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Micro-Scale Regenerative Heat Exchanger

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A micro-scale regenerative heat exchanger has been designed, optimized and fabricated for use in a micro-Stirling device. Novel design and fabrication techniques enabled the minimization of axial heat conduction losses and pressure drop, while maximizing thermal regenerative performance. The fabricated prototype is comprised of ten separate assembled layers of alternating metal-dielectric composite. Each layer is offset to minimize conduction losses and maximize heat transfer by boundary layer disruption. A grating pattern of 100 micron square non-contiguous flow passages were formed with a nominal 20 micron wall thickness, and an overall assembled ten-layer thickness of 900 microns. Application of the micro heat exchanger is envisioned in the areas of micro-refrigerators/coolers, micro-power devices, and micro-fluidic devices.

I. Introduction

MESO and/or micro-scale devices operating on the Stirling cycle are an attractive concept based on the high efficiencies realized for Stirling machines at traditional scales. A further attraction of micro-scale Stirling devices is the ability of the Stirling cycle to be used for generating power where a temperature difference is maintained; or, in the "reverse" cycle, producing refrigeration with power input. However, two critical performance issues become highly problematic at the micro-scale for Stirling devices: axial thermal conduction and pressure drop.

In the case of axial thermal conduction, the temperature differential between the hot and cold ends of a Stirling device is predominantly maintained by the regenerator (i.e. regenerative heat exchanger). The regenerator's primary function is to alternately store and release heat from/to the working gas on every cycle. Axial thermal conduction through the regenerator introduces a direct loss to the Stirling device performance. Therefore, a trade-off exists between maximizing heat transfer from the working gas to the regenerator, while minimizing axial conduction losses from the hot end to the cold end through the regenerator. At traditional scales, this trade-off is adequately addressed using a variety of techniques (e.g. stacked screens, tube bundles, packed beds, porous media, concentric tubes, spiral foils, etc.). However, as the conduction length is reduced to the order of millimeters or less, traditional techniques are inadequate, and minimizing axial conduction losses become paramount.

Pressure drop in a regenerator is exacerbated by the large surface area to volume ratios inherent in fluid passages at the micro-scale. Viscous forces in such small passages enable the growth of large boundary layers (relative to the passage diameter) and correspondingly large pressure drops and lower heat transfer film coefficients. Micro-scale regenerators must address this pressure drop issue without unduly compromising the heat transfer performance of the device.

Limited prior art exists for meso/micro-scale regenerators. Bowman, et al.[1], describe several regenerator concepts which are evolutionary extensions of traditional-scale regenerators. However, they possess contiguous solid structures from the hot to cold end of the device thereby providing a significant thermal path for axial conduction losses. Furthermore, for all the regenerators except a reticulated open-cell ceramic concept, the flow passages are continuous and unbroken allowing significant boundary layers to develop. Moran[2] addressed the axial conduction loss problem with a regenerator composed of multiple layers with low thermal conductivity interfaces. This configuration eliminates the contiguous single-material structural thermal path from the hot end to the cold end. One of these regenerator variations also uses converging-diverging flow passages to reduce boundary layer formation. Nevertheless, further reduction in axial conduction losses and pressure drop are needed to improve the performance of micro-scale Stirling devices.

II. Design and Analysis

A. Design Concept

The primary function of a regenerator placed between the compression and expansion spaces of the Stirling device is to alternately accept and dissipate thermal energy to a working fluid during oscillatory flow with minimum flow resistance. A secondary function is to minimize heat transfer in the axial direction between a hot and cold temperature source, thus maintaining a temperature differential in the axial direction. Figure 1 shows sketches in partial isometric perspective and top view of two layers of a micro-regenerator design that addresses these key functions at the micro-scale.

The regenerator is composed of layers of grating structure where each layers is offset by one-half of a single-cell opening in both directions relative to adjacent layers. As a result, alternating layers are aligned. Additionally, the grating is a composite of high thermal conductivity and low thermal conductivity materials within each layer. Referring to the top sketch in figure 1, as hot fluid flows through the regenerator from the top to bottom, thermal energy from the fluid is transferred to the regenerator and stored. When the flow is reversed, cold fluid flows through the regenerator from bottom to top, and thermal energy is transferred back to the fluid. This process maintains cold temperatures below the regenerator, and hot temperatures above the regenerator.

The novel features of this regenerator design include:

- A microstructure with a high number of layers (state-of-the-art microstructures generally consist of four layers or less)
- Composite material layers composed of high conductivity and low conductivity materials
- Layer-to-layer offset

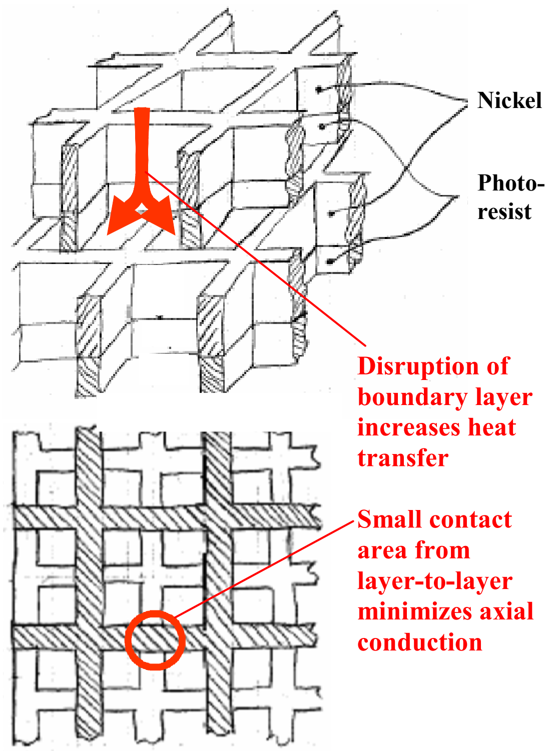

Figure 1. Layer-offset grating pattern regenerator design composed of nickel and photoresist (isometric and top views)

These combined features enable several unique performance characteristics. First, the axial conduction is minimized by introducing many layers with low conductivity material at each interface, and with greatly reduced interfacial contact area due to the offset technique. The result is a minimized effective thermal conductivity in the axial direction of the regenerator. Once the regenerator is installed within a micro-Stirling device, some delamination of the layers is permissible provided the alignment is maintained and no debris is produced. In fact, delamination will further enhance the performance by lowering the axial conduction. The regenerator design therefore provides some robustness relative to assembly and operational degradation.

Second, the layer-to-layer offset and reasonably high porosity attainable with this regenerator results in low pressure drop. The offset disrupts boundary layer formation; while porosity is indirectly proportional to pressure drop (i.e. higher porosity results in lower pressure drop). Finally, the use of high conductivity material in each layer, and offsets between layers, result in improved heat transfer between the regenerator and the fluid. Disruption of the boundary layer by the offset increases the heat transfer film coefficient between the regenerator and the fluid resulting in better thermal energy transmission.

B. Analysis

A design trade analysis that accounts for fabrication capabilities was conducted in order to converge on an optimized regenerator prototype design that balances the critical performance parameters of the device. Table I summarizes the parameters that were selected to be held constant for the design trade analysis. The following constraints were also imposed based on the design space selection, fabrication limitations, and assembly capabilities:

- Cell wall thickness greater than or equal to 10 μm*
- Cell opening between 25 and 500 μm
- Nickel thickness between 10 and 50 μm
- Photoresist thickness between 0.06 and 40 μm
- Ratio of nickel thickness to overall layer thickness less than or equal to 10
- Ratio of nickel thickness to photoresist thickness greater than or equal to 1
- Number of layers less than or equal to 10

Table I. Constant parameters for the design trade analysis

PARAMETER	VALUE	COMMENTS
Overall width	1 cm	1-cm^2 footprint selected as reasonable for testing and prototype application
Swept volume	0.5 mm^3	Volume of working gas flowing through regenerator on each cycle
Operation frequency	1000 Hz	Chosen to be near expected resonance of micro-scale Stirling device
Temperature difference	20 ^{o}C	Target steady state temperature difference across regenerator
Working gas	Helium	Properties evaluated at 27 ^{o}Cand 10 bar

Four key performance parameters were analyzed: (1) axial heat conduction through the thickness of the regenerator; (2) pressure drop through the regenerator; (3) dead volume ratio; and (4) porosity. The importance of minimizing axial heat conduction and pressure drop has been discussed previously. The axial conduction was calculated using a one-dimensional thermal resistance network that accounted for the structure and materials of each layer of the regenerator. Since the layers are bonded during assembly, layer-to-layer interface resistance was assumed negligible. However, thermal constriction resistance was accounted for due to the changes in cross-section from layer to layer. Pressure drop was calculated using a porous media correlation.

The dead volume ratio (i.e. dead volume divided by swept volume) is indirectly proportional to Stirling device performance, and therefore must also be minimized. The dead volume includes the open area of the regenerator in which the working gas resides. Swept volume is the volume of working gas "swept out" by the motion of the pistons†. The dead volume ratio is calculated directly from the geometry of the regenerator and the assumed swept volume shown in table I.

Porosity of the regenerator, in addition to having a direct effect on pressure drop, gives an inverse indication of the amount of regenerator material available to transfer heat to and from the working gas. Since pressure drop is already calculated independently in the design trade analysis, the porosity is used as an inverse indicator of the regenerator's thermal capacitance. Therefore, an optimum design would have a porosity that balances pressure drop and thermal capacitance. Porosity is calculated directly from the geometry of the regenerator.

C. Optimization and Sensitivity Analysis

Table II shows the results of several optimization runs with different optimization targets, along with the final selected design that attempts to balance these single-parameter optimizations. Each of the three optimized designs (i.e. minimum axial conduction, minimum dead volume ratio, and minimum pressure drop) indicate excellent performance in the target parameter. However, none of the single-parameter optimizations yields good performance across all key parameters. The final column is a design that yields good overall performance with low axial conduction, reasonable dead volume ratio, and a porosity value low enough to insure adequate thermal capacitance without producing unacceptable pressure drop. A sketch of this balanced design is shown in figure 2.

Using the balanced design parameters shown in the last column of table I as a baseline, a sensitivity analysis was performed to provide insight into the effects of fabrication variability of the opening size on the critical performance parameters. Holding all other parameters constant, the cell opening size was varied from 50 to 150 μm; and the sensitivity of axial conduction, pressure drop, and porosity on opening size determined (see fig. 3).

The response of axial conduction and porosity as a function of cell opening size was found to be mildly nonlinear. However, pressure drop increased dramatically below an opening size of about 80 μm. Based on the

* This was raised to 20 μm for the final design due to fabrication feasibility concerns with the process used.
† Or, in the case of the proposed micro-scale Stirling device, the volume swept out by the moving diaphragms.

sensitivity analysis, variability of ±20 µm in the opening size (with a nominal opening of 100 µm) due to the fabrication process was deemed acceptable.

Table II. Optimized and final design variable parameters

PARAMETER		MIN. AXIAL CONDUCTION	MIN. DEAD VOLUME RATIO	MIN. PRESSURE DROP	BALANCED DESIGN
Cell wall thickness	µm	10	43	76	20
Cell opening	µm	500	98	500	100
Nickel thickness	µm	50	10	10	50
Photoresist thickness	µm	40	0.06	0.06	40
Axial conduction	***W***	***0.37***	***3.49***	***3.43***	***0.48***
Pressure drop	***kPa***	***7***	***184***	***2***	***51***
Dead volume ratio	***-***	***0.0173***	***0.0006***	***0.0014***	***0.0115***
Porosity	***%***	***96***	***31***	***72***	***64***

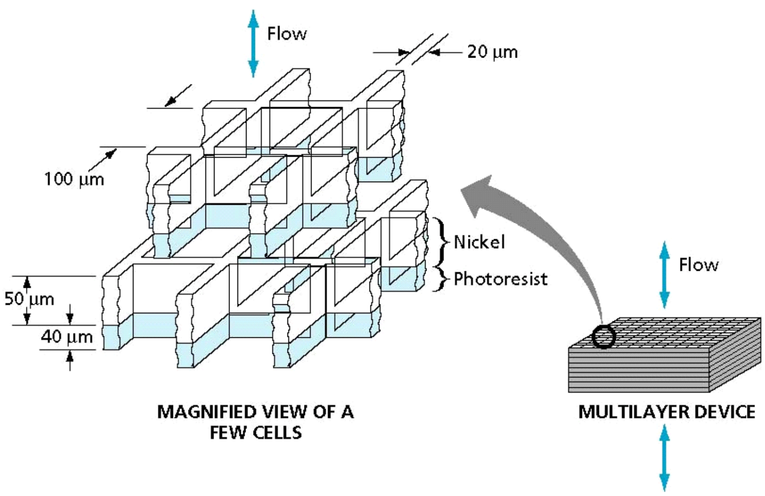

Figure 2. Sketch of balanced design

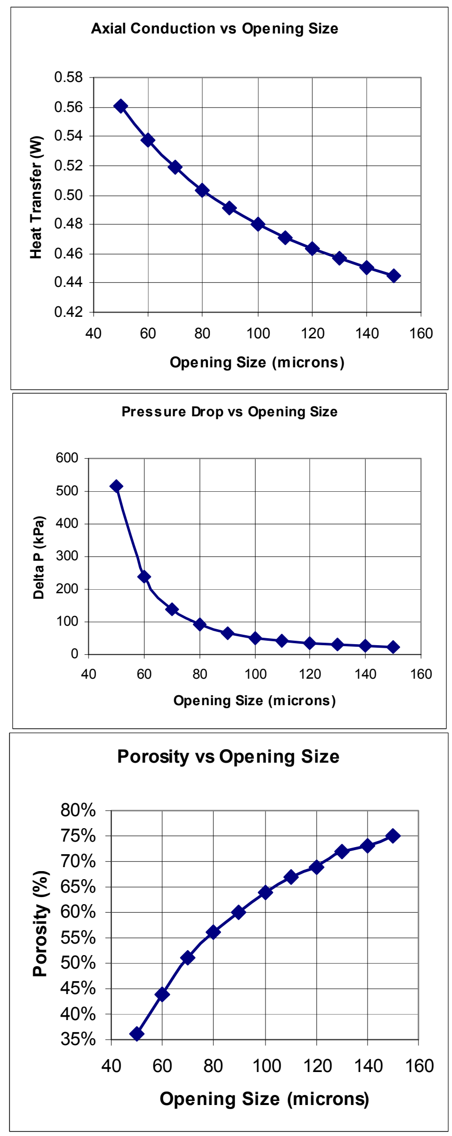

Figure 3. Effect of opening size on axial conduction, pressure drop, and porosity

III. Fabrication

The regenerator prototype was fabricated and assembled using a single layer-by-layer technique comprised of the following steps:

1) Substrate surface preparation
2) Application of sacrificial layer
3) Application of diazo resist
4) Ultraviolet exposure of diazo resist
5) Electro-deposition of nickel regenerator matrix
6) Application of photoresist layer
7) Ultraviolet exposure of photoresist layer
8) Removal of single layer structure from substrate
9) Repeat of steps 1-8 until nine good layers are produced
10) Assembly of layers into finished device

Figure 4 shows the mask design for fabrication of an array of nine individual layers simultaneously on one wafer. A similar mask (not shown) produces nine more layers with the desired single-cell opening offset. Each mask is produced on a three-inch wafer, and contains wafer alignment marks to insure proper alignment.

An enlarged view of one of the mask squares representing a single regenerator layer is shown in figure 5. Small alignment marks surround the regenerator layer, and a cross pattern of solid nickel in the center provides increased structural support. Each of the nine regenerator layers contains a unique identifier at the center.

A microphotograph of a fabricated regenerator layer after deposition of the nickel is shown in figure 6. Figure 7 provides a view of a larger portion of the regenerator layer including the center support structure. The overall assembled regenerator has dimensions of one 10 mm square by 0.9 mm thick, and contains ten of these regenerator layers. Each layer is composed of 50 microns of nickel deposited on 40 microns of low conductivity photoresist. The square-cell openings in the gratings are nominally 100 µm square with solid walls on the order of 20 µm thick. Each grating layer is offset by 50 µm in both directions, so that alternating layers are duplicates and in precise alignment.

IV. Concluding Remarks

A micro-scale regenerator has been designed, analytically optimized, and fabricated. The regenerator is composed of multiple layers of photoresist-nickel structure in an offset grating pattern. The offset pattern and composite structure minimizes axial conduction losses and disrupts boundary layer formation for improved heat transfer.

Testing is currently underway with the regenerator in a meso-scale Stirling simulation test fixture[3]. Initial results indicate that the flow resistance of the regenerator is comparable to competitive regenerator materials and configurations. Thermal performance testing of the regenerator is pending.

Although the regenerator has been developed for use in a micro-scale Stirling devices, the general design may also be applicable in micropower and microfluidic devices where the maintenance of a temperature differential along a millimeter or less conduction length is required. In addition, the geometry lends itself to micro-scale heat exchangers where the offset grating pattern mimics enhanced surface compact heat exchangers at the traditional scale, and provides correspondingly high heat transfer rates.

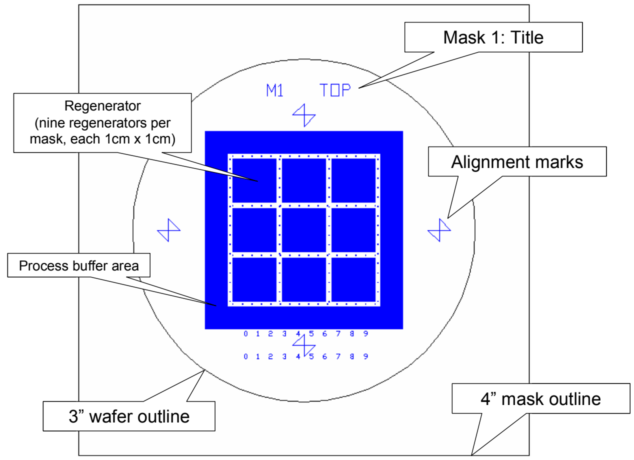

Figure 4. Mask design for nine regenerator layers

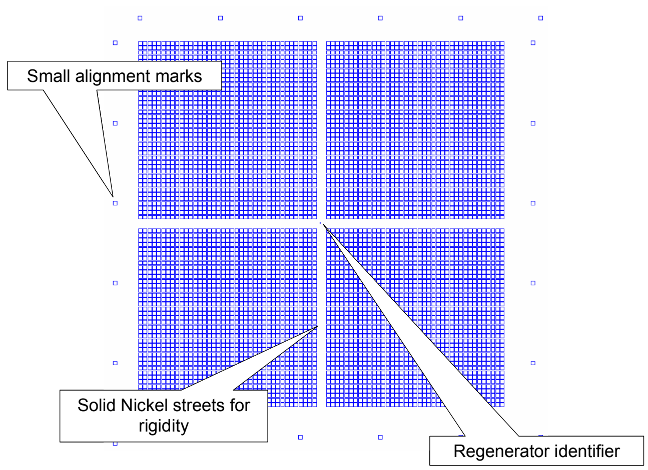

Figure 5. Mask for a single regenerator layer

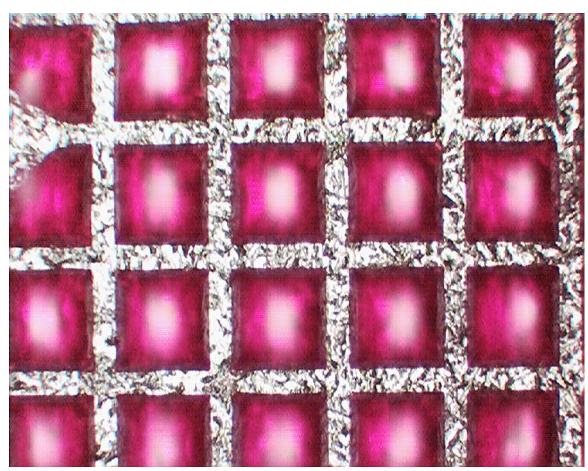

Figure 6. Microphotograph of a single regenerator layer following nickel deposition

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[1] Bowman, L., and McEntee, J., “Microminiature Stirling Cycle Cryocoolers and Engines”, US Patent No. 5,941,079, Aug 24, 1999.

[2] Moran, M.E., “Micro-Scalable Thermal Control Device”, US Patent No. 6,385,973 B1, May 14, 2002.

[3] Moran, M.E., Wesolek, D.M, and Rebello, K.J., “Microsystem Cooler Development”, 2nd International Energy Conversion Engineering Conference, Providence, RI, Aug 16–19, 2004.

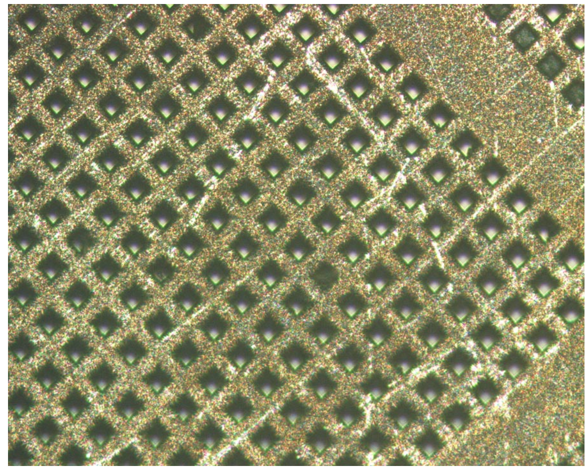

Figure 7. Microphotograph of regenerator layer showing center support structure

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13. ABSTRACT ***(Maximum 200 words)***

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