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THERMAL TRANSPIRATION BASED MICROSCALE PROPULSION AND POWER GENERATION DEVICES

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Motivation

With the continually decreasing size and weight of communication, control and instrumentation systems for aerospace vehicles due to advances in microelectronics and micro electro-mechanical systems (MEMS), there is considerable interest in miniaturizing the propulsion and power systems as well. While many miniature space and airbreathing propulsion system concepts have been proposed, e.g. [1], most require moving parts. All miniaturized propulsion devices with moving parts experience more difficulties with heat and friction losses due to higher surface to volume ratios than their macroscale counterparts. Moreover sealing, fabrication and assembly are much more difficult at small scales because microfabrication processes have much poorer relative precision than convectional macroscale processes.

Additionally, all air and space vehicles, regardless of size, require electrical power. The use of combustion processes for electrical power generation provides enormous advantages over batteries both in terms of energy storage per unit mass and in terms of power generation per unit volume, even when the conversion efficiency in the combustion process from thermal energy to electrical energy is taken into account. Most current micro-scale power generation concepts employ scaled-down versions of existing macroscale devices, in particular internal combustion engines, though again such micro-devices experience more difficulties with heat losses, friction, sealing, fabrication, assembly etc. than their macroscale counterparts. Consequently, the advantages of combustion processes over batteries for small-scale electrical power sources have not yet been exploited, though research is ongoing [2, 3].

Approach

Because of these difficulties, we propose a microscale or mesoscale propulsion system with no moving parts and not requiring precision manufacturing, applicable to either space or airbreathing vehicles, based on a catalytic combustion-driven thermal transpiration pump. Thermal transpiration occurs in gases in porous membranes or capillary tubes when (1) the mean free path of the gas molecules is comparable to the pore or tube diameter and (2) a temperature gradient is imposed in the solid phase along the length of the pore or tube. Under such conditions, a pressure gradient is induced in the gas, which causes a flow from the cold to hot end of the pores or tubes. A pumping device based on this principle is sometimes called a "Knudsen compressor" after M. Knudsen who first studied thermal transpiration in the early 1900's [4]. Requirement (1) indicates that using conventional MEMS materials and machining techniques producing pore sizes of microns or larger, Knudsen compressors can only be used for very low-pressure gases. However, aerogels and nanoporous oxides have pore sizes of typically 10 nm, which is comparable to the mean free path of air molecules at ambient conditions, thus they are ideal for constructing Knudsen compressors operating at near-ambient pressures. Moreover, aerogels have very low thermal conductivity, thereby enabling a temperature gradient to be sustained across the aerogel with minimal thermal power requirement. Aerogel-based thermal transpiration devices have recently been demonstrated for vacuum pump applications by Vargo *et al.* [5] using electrical heating to sustain the temperature gradient.

We propose to take the concept introduced by Vargo *et al.* [5] one step further by using heat release from catalytic combustion instead of electrical heating. Such a pump/propulsion system has *no moving parts, no supplemental working or pressurization fluids, very low mass and integrates pressurization and thrust generation.* Figure 1 (left) shows the basic building block unit. As in Vargo *et al.*, the reactants first flow through a low-temperature "thermal guard" consisting of a plate with microchannels (not nanoscale pores as in the aerogel). The thermal guard material has a thermal conductivity much higher than that of the aerogel and is non-catalytic to the fuel, plus the thermal guard pore size is much larger than the mean free path of the molecules so that no thermal transpiration occurs in this region. The reactants then pass through the aerogel membrane where the pumping occurs due to the temperature difference across the membrane. The reactants then pass through a second catalytic thermal guard and are converted into products, resulting in heat production. The heat release in the high-temperature thermal guard, combined with the low thermal conductivity of the aerogel, sustains the temperature gradient and thus the pumping action is self-sustaining. Catalytic combustion is ideal for this application because it is localized on catalytic surfaces that can be

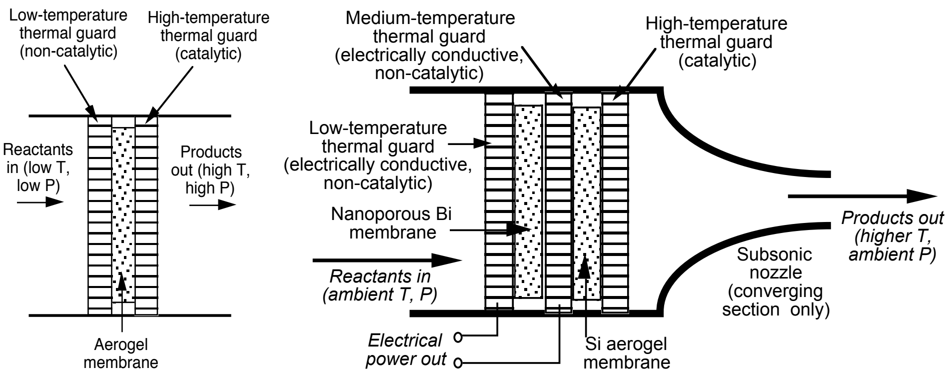

Figure 1. Schematic diagrams of thermal transpiration pumps. Left: single-stage device, stand-alone or incorporated into the center of a Swiss-roll combustor; right: possible integrated power generation and propulsion device.

located on the hot side of the Knudsen compressor, making the thermal resistance between the combustion gases and the hot side of the compressor negligible.

Recently the UCLA group investigated nanoporosity for improving thermoelectric properties [6]. It was found that the thermoelectric figure of merit was higher for nanoporous bismuth than for the bulk material under some conditions. Thus it is possible that by using this material rather than more conventional nanoporous materials such as silica aerogel, *both propulsion and power generation could be obtained in one device with no moving parts* (Fig. 1, right). In the design shown, the lower temperature pumping is accomplished with nanoporous bismuth whereas the higher temperature pumping is accomplished with silica aerogel. A third thermal guard is inserted between the two materials to extract the electrical power from the bismuth stage.

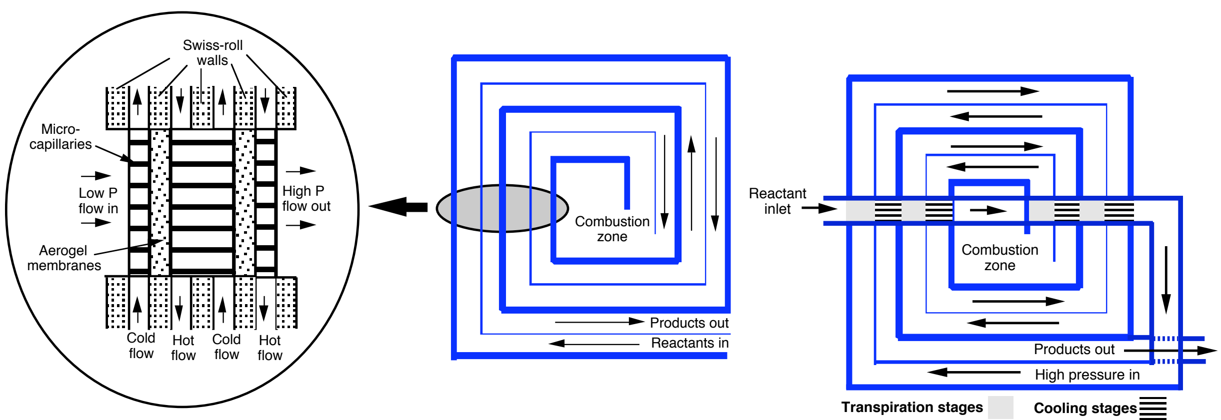

Figure 2. Proposed implementations of thermal transpiration pumps into Swiss roll combustors. Generic "Swiss roll" combustor (center) and multi-stage thermal transpiration pump integrated into the turns of a Swiss-roll combustor (left and right) (note transpiration and cooling stages are reversed going toward vs. away from center of combustor.)

Vargo *et al.* [5] showed that it is possible to construct a staged Knudsen compressor where the aerogel membranes are separated by cooling stages with pore sizes much larger than the mean free path of the molecules (so that no reverse thermal transpiration occurs in the cooling stages.) In this way a larger pressure rise can be obtained than is possible from a single stage. This pattern of alternating heating and cooling sections is readily available within a spiral counter-current “Swiss roll” heat exchanger and combustor [7], in which multiple adjacent hot (product) and cold (reactant) channels are present. Figure 2 shows how Knudsen compressors could be incorporated into a Swiss roll combustor for multi-stage pressurization. The microchannels of the thermal guards would instead be microcapillary tubes that are exposed to the flow in the channels of the Swiss roll device. The system acts as sets of cross-flow heat exchangers for providing the alternating temperature gradients with temperature increasing (in the direction of flow) in the aerogel membranes and decreasing in the microchannels.

Vargo and collaborators [5] developed a model of the performance of thermal transpiration pumps. This model can be used to predict the performance of thermal transpiration pumps for propulsion using the usual thrust equation based on a 1D momentum balance and the standard isentropic compressible 1D flow equations [8] for gas expansion to ambient pressure (matched exit condition). The predictions (Fig. 3) are expressed in terms of standard figures of merit, e.g. the dimensionless thrust ≡ $F/\mathbf{m}a_1$, where F is the thrust, **m** the total mass flow rate and a_1 the sound speed at ambient conditions, and the dimensionless thrust specific fuel consumption ≡ (thermal power)/Fa_1, where the thermal power is simply the product of the membrane thermal conductivity, area and temperature gradient of the aerogel. Figure 3 (left) shows that an optimal pore diameter exists, but the maximum of pumping efficiency and minimum of thrust specific fuel consumption are relatively shallow so that precise matching of pore diameter to operating conditions is not required. Figure 3 (right) shows that there is a substantial benefit to higher hot-side temperatures, *e.g.* beyond the temperature limit of nanoporous bismuth (270˚C). For this reason the hybrid system of Fig. 1 (right) is preferable when combined propulsion and power generation is required and maximum performance of both is desired. Interestingly, the predicted performance data are of the same order of magnitude as that calculated theoretically for commercial aircraft gas turbine engines; for a typical idealized turbojet cycle the values of specific thrust and thrust specific fuel consumption are 2 and 3, respectively [8].

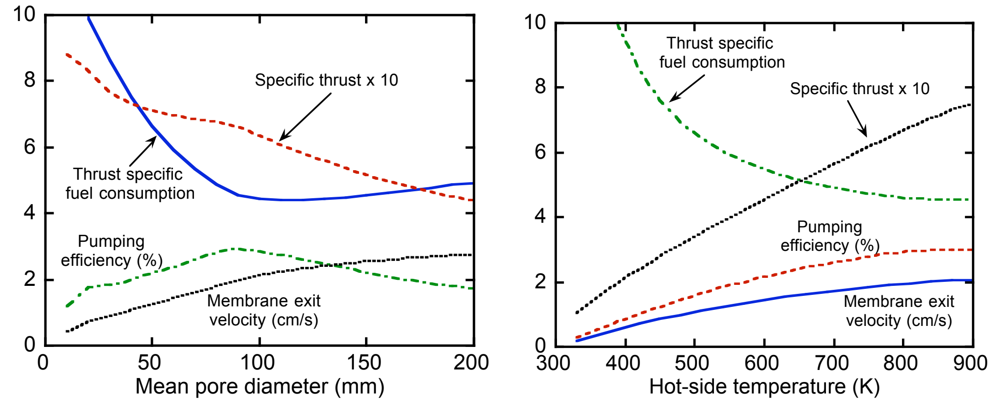

Figure 3. Predicted performance of Knudsen pumps and propulsion devices. Left: effect of mean pore diameter of nanoporous membrane; Right: effect of temperature on hot side of membrane. Membrane thickness 1 mm, cold-side temperature 300K, cold-side pressure 1 atm, hot-side temperature 800K.

Preliminary results

Although NASA funding has not yet begun, an initial test of the stand-alone thermal transpiration system was made using commercially available silica aerogel with thermal conductivity of 0.016 W/m˚C and density 0.1 g/cm^3, machined using traditional techniques into a disk 4 mm thick x 30 mm diameter. The test fixture is shown in Fig. 4 (left). The thermal guards were sealed into inlet and outlet plenums with o-rings. On the outlet-side (hot-side) thermal guard, an additional sub-plenum with a platinum gauze catalyst screen was installed, though in the tests described below only air was used as the test gas and an electrical heater was wrapped around the outlet-side plenum to create the temperature gradient across the aerogel membrane. K-type thermocouples were attached to both thermal guards to measure the temperature differential across the aerogel. Steady-state flow rates were measured by displaced water in a graduated cylinder. This simple test fixture was found to produce steady pumping for at least several hours of continuous operation. Figure 4 (center and right) shows typical quantitative results. The measured pressure differences and flow rates obtained are about a factor of two lower than the predicted values from the analytical model, almost certainly because the aerogel membrane is not sealed on the outside surface. Nevertheless, it does demonstrate the possibility of thermal transpiration pumping in a configuration similar to that shown in Fig. 1. Means for sealing the sides of the aerogel without causing a thermal or electrical short circuit have been identified and will be pursued in this work.

Project objectives

The goal of this work is to test the feasibility of creating miniature propulsion and power generation devices employing nanoporous materials for four purposes relevant to space applications:

(1) Thermal transpiration based propulsion, integrating nanoporous materials with a catalytic combustor having lower thermal contact resistance with the hot side of the nanoporous membrane to create a combustion-driven thermal transpiration pump for propulsion applications. This will employ SiO_2 aerogels and nanoporous materials to accomplish thermal transpiration along with conventional catalyst materials and supports. Both simple linear designs (Fig. 1) and multi-stage Swiss-roll designed (Fig. 2) will be tested.

(2) *Combustion catalysts encapsulated in nanoporous material* for use with (1) above as a possible (but not required) integrated performance enhancement.
(3) *Thermal insulation.* The use of nanoporous materials *sealed with low thermal conductivity materials to prevent gas leakage and patterned using fabrication processes borrowed from MEMS technologies* is an important performance enhancing technology.
(4) *Integrated power generation and thermal transpiration pumping using nanoporous bismuth.*

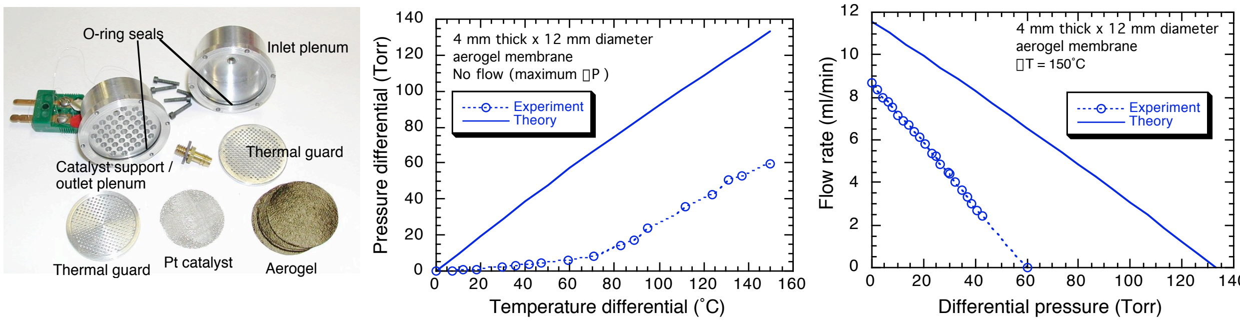

Figure 4. Left: Disassembled view of catalytic combustion driven thermal transpiration pump test fixture. Center: maximum (zero flow) pressure differential as a function of temperature difference across the aerogel membrane. Right: volume flow rate as a function of pressure differential for 150˚C temperature difference across the aerogel membrane.

Potential applications of the results

In addition to the self-pressurizing propulsion/power generation application proposed in the current work, catalytic combustion driven thermal transpiration compressors could also be used for virtually any small-scale pumping application such as microscale gas sampling instrumentation (e.g. a micro-mass spectrometer), pneumatic accumulators for mechanical actuators and active cooling systems for dense microelectronics. Combustion-driven thermal transpiration pumps have a distinct advantage for these applications in that fuel, rather than electricity that must be generated at very low efficiency, provides the power for the pump. One particularly useful spinoff might be to non-propulsive miniature power generation. Many such methods have been proposed, *e.g.* [1, 2, 3], but most leave unresolved critical "balance of plant" issues, in particular pressurization for fuel and air. In the case of thermoelectric-type systems, even if sufficient fuel and air pressure are available to push the reactants through the generator, additional pressure enables more aggressive fins to be attached to the thermoelectric devices. This reduces the thermal resistance between the gases and the thermoelectric elements, which increases the temperature difference across the elements (as opposed to the temperature difference between the gases and the surfaces of the elements), which in turn improves thermoelectric device performance greatly.

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