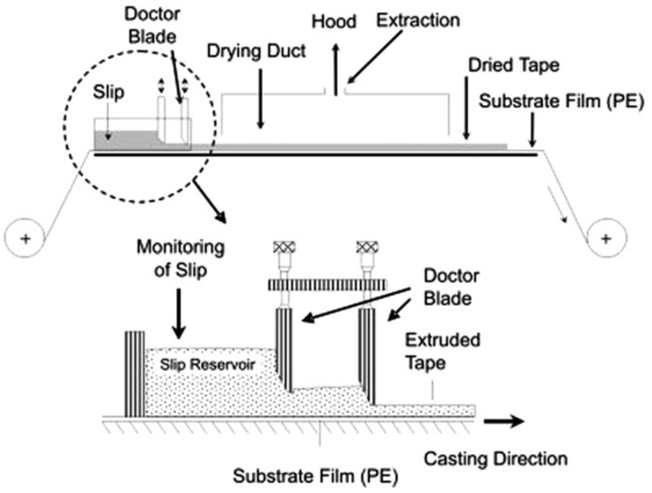

Fig. 16. The so-called doctor blade process for the production of green tape [32].

The shaping criterion denotes the current capability to machine complex geometries for each kind of material. It reflects the cost of the materials to be manufactured. The cost associated with fitting different parts (i.e. joining or bonding) is not included because it depends on the materials to be fitted. Therefore, to make the evaluation fairly straightforward, the “fitting evaluation” was excluded from the above ten performance criteria for each application. As a general guideline, polymers and discontinuous composites are easily shaped into complex geometries by the mold-casting method. The machining cost of ceramic composites, however, is often higher than other materials due to their hardness and the increased difficulty of manufacture.

The material cost criterion denotes the cost of the material itself. It depends to large extent on the quality and method of manufacturing the material. Thus, copper and ceramic composites are always in the highest range of the material cost in present, while aluminum (and most polymers) are in the cheapest range. The thermal conductivities and densities of these materials were retrieved from property databases. The temperature limits of these materials can usually be ranked in the following ascending order—polymers, metals, ceramics, ceramic matrix composites (CMCs), and carbon materials. The material strength criterion denotes the mechanical properties of these materials. It is a complex issue, and many factors are involved.

The criterion of compatibility with working fluids was separated into three categories: with halocarbon and ammonia refrigerants, with LiBr–H_2O and ammonia–water systems, and with highly corrosive fluids. It will be more convenient to evaluate different applications. This criterion includes resistance to chemical attack and permeability of the materials. Fouling resistance is another criterion which will influence the performance of heat exchangers over time. Usually, ceramics and polymers possess the highest fouling resistance. After carefully assigning rating grades for each material and each criteria, a few heat transfer applications where ceramic materials could be (or, currently are) competitive were suggested. These target applications are discussed in the next section in more detail.

6. Possible target applications of ceramics and CMCs

Using these criteria, five different heat exchanger applications were identified where the replacement of construction materials with ceramic could be advantageous over other materials.

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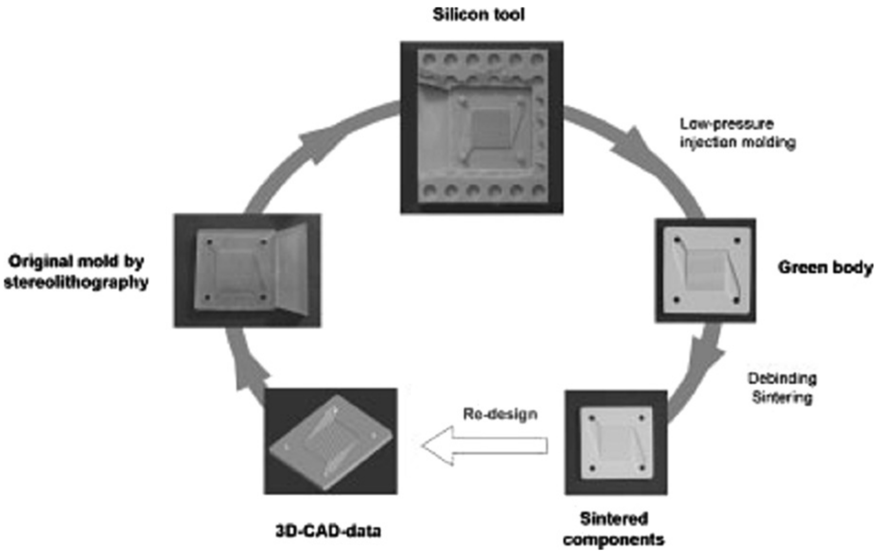

Fig. 17. Rapid prototyping process for the manufacture of ceramic heat exchangers [7].

6.1. Evaporators in evaporative cooling systems for air-conditioning

In direct evaporative cooling systems, the cooling water is cooled as it flows through the tubes of the evaporator. An air flow is forced across the outside of the evaporators with a series nozzles spraying water directly over the tubes. Water lost through evaporation is replaced by make-up water. Such evaporators have some features of both air-cooled and water-cooled condensers. But they are very sensitive to fouling, because impurities remain behind when the water is evaporated.

In these applications, tube and fin-and-tube heat exchangers are commonly used. However, the structural strength of the tubes, fins and headers in this kind of evaporator is much less important than in other systems because the pressure inside the tubes is usually no more than one atmosphere higher than the ambient air pressure. Thus, these systems could benefit from ceramic tubes. In these systems, compatibility with coolant is less important because the outside wet surface of the tubes exposed to the air is prone to be corroded. Compatibility with halocarbon/NH_3 and LiBr–H_2O is irrelevant in this application.

6.2. Recuperators and generators in LiBr/H_2O absorption chillers for air-conditioning

Absorption chillers using the LiBr–H_2O mixture have many advantages, including quiet, reliable operation, reasonable efficiency, and the possibility of cooling through the recovery of co-generated heat. Thus, LiBr/H_2O absorption chillers are widely used where electricity is expensive but inexpensive heat is available. Large-capacity direct-fired and waste-heat driven cooling systems have been studied and commercialized, but it is difficult to extend their use to small capacity air-conditioning systems. One obstacle to a wider application of gas-fired absorption chillers is their high first cost, which can exceed twice that of an electric unit on a per-ton basis. Absorption machines consist mainly of heat exchangers, so their price is dominated by the heat exchanger cost. Therefore, the cost criterion is very important in this application. Usually absorption machines work with shell-and-tube heat exchangers, which are more expensive at small scales, as compared to fin-and-tube designs. The structural strength of parting sheets and headers is less important than halocarbon/NH_3 systems because they only need to endure the vacuum pressure which is less than one atmosphere. The structure strength of fins is unimportant, since there is usually no fin or few fins in these recuperators. Compatibility with LiBr/H_2O is very important for the parting sheets, fins and headers in this application.

Another major obstacle to greater application of LiBr/H_2O absorption chillers is the corrosive nature of LiBr/H_2O to most metal materials. The performance of LiBr/H_2O absorption chillers can be improved by using plate or plate-fin type recuperators in the solution cycle. The heat exchanger fluids are both LiBr/H_2O solutions. Thus, the recuperator may benefit from ceramic materials. The steam generating plate or plate-fin type generators may also benefit from ceramic materials for this same reason. In this device, the heat exchanger fluids are LiBr/H_2O solution on one side and steam on other side. In both cases, the main parts considered for replacement are parting sheets, fins and headers.

Limited information is available describing the operation of absorption chillers with non-metallic and compact heat exchangers [35–38]. Flamensbeck et al. [35] designed, built, and tested

Table 5
Definitions of rating grades for properties of the candidate materials.

Criteria	1	2	3	4	5
Shaping (Machining)	Very difficult	Difficult	Moderate	Easy	Very easy
Material cost	Very high	High	Moderate	Low	Very low
Thermal conductivity (W/mK)	0.1–0	10–100	100–250	250–400	>400
Temperature limit (°C)	<300	300–500	500–1000	1000–1650	>1650
Material strength	Very low	Low	Moderate	High	Very high
Compatibility with 3 fluids	Very poor	Poor	Moderate	Good	Excellent
Fouling resistance	Very poor	Poor	Moderate	Good	Excellent
Material density (g/cm^3)	>8	5–8	3–4	1–2	<1

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Table 6
Rating grades for properties of ceramics versus conventional materials.

Criterion	Metal	Metal	Metal	Ceramic	CMC
	Copper	Aluminum	Stainless steel	SiC	SiC/SiC
Shaping (Machining)	5	5	5	2	2
Material cost	2	4	3	4	3
Thermal conductivity	4	3	2	3	4
Temperature limit	3	3	3	4	4
Material strength	5	5	5	2	3
Compatibility with halocarbon	5	5	5	5	5
Compatibility with LiBr–H_2O	3	3	3	5	5
Compatibility with corrosive fluids	2	2	4	5	5
Fouling resistance	3	3	3	5	5
Material density (i.e. weight)	1	4	1	3	3

a double-effect absorption heat pump with a heating capacity of about 45 kW. The generator was a direct-fired pool boiling apparatus. All other components were plate heat exchangers. The absorbent was a mixture of 50% NaOH and 50% KOH. All heat exchangers except the direct-fired generator were plate heat exchangers and were constructed of stainless steel. In order to minimize corrosion, the generator was made of nickel. To overcome an unacceptably high-pressure drop, which would cause a loss in temperature lift when plate heat exchangers are used as the absorber and evaporator, flash evaporation and adiabatic spray absorption were adopted, i.e. performing both absorption and evaporation adiabatically.

6.3. *Primary heat exchangers in gas-fired furnaces for space heating*

Tube or tube-fin type heat exchangers are targeted in this application. The heat exchanger fluids are exhaust gas and water. The main parts considered for replacement are tubes, fins and headers.

The conductivity is less important, because the temperature difference between exhaust gas and coolant is usually very large; often there is no fin or few fins on the gas-side. The exhaust gas temperature is usually higher than 500 °C. Thus, the temperature limits of the heat exchanger materials are very important in this application. The compatibility with the coolant also becomes very important since the parts of heat exchangers are exposed to a (potentially) corrosive gas in a high temperature environment.

6.4. *High temperature recuperators and chemical digesters*

Ponyavin et al. [39,40] performed a numerical analysis using FLUENT of the thermal performance of a compact ceramic heat exchanger which will be used as a chemical decomposer for the production of hydrogen via the sulfuric acid decomposition reaction ($T > 850$ °C). The heat exchanger being modeled was manufactured using fused ceramic layers and possessed channels less than 1 mm in size. In a related work, two fuel reforming microchambers (12 mm × 12 mm × 1 mm) were packed with a commercially available ceramic catalyst (i.e. CuO/ZnO/Al_2O_3) to aid in the production of hydrogen gas [41]. A compact ceramic heat exchange reformer was also suggested by Zhang et al. [42] for use in a high temperature solid oxide fuel cell/gas turbine (SOFC/GT) system. In these systems, the waste heat from the high temperature fuel cell is used in the steam reforming reaction (I), water gas shift reaction (II), and CO_2 direct reforming reactions of methane (III) for the production of hydrogen and other hydrocarbon fuels. The passage walls of the recuperator are coated with nickel which serves as the catalyst in these reactions. In this study, a dynamic simulation of a counterflow compact heat exchange reformer is performed to study how various parameters such as the steam-to-carbon ratio, passage operating pressure, and hot gas inlet temperature affect the mole fractions of methane, hydrogen, and water in the product stream. A modular-based, volume-resistance modeling technique and lumped-distributed parameter method, however, was used so only general characterization and optimization guidelines could be performed. Due to the higher gas temperatures (often reaching 1200 K) and the corrosive nature of some of the produced gases, however, ceramic materials are (and will likely remain) an attractive option for heat exchanger construction in these applications.

Other relevant studies of high temperature ceramic recuperators include Yang et al. [43], McDonald [44], McDonald [45], and Omatete et al. [46]. McDonald [44] argues that technology may advance to a stage where 40% efficiency may be attained by gas turbine engines using high-temperature metallic recuperators; however, in the long term, McDonald believes that the full performance potential of microturbines can be achieved only with ceramic recuperators. Recently, McDonald and Rodgers [47] launched a three-year research and development effort aimed at designing, fabricating and testing a 7.5 kW ceramic microturbine demonstrator, which for the first time would involve the coupling of a ceramic radial flow turbine, a ceramic combustor, and a compact ceramic high effectiveness recuperator. Utriainen and Sundén [48] also advocates for new materials and new heat transfer surface designs for microturbine recuperators.

6.5. *Open-cell foams for reactive heat exchange processes and filtration*

For filtration and catalytic heat exchange, high temperature limits and good fouling resistance are important since the pressure drop can be significant in these applications. Some work has already been performed in this area. Lévêque et al. [49] examined

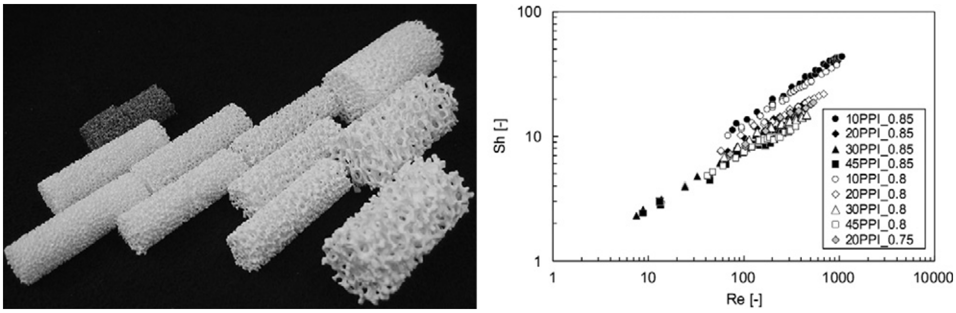

Fig. 18. Experimental Sherwood number data as a function of the Reynolds number for nine different alumina foam samples [57].

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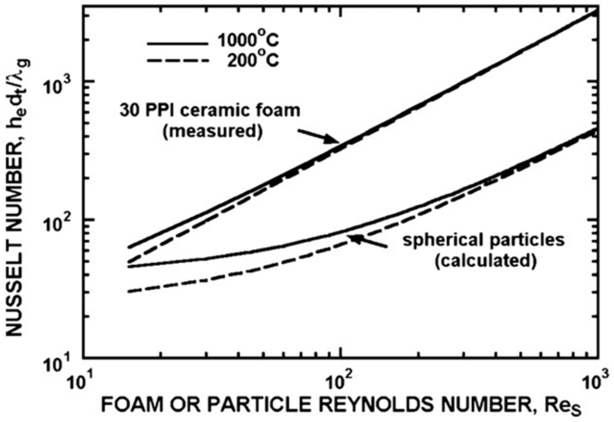

Fig. 19. Heat transfer comparison between equivalent 30-PPI α-Al_2O_3 foam and particle beds [54].

the hydraulic performance of a silicon carbide (β-SiC) foam for possible use in a distillation column. The tested foam had a volume void fraction of 92%, and a specific area of 640 m^2/m^3. The pressure drop for the foam was found to be slightly higher but comparable to other common packing materials such as M250Y, CY, and Pall rings. Good mass transfer performance was observed, and Lévêque et al. [49] suggest that the foam might be best used in reactive distillation applications due to its unique structural and mechanical properties and its ability to be coated with catalyst. Coquard et al. [50] developed a FEM model for estimating the effective thermal conductivity of ceramic and metallic open-cell foams. The authors also noted that the concentration of the solid phase at the end of adjoining struts slow down heat conduction in the cellular matrix. Thus, the repartition of the solid phase along the length of the struts was identified as a key parameter affecting the conduction of heat in these materials.

In another paper, Kim [51] used the porous ceramic material (ISOLITE®) as a catalyst support in a micro methanol reformer for portable fuel cell applications due to its large surface area and thermal stability. The catalyst support was composed of 40% Al_2O_3 and 55% SiO_2 with trace amounts of other metal oxides, and the porosity was approximately 71%. The average bulk pore size was between 100 and 300 μm, while smaller scale pores were a few microns. Other excellent studies concerned with ceramic catalytic foams for micro-reaction and/or micro-separation include Zampieri et al. [52], Peng and Richardson [53], Twigg and Richardson [54], and Tsinoglou et al. [55].

Albanakis et al. [56] evaluated the thermal-hydraulic behavior of several porous materials when treated as volumetric receivers under concentrated solar radiation. Various foam materials including Ni and Ni alloy, inconel, copper, aluminum and SiC were studied; however, only a detailed comparison between the Ni and inconel foams was provided. The pore size for the inconel and nickel foams was found to be 0.58–0.6 mm using X-ray microtomographs, and the porosities were 93% and 92% for the inconel and the Ni foams, respectively. In another study by Incera Garrido et al. [57], the mass transfer and pressure drop properties of alumina (Al_2O_3) foams with pore densities between 10 and 45 PPI and porosities between 75% and 85% were evaluated. Correlations were developed for the Sherwood number (dimensionless mass transfer coefficient) of the foams which was found to increase with decreasing pore count at constant hydrodynamic conditions (see Fig. 18).

Thermal-hydraulic correlations can also be found in Peng and Richardson [53], Twigg and Richardson [54], Giani et al. [58], and Groppi et al. [59]. In Peng and Richardson [53], axial and radial temperature profiles in 30 PPI α-Al_2O_3 foam cylinders are reported from which radial heat transfer correlations were derived for one- and two-dimensional reactor models. The 1-D correlation developed for the temperature range 100–400 °C agreed within 10% with that previously reported for 700–900 °C and gave an overall heat transfer coefficient that was about a factor of four higher than smooth glass spheres (see Fig. 19).

7. Conclusions and recommendations

An extensive literature review and critical evaluation of the potential benefits of ceramic and ceramic composite materials has been conducted and has produced a thorough compilation of performance data, physical/chemical properties, and other characteristics. Key features of a few of the most promising ceramic materials have been investigated to identify specific usages in heat exchangers based on a rating system comprised of ten performance evaluation criteria. The thermal and mechanical properties of individual ceramic materials were collected in tabular form; however, thermal-hydraulic performance data are found to be limited. Heat exchanger designs are explored including the replacement of materials in existing designs and the use of these new materials with changes in heat exchanger configuration.

Possible uses for ceramic materials in heat exchangers that hold substantial relevance and potential merit are discussed; however, many of these proposed applications have not been sufficiently studied to allow for a complete assessment of cost and benefit. Practical issues related to implementing the designs, including thermal performance, thermal/mechanical/environmental constraints, and manufacturing and installation issues, were also considered.

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