A Lightweight, High-Effectiveness Recuperator for Next-Generation Airborne Cryocoolers

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ABSTRACT

Next-generation turboelectric aircraft aim to decouple power generation from propulsion by using gas turbines driving electric generators connected to electric propulsion motors. The power density requirements for these electric machines can only be achieved with superconductors, which in turn require lightweight, high-capacity cryocoolers. However, current cryocooler technologies offer cooling capacities that are too low and masses that are too high to meet projected aircraft needs. For turbo-Brayton cryocoolers, the recuperative heat exchanger historically has been the largest and most massive component, and offers the most potential for size and weight reduction. Improvements may be achieved through the use of smaller flow passages; orthotropic core thermal resistance, to decrease resistance between flow streams while increasing axial resistance from warm to cold ends; and lighter-weight materials. To this end, a recuperator that implements all such improvements has been developed. The recuperator core consists of a stack of copper-polyimide plates. Miniature flow features are etched into the copper to provide the flow path for the recuperated gas stream. The small flow features etched into the conductive copper substrate promote heat transfer radially between flow streams, while the polyimide acts as a thermal resistor in the axial direction. The laminates are bonded together. The result is a compact, monolithic core that achieves high specific conductance. This new recuperator technology fills a void between high-performance, lightweight recuperators for space applications and commercial high-capacity cryocoolers. This paper describes the design and testing of a prototype recuperator.

INTRODUCTION

Turboelectric propulsion with superconducting electric generators and motors has the potential to revolutionize air transportation. A key enabling technology will be efficient, lightweight cryocoolers to cool the superconductors below their critical temperature. However, the weights of current commercial cryocoolers are too high and their efficiencies are too low to be practical for aircraft. Turbo-Brayton cryocoolers are well-suited for this application, as their performance scales well to higher loads. Efficiency of the turbo-Brayton cryocooler improves and the ratio of cryocooler mass to input power decreases with size [1]. This is because the losses in the turbomachines used in the refrigeration cycle become a smaller fraction of the delivered cooling as the machine capacity increases. Nevertheless, meeting the weight challenges for the turbo-Brayton cryocooler will require innovation in design of all of the major cryocooler components. Advancements in high-capacity compressors and turboalternators [2] have been previously developed, and are suitable in the present study to obtain on the order 1000 Watts of cooling down to 15 K, although additional

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development is needed to optimize the size and weight of the turbomachines. The recuperative heat exchanger has historically been the heaviest and largest component, however, and thus offers the most potential for mass and size reduction of the cryocooler system.

Some advancements in lightweight recuperator alternatives have been developed and demonstrated, including the shell-and-microtube recuperator [3], which is being qualified for NASA space applications. This recuperator has achieved a recuperated heat transfer of 5.2 kW and a specific conductance of 320 W/K/kg for helium down to 20 K. Advanced micro-tube designs under development may achieve up to 700 W/K/kg. Ultimately, however, the microtube recuperator is limited by a relatively high axial conduction penalty of the stainless steel tubes and shell, and requires relatively long aspect ratios to achieve the high effectiveness generally required for turbo-Brayton cryocoolers. Furthermore, the higher material density of the mostly stainless steel design is a drawback relative to more lightweight aerospace materials. An ideal recuperator for such high-capacity aerospace applications would achieve the required mass gains with a more compact core, by reducing sizes of flow passages, reducing axial conduction, increasing heat transfer between flow streams, and using lighter-weight materials. This paper discusses the design of a novel type of lightweight, compact laminated slotted plate recuperator (LSP) that implements these improvements. Additionally, the paper describes the development and testing of a hardware prototype that validates the core fabrication processes and performance.

SIGNIFICANCE OF DEVELOPMENT

A trade study for the lightweight, high-capacity cryocooler revealed a potential for significant weight and size reduction for the LSP recuperator relative to alternative technology, resulting in overall cryocooler mass reduction. While the extensive use of polyimide in the LSP recuperator would be a drawback for systems where long life with no maintenance is critical (as in space applications), for more maintenance-accessible terrestrial and airborne applications, the LSP recuperator could fill a niche need for lightweight recuperators where the component life and material outgassing rates are not critical.

Factors contributing to the potential weight reduction of the LSP are the smaller characteristic dimension for heat transfer, the reduced axial conduction, and continuous reset of the thermal boundary layer for heat transfer enhancement. The present embodiment of the LSP offers characteristic hydraulic diameter of around 128 micron, which bests the smallest demonstrated microtube tube diameter of 360 micron. Additionally, the polyimide spacer of the LSP boasts a thermal resistance that is 30-60 times as resistive as the stainless steel microtube; it also forms an axial gap between the thermally conductive portions of the laminate core, allowing for boundary layer reset. The result for the LSP is a much smaller axial length required to achieve the same effectiveness. However, a key technical challenge is to provide a reliable means of sealing to prevent cross-stream leakage and for attaining sufficient axial compression strength to prevent buckling. The goal is thus to attain a low-leak design that can withstand the compression pressures required to keep the stack intact, all while providing maximum flow area for high-capacity heat transfer.

RECUPERATOR DESIGN AND ANALYSIS

The innovation in this technology is a compact core consisting of a stack of bonded laminated slotted plates; the plates themselves comprise a conducting copper layer and an insulating polyimide layer. The copper layer contains the fin and slot features for convective heat transfer between axial countercurrent flow streams, and the polymer layer provides sealing, structural support, and thermal resistance against parasitic axial heat transfer.

The plate layout is arranged into a set of annular rings containing a pattern of involute arrays of heat transfer fins and flow slots, with alternating counter-current flow streams separated from one another by the polymer sealing surfaces. Each plate has axial height of approximately 86 microns. The fin and slot features have nominal width of 64 microns each. A magnified image of these features is shown in Figure 1.

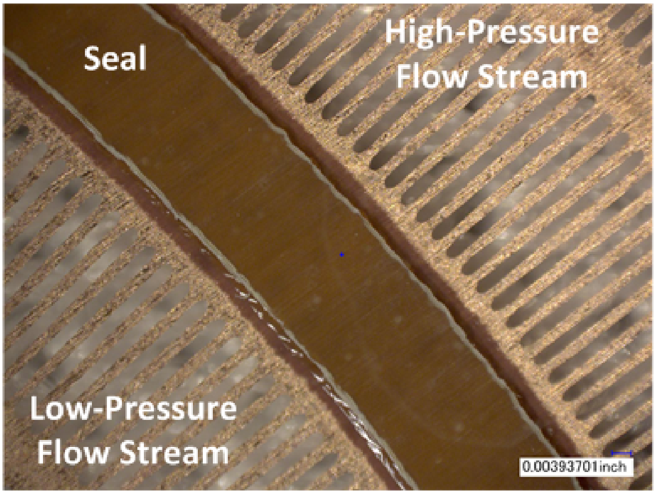

Figure 1. Prototype LSP plate features

In order to demonstrate the feasibility of the bonded LSP technology, a smaller prototype recuperator core was designed with 5.1 cm diameter and 1060 LSP plates, constituting a core of approximately 9.8 cm in axial length.

The core is bonded to a pair of machined stainless steel headers that transition the flow from tube ports to an array of flow distribution features matching the layout of the core plates. To make the module hermetically sealed to the exterior environment, the core is compressed into a stainless steel shell, and the shell is welded to the headers to close out the module. Figure 2 shows the assembly drawing of the prototype module.

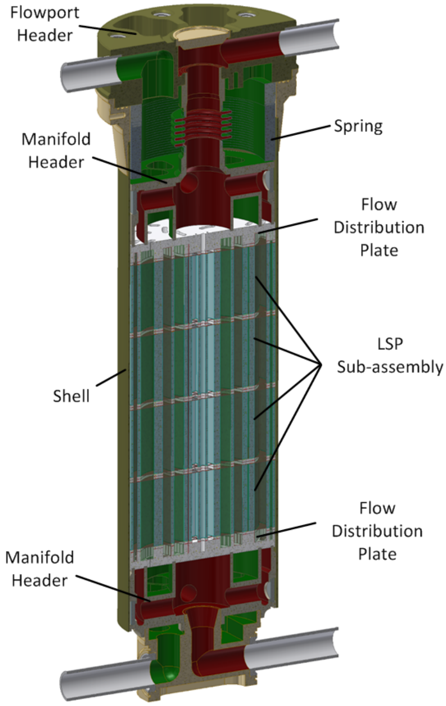

Figure 2. Prototype LSP recuperator assembly

Various thermo-fluid and structural analyses were performed using both spreadsheet and computational fluid dynamics models to assess the performance of the LSP recuperator and the impact of various design features on the performance of the core. The nominal operating conditions of the recuperator prototype are 1.36 g/s of helium with warm-end temperature of 300 K and cold-end temperature of 20 K. The recuperator was designed for a high-side pressure of 9.9 atm and low-side pressure of 6.6 atm. The temperature and pressure fluid states match expected cryocooler conditions. The expected prototype recuperator effectiveness and non dimensional pressure drop at design conditions are 0.9893 and 1.7%, respectively. Approximately 10% of this pressure drop is due to losses in the headers.

The prototype represents an approximately 1/8th scale version (in terms of UA) of a larger set of recuperator modules that were designed to be integrated into a high-capacity cryocooler. The larger recuperator modules provide cooling for a two-stage cryocooler, and are subdivided into an upper stage, cooling to 100 K, and a lower stage, cooling to 20 K.

RECUPERATOR FABRICATION

The key steps in the fabrication of the recuperator are photochemical etching of the miniature flow features and seals, and bonding of the plates and headers into a monolithic core. Flow feature sizes must be minimized to improve stream-to-stream heat transfer, and seals must be uniform in width and height to minimize core leaks. Any core leakage manifests itself as cross-stream leakage from the high-pressure to low-pressure flow streams; at the cryocooler level, this cross-stream leakage bypasses the turboalternator and degrades cooling performance.

Minimum limits on fin and slot feature sizes were developed through a series of etching trials in cooperation with an etching vendor. Sealing structural limits were determined through a series of spreadsheet and finite element analyses, as well as experimental trials, resulting in a minimum seal width. The seal width is a function of several variables: geometric layout of the sealing features, required compression force to prevent tensile failure from delamination, stacking misalignment tolerances during assembly; achievable limits on widths from the etching process, and structural yield limits for buckling and crushing. Etching trials and plate inspections honed the process of repeatedly producing flow features and sealing features that met design requirements, in preparation for core assembly.

Following assembly and bonding, the core is closed out with a thin, stainless-steel shell that acts as both a hermetic boundary and a tension member to keep the core in compression. The warm-end header consists of two sections: a floating header that is bonded to the core laminate stack, and a flow-port header that is welded to the outer shell. A wave spring and spring shim are inserted between the two warm-end header sections to maintain a more uniform compression load on the core during all foreseeable operating conditions. The core compression load prevents tensile failure of the stack by protecting against thermal contraction mismatch between the core and shell, and also by accommodating stress relaxation of the material under load. To facilitate the ability to disassemble the prototype recuperator, the shell consists of two sections with a pair of bolted flanges that are sealed with a ring of indium. Final closeout of the recuperator is completed by compressing the shell to the mating flange on the cold header, over the core assembly, until the flanges are in close contact. Then bolts are used to maintain load at the flanged joint. Figure 3 shows the completed prototype assembly.

RECUPERATOR TESTING

The recuperator was tested for external leakage, cross-stream leakage, proof pressure based on the requirements of the test facility, pressure-flow performance, and thermal performance at cryogenic temperatures. The first three of these tests verified workmanship and established viability of the heat exchanger for installation into a cryocooler or test facility. The pressure-flow and thermal performance tests were compared with model predictions to validate the recuperator performance.

The cross-stream leak test was completed by pressurizing one side of the recuperator to design pressure differential, while the ports for the opposite flow stream were open to allow flow to exit to

Figure 3. Completed LSP prototype

ambient. The result, with gas state corrected to operating conditions, was a 0.3% leak rate relative to design flow, meeting the goal of <1% leakage.

Pressure drop through the recuperator was measured with room-temperature steady-state nitrogen flow using a laminar flow meter to measure flow rate and an absolute pressure transducer to measure pressure drop. Dynamically similar conditions were achieved for slots in the core plates, between design and test conditions, by matching the test Reynolds number to the average Reynolds number at cryogenic design conditions. Flow rate was varied to develop a performance curve for flow rate versus pressure drop, for both high- and low-pressure flow streams. The results, as shown in Figure 4, show a good agreement between model predictions and test conditions, particularly at the dynamically similar condition. At higher flow rates, the actual pressure drop deviated somewhat from the design predictions, indicating that kinetic losses were somewhat lower than predicted by the model.

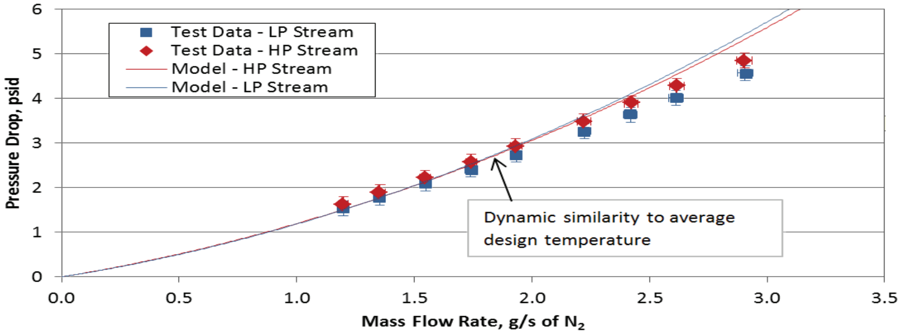

Figure 4. Pressure-flow test data for LSP recuperator. At Reynolds number corresponding to that of average design temperature, the model is in good agreement with results. At higher flow rates, the model appears to over-predict kinetic losses.

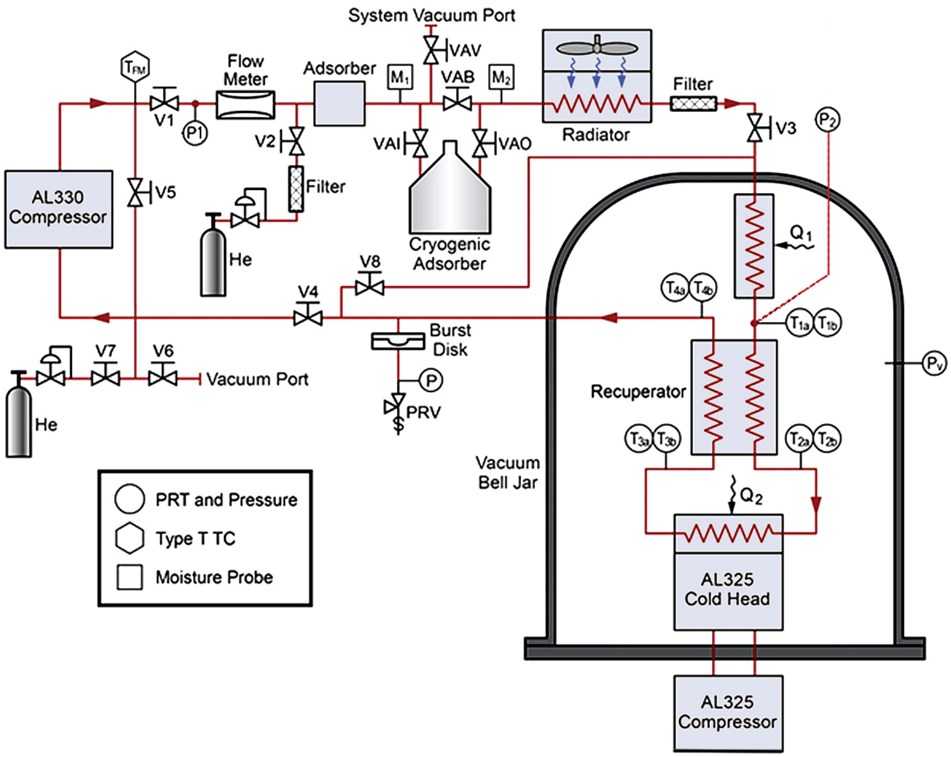

Figure 5. Cryogenic thermal test facility

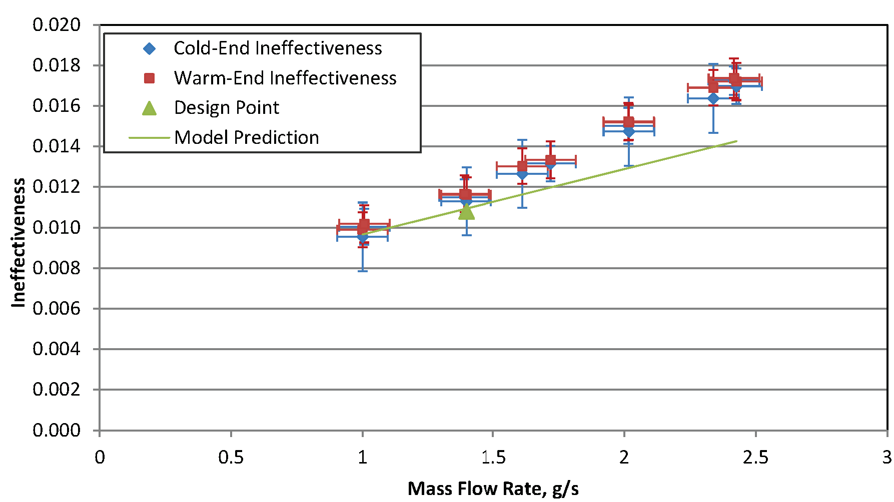

Figure 6. Thermal ineffectiveness of the recuperator

To evaluate thermal effectiveness, the recuperator was tested under cryogenic conditions. To maximize the stream-to-stream temperature difference and ensure adequate fidelity in the thermal measurements, the warm end of the recuperator was held at 300 K and the cold end was varied between 24 K and 50 K. The test facility schematic is shown in Figure 5. Temperatures were measured at the inlet and outlet ports of both flow streams of the recuperator using redundant, in-line Platinum Resistance Thermometers (PRTs), and the flow rate was measured using a spring-loaded rotameter. The facility operates in a closed-loop mode, allowing testing for a sufficient time period to reach steady state thermal conditions at each data point. The recuperator was covered with Multi-Layer Insulation (MLI; 7 layers at the cold end and 1-3 layers at the warm end) to limit external parasitic losses to approximately 80 mW, which is a small fraction of the total heat transfer rate within the unit (nominally 2 kW).

During the thermal test, a total of 11 data points were collected. The heat transferred between the two flow streams ranged from 1.3 kW to 3.3 kW. The redundant temperature sensors were in agreement with one another within the 2-σ uncertainty band for all but two of the 44 temperature readings. The calculated thermal ineffectiveness at the design point was 0.0115 with a heat imbalance of 0.37 W. The thermal ineffectiveness is shown in Figure 6 as a function of flow rate. The data are self-consistent and show low magnitude of parasitic heat transfer throughout. The model predictions compare well with test data at the design point, with an ineffectiveness difference of only 0.0008 between the two. At higher flow rates, the model appears to under-predict ineffectiveness slightly, which may result from less gas expansion between fin layers than assumed in the modeling, and thus less interaction with the fins' axial heat transfer surfaces, at the higher flow rate.

CONCLUSIONS

Creare has developed a novel embodiment of a lightweight, high-capacity, high-effectiveness laminated slotted plate recuperator using fully-bonded, etched plates that consist of a conductive metal heat transfer interface with a resistive polyimide spacer. This paper discussed the design, fabrication, and testing of a prototype LSP recuperator. Thermal performance test results for the 5.1 cm diameter prototype showed an effectiveness of 0.9885 at the design point, which was in accord with model predictions. While the present effort focused on development of the fabrication methods and thermal performance of the recuperator, future efforts to reduce weight, including scale-up of module size, reduction of compression loads, and transition to lightweight titanium alloy header and shell materials will likely generate a weight savings of approximately 24% compared to similar-performance microtube recuperators. The results suggest that the LSP recuperator is well-suited for integration into future lightweight, high-capacity turbo-Brayton cryocoolers for airborne and terrestrial applications.

ACKNOWLEDGMENTS

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