

# Multiscale, Ceramic Microsystems for Heat and Mass Transfer

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## Abstract

*Structures with several dimensional length-scales can be integrated with ceramic microsystems by using ceramic processing methods that produce components with novel functions. For example, structures optimized for heat transfer can be incorporated with structures designed for gas separation to produce microreactors in low cost, compact packages. Examples of incorporating multiple forming methods with, and without, one-step densification approaches will be described. This presentation will describe several examples of components incorporating multiscale structures. Typical applications are power electronic heat management, microreactors for chemical processing, and industrial heat exchangers. Features of design optimization methods that are unique to ceramic microsystems will be described. The objective of the presentation is to demonstrate the potential for ceramic microsystems in a broad range of applications and describe the benefits and challenges associated with their design, fabrication, and operation.*

Keywords: microreactors, ceramics, manufacturing, heat management

## Introduction

Novel technological devices often incorporate multiscale physical requirements, such as turbulent mixing of fluid reactants (or products) and laminar flow of heat transfer media. Other examples of multiscale physical requirements are diffusion controlled mass transport through membranes and reaction-rate controlled heat dissipation; and conductive heat transport coupled with active cooling involving both turbulent and laminar conditions. Integrating multiscale physical behavior in microsystems provides significant benefits for performance, efficiency, cost and size.

A convergence of needs and capabilities has promoted the growth of ceramic, microchannel technology over the past 10 years. Applications are as diverse as lab-on-a-chip for pharmaceutical development, membrane reactors for point-of-use generation of hazardous chemicals or high purity gas, high temperature heat exchangers for chemical processing or power conversion, and thermal management for power electronics, photovoltaics, and lighting.

Where properties such as corrosion resistance, electrical resistivity or impedance, or high temperature durability are required, materials selection is often limited to ceramic materials. In addition, some ceramic materials, such as ion-

transport membranes, may have properties that cannot be obtained in other materials. A benefit of microchannel designs for applications requiring ceramics is that the volume of material that may be subject to high stresses is typically lower than would be the case for a more conventional design meeting the same performance requirements. The significantly lower volume of material at lower stress translates to a substantial improvement in the mechanical reliability of the component. Smaller components also reduce materials costs. Provided that low cost manufacturing methods, including some described below, are utilized, device costs can be low. Therefore, ceramic microsystems can mitigate common barriers to commercialization of novel ceramic devices: reliability and cost.

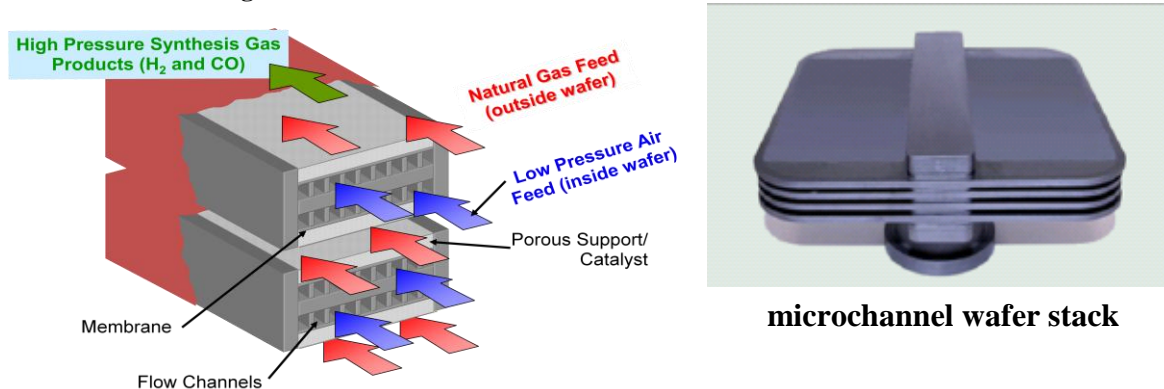
As the benefits of ceramic microchannel devices are understood, interest in their use in new applications has grown. Substantial benefits are predicted for many devices that incorporate multiscale physical behavior. Experience in designing and fabricating such devices is limited; however, some key features will be described below.

## Applications

There are many applications requiring multiscale structures, which accommodate

Device	Scale	Structure	Scale	Structure	Application
Microfluidic membrane reactor	micron	microchannels	submicron	porous layers with micron and submicron pores	Energy, Chemicals
Compact Heat exchanger	micron	microchannels	submicron to millimeter	porous layers with micron and submicron pores, foams	Energy, Chemicals
Planar, heat pipe	micron	microchannels	submicron	porous layers with micron and submicron pores	Microelectronics
Thermal management package	micron	microchannels	millimeter	fins, foams	Microelectronics, Energy, Lighting.

**Figure 1** A membrane reactor for processing fuel delivered by microchannels with feed gas flowing in external ducts.



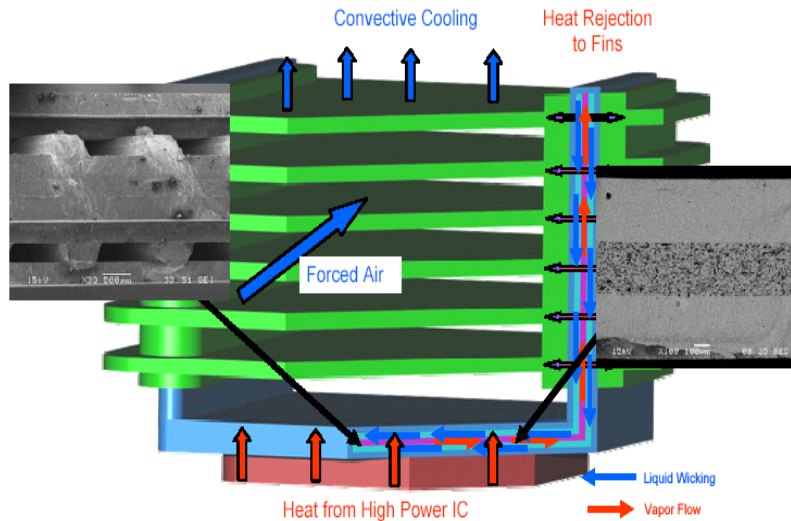
multiscale physical behavior. Table I summarises some examples of these applications and the scale of structure and behavior involved. One of the applications for ceramic microchannel devices that requires multiscale physical behavior is a membrane reactor designed to produce synthesis gas ( $H_2 + CO$ ) from natural gas ( $CH_4$ , methane), Figure 1. Synthesis gas can be used as a fuel for enabling  $CO_2$  capture and as a feedstock for liquid fuels (gas-to-liquid) or other chemical processes. The conversion of natural gas to synthesis gas is a high temperature process. Various oxide materials possess sufficiently high oxygen conductivity that they are attractive membranes for this process. Air can be supplied to one side of the membrane and

oxygen passes through and reacts with methane to form synthesis gas. Use of a membrane reactor simplifies the overall process flow and, hence, reduces capital and operating costs<sup>1</sup>.

Microchannel reactor designs provide the reliability required to utilize the attractive properties of the ceramic membrane material<sup>2</sup>. Due to the small length scales involved in mass and heat transfer, these membrane reactors operate efficiently and large numbers of them can be combined economically for large scale production, on the orders of tens of millions of cubic meters of natural gas converted per day.

The requirement of supporting the membrane layer to provide the required reliability

**Figure 2** Schematic illustration of a planar heat pipe for microelectronic cooling.



dictates the range of widths of the microchannel support layers. This range, typically 50-300  $\mu\text{m}$ , subsequently constrains the desired range of flow in the gas channels to be laminar so that excessive pressure drop does not occur. On the other hand, on the methane side of the device, the desire is to rapidly mix gases, using turbulent flow, so that auto-thermal reforming can prevent excessive heating from the exothermic partial oxidation of the methane. Therefore, this device must address physics at both scales.

To obtain a device capable of providing both laminar and turbulent flow regimes for gases, membrane devices supported by internal microchannels are assembled into stacks with adequate spacing to allow turbulent conditions to occur on the membrane surface. An additional feature of the device is a porous layer on the methane side of the membrane that increases the surface area for gas-solid interaction and can also provide a support for catalysts.

Similar to the microchannel reactor described, a similar design can be used to fabricate compact, high temperature heat exchangers<sup>2,3</sup>. Depending on the viscosities and flow rates of the fluids, one fluid can be fed through microchannels; the other, in external flow ducts. Regardless of the specific orientation, the microchannel design provides efficient heat transfer, component reliability, and compact designs.

Another example of a multiscale, microsystem currently being developed, is a ceramic, planar heat pipe for high power or other

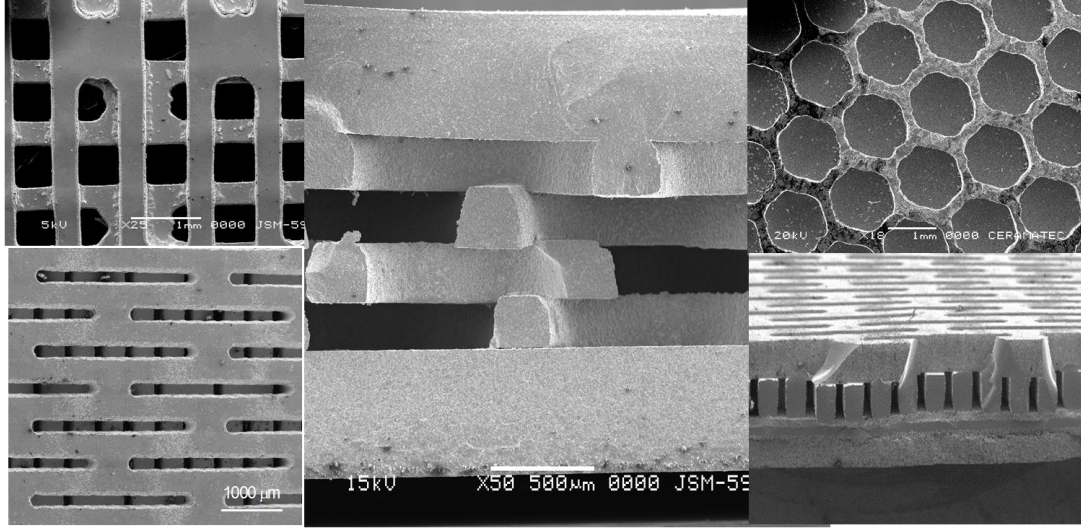
applications also requiring electronically insulating properties or matched thermal expansion behavior. For these applications, ceramic materials such as silicon carbide or aluminum nitride are desirable. A heat pipe contains structures with several scales of behavior: low pressure-drop gas channels, high capillary pressure wicks, and a high surface area heat rejection zone, see Figure 2. Fortunately, novel microchannel structures containing internal porous regions, which can act as wicks, can provide the scales of behavior required.

Another example of a multiscale device is a thermal management component designed to cool light emitting diodes<sup>4</sup> or concentrated solar photovoltaic applications<sup>5</sup>. In this case, heat conduction is achieved by rapid transport of liquid, heat transport media through microscale features to heat dissipation fins. Similar to the heat pipe devices for cooling other electronic components, the high effective thermal conductivity of these devices facilitates cooling of extremely high heat flux applications.

#### **Fabrication Methods**

The applications described above illustrate the utility of microsystems with features designed for multiscale behavior. Incorporating multiscale structures in individual devices, however, is often a significant challenge. Fortunately, ceramic packaging and microsystem technology, combined with other novel approaches, can often facilitate fabrication of multiscale devices.

**Figure 3** Examples of features available in microchannel devices.



The microchannel membrane reactor and the compact heat exchanger, described previously, is a straightforward example of fabricating multiscale devices with proven technology. Both of these systems manage heat and gas flow on different scales. Therefore, both systems are assembled from similar components: planar, microchannel devices. Both systems utilize stacks of the planar, microchannel components with a minimal number of manifold components for each stack. Since the manifold usually involves a connection to a dissimilar material, minimizing the number of such connections mitigates the numerous materials compatibility issues involved in operation in high temperature or other extreme environments typically associated with these applications.

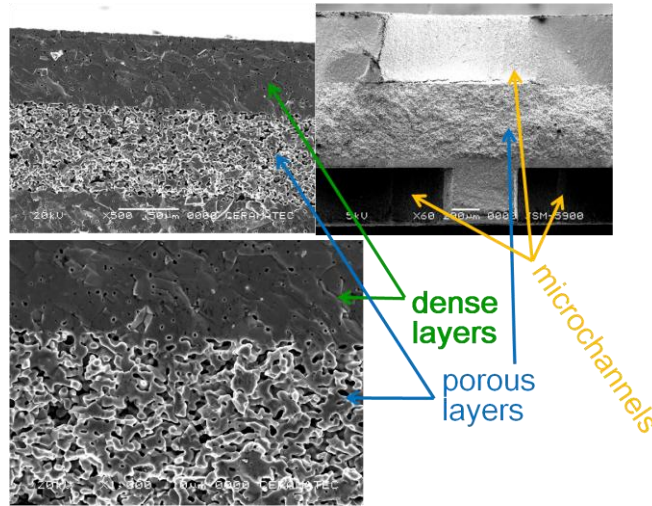
Planar microchannel components can be made by a number of fabrication routes. Commonly, tape featuring and lamination are used. Ceramic powder, of the desired chemical and physical properties, is blended in solvent with organic binders, plasticisers and other additives to produce a slip suitable for tape casting. Various combinations of blade geometry, viscosity, and drying arrangements are used to cast rolls of tape ranging from one to several hundreds of microns thick. The tape can be featured by laser cutting or punching to introduce the regions that will become microchannels. Regardless of the featuring method

used, a wide variety of microchannel designs can be obtained via this method, see Figure 3. The featured tape is laminated, using various combinations of heat, pressure, and solvents. The laminates are then sintered, at elevated temperatures, to remove the organic material and cause the ceramic powder to densify.

The planar components can be assembled into stacks using a variety of sealants including ceramic inks, glasses, brazes, and diffusion bonding. To obtain the desired spacing for the mass and heat transport on the non-microchannel side of the system, auxiliary components may be required to obtain the desired configuration. Finally, manifold components can also be attached to enable connections with dissimilar materials, or to provide the desired connections to upstream and downstream components.

The heat pipe component described earlier relies on integral gas channel and wick structures made using a one-step densification process within a single device. Incorporating features of these scales requires fabrication methods that can produce a leak tight ceramic article with both dense regions for the gas channels and porous regions for the wick structures. Typically, pore formers are used to produce regions of material that will retain porosity after an amount of shrinkage compatible with densifying the remainder of the body.

**Figure 4** Examples of co-sintered porous layers with dense layers and layers containing microchannels.



There are a variety of materials that can be used as pore formers, ranging from carbon black to microcellulose to polystyrene. Since the pore radius and the permeability of the wick structure are critical to effective performance, significant effort is often required to develop a process capable of providing the desired characteristics, see Figure 4. Pore former size and volume fraction are critical factors, as is the particle size of the powder used in the porous layer. The appropriate thermal treatment allows sufficient time for removal of the fugitive pore former, and other organics, prior to densification of the body.

An example of a novel fabrication method applicable to multiscale structures is that of bonding ceramic tape to green, foam replicant structures and co-sintering them. This is an alternative method for obtaining structures combining high-surface area and low pressure drop with pressure boundaries and other rigid structures.

Furthermore, the process of replicating foam facilitates control of the porous structure. Examples of these structures with pore sizes on the order of millimeters are shown in Figure 5, and relationships between strength, pressure drop and cell size or porosity are shown in Figure 6 and Figure 7.

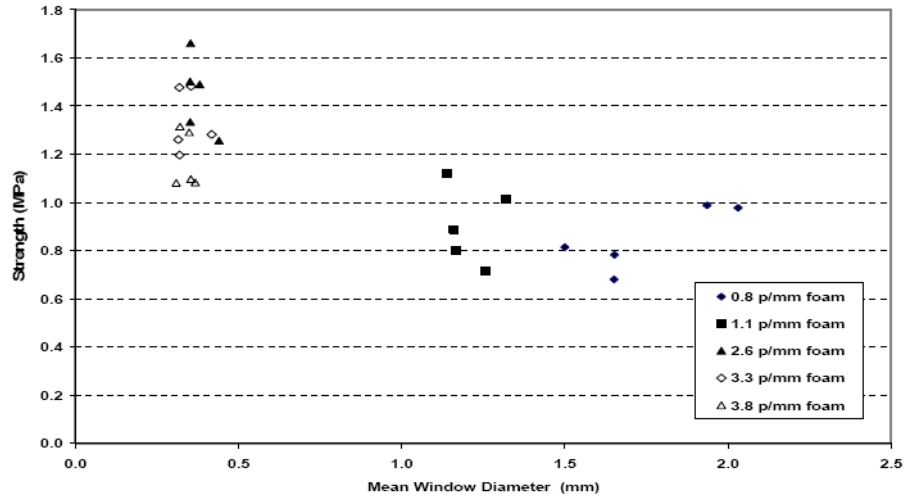
#### Design approaches

The data shown for the foam structure illustrate the requirements for designing multiscale structures. The foam strength is proportional to the strut length, whereas the pressure drop is proportional to the cell opening. Neither of these parameters is directly related to the pore size or pore density (pores per millimeter, or pores per inch) that are typically used to characterize the preforms. Fortunately, in this kind of open cell foam, the cell opening is proportional to the strut length and relatively simple assumptions about the relationship between strut length and opening

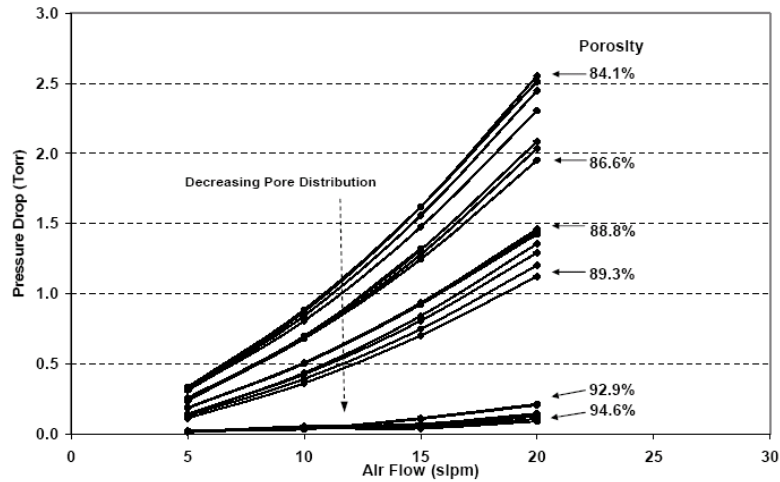
**Figure 5** Millimeter scale foam bonded to dense layers.



**Figure 6 Strength of foams as a function of cell (window) diameter**



**Figure 7 Pressure drop of foams as a function of porosity and air flow.**



could be used to model the pressure drop and strength correlations<sup>6</sup>.

In other designs, however, both numerical methods and experimental measurements may be required to develop and improve designs. Often, due to the combinations of structural scales, multiscale or multiphysics models must be used and combined. For example, a three-dimensional finite element model of even a single component of the membrane reactor, heat exchanger, or heat pipe is computationally intensive. Therefore, a global-local approach is usually more efficient. In this case, the component can be modeled on one scale with effective properties that capture the behavior of the finer scale features and the output used as boundary conditions on a local model that includes all the details of the fine structure. This approach

may also apply to modeling the influence of multiple fields on the components, such as thermal and chemical reaction kinetics. Likewise, to provide input data, independent test data, and model validation, a series of controlled experiments with samples representing different length scales must also be conducted. An example of this approach is shown in Figure 8 where a global thermal model was used to calculate temperature distributions that were then input into a global mechanical model to predict global displacements, followed by applying the global displacements to a local model of microchannel regions to estimate the resulting stresses. The stresses can be compared with the strength of structures, derived from experimental testing, and environmental effects on the material properties

can also be accounted for, given the appropriate data from experimental measurements, see Figure 9.

**Conclusions**

Integrating structures with different physical scales allows ceramic microsystems to be used in a variety of novel applications for energy conversion and utilization, microelectronics cooling, and even industrial chemical processing. Several examples have been provided of components, based on ceramic microsystems, that utilize physical behavior at different scales. Examples of fabrication techniques for multiscale structures have also been provided and shown to incorporate many of the techniques used in ceramic microsystem processing. Novel structures can be obtained by incorporation of engineered porous layers, with porosity on the micro or millimeter scales. Despite the added complexity of concurrent, multiscale and multifield physical behavior, methods exist for modeling and designing desired components. Further development of multiscale components offers the opportunity for commercialization of new devices to improve, or even replace, existing technology in energy, microelectronics, chemical processing, and other fields.

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