Recuperative Cooling Capability of Miniature Thermoacoustic Expanders (MTAEs) around 77 K

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ABSTRACT

An experimental study of the cryogenic recuperative cooling performance of a **m**iniature **t**hermo**a**coustic **e**xpander (MTAE) is reported in this paper. The feasibility of an MTAE **r**ecuperative **c**ooling **s**ystem (MRCS) run at a low mass flow rate (<180 mg/s) in the temperature range around 77 K is experimentally demonstrated in a basic recuperative cooling system configuration (a recuperator and an expander). The MRCS could serve as a second-stage cold head that provides the distributable cooling power for LWIR and VLIR multiple-band focal planes.

The MRCS is driven by a supply of helium that is first precooled elsewhere to a temperature close to 77 K. The temperature drop on the MRCS cold-stage is created by the cooling power from the MTAE expansion. The steady cooling power (temperature drop) is produced on the cold-stage of the MRCS with the temperature span of 15~20 K between the warm-end of the recuperator and the MTAE cold-stage. This experiment demonstrated the MTAE's cooling capacity in the MRCS and explored the critical flow and structure parameters in the recuperator as well as design shortfalls in the MTAE prototype body, which incurred a large thermal shunt and significant cooling power loss in the cold-stage of the MRCS.

INTRODUCTION

Cryocoolers are vital parts for space infrared surveillance and tracking systems, where they are used to cool down infrared focal plane arrays (IRFPA) so as to improve image quality and reduce the intrinsic thermal noise level of the sensors. Both recuperative and regenerative types of cryocooler systems are available to provide cooling power over a wide range of temperatures from 100 K (for MWIR) to as low as 10 K for enhanced LWIR and VLWIR sensitivity. The coolers are also used to cool down optics, mirrors, and shields.

The variable demands of IRFPA payloads not only stimulate the continuous improvement of active cryocooler systems and components, but also the pursuit of new thermal management solutions to deliver cooling power over modest distances or to multiple IR payloads. In spite of the fact that regenerative cryocoolers (e.g. pulse tube coolers) have revolutionized infrared space missions and have largely supplanted other thermodynamic cycles of cooling systems, recuperative cooling systems, such as reverse turbo-Brayton coolers (RTBC) and Joule-Thomson coolers (J-T coolers), are irreplaceable in key situations. Because recuperative cooling systems naturally segregate the compression warm-end from the payload cold-stages, this type of cryocooler offers advantages where power dissipation and vibration needs to be well isolated from the cryogenic payload. The

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DC flow attributes of recuperative coolers also make them flexible in terms of providing distributed cooling power to multiple payload locations without adding system complexity. Thus, the development of MTAE is motivated by implementing the advantages of J-T and RTBC expanders in miniature scales.

The MTEA is a novel expansion device that uses high-intensity acoustic wave systems to produce cooling power from dc pressure drops [1][2][3]. Because of the feasibility to scale down to very low mass flow rates (<100 mg/s), MTAEs are an ideal solution for miniature recuperative types of cryocoolers. In comparison with existing systems, MRCS have no moving parts in the cold-stage, making them potentially highly reliable and suitable for long-term missions. Unlike regenerative types of cryocooling systems, MRCS are also free of vibration at the cold-stage.

The current experimental study is focused on the examination of MRCS cooling performance. The main objective of this recuperative cooling experiment is to demonstrate the feasibility of MTAE operation in a simple recuperative type of cryocooler system. The stability of MTAE cooling performance is checked under the condition of supply gas temperature below 80 K. The experiments are to demonstrate the feasibility of MRCS refrigeration and heat transportation in a miniature MTAE in the cryogenic temperature rage close to 77 K.

MTAE MECHANISM

As the core system part, the MTAE operating mechanism is first described to provide a better understanding of the cooling power and enthalpy streaming produced in MRCS. The operating mechanism of an MTAE is illustrated schematically in Fig. 1. The mass flow route is marked by the dotted line entering at T_{in} and exiting at T_c. Also noted is the enthalpy streaming and the temperature variation inside the MTAE along the longitudinal flowing direction of mass and energy streaming.

As the DC pressurized supply gas enters the MTAE at T_{in}, it is first expanded through a convergent nozzle. In this stage, the gas stream temperature isentropically drops from its entering value (point "a" in Fig. 2) to a very low temperature at the nozzle exit, which is marked in Fig. 2 as temperature point "b". As a result, a high-speed jetting flow is formed carrying high kinetic energy into the oscillating chamber and driving acoustic waves into the resonant tubes where the DC flow is converted to AC flow. Inside the resonant tubes the periodic oscillation of the gaseous column results in thermoacoustic streaming and enthalpy flow like what occurs in a pulse tube cooler without regenerator. In this stage, there is a significant temperature recovery due to irreversibility of flowing, which is indicated by the temperature raising from the point "b" to point "c" in Fig. 2. By this mechanism, the high intensity acoustic wave system created by the DC pressure drop that is usually dissipated locally in a conventional J-T expander, is used to extract and remove heat from the pressurized supply gas. This thermoacoustic dissipation in the resonant tubes results in the significant temperature increase in the gaseous column that is rejected to the heatsink on the end of resonant tubes as indicated by temperature point "d" in Fig. 2. How the MTAE creates cooling power from the DC pressurized supply gas is attributed to its simple novel structure that enables it

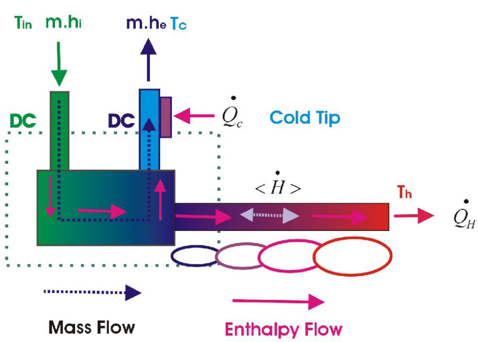

Figure 1. Illustration of MTAE Operating Mechanism

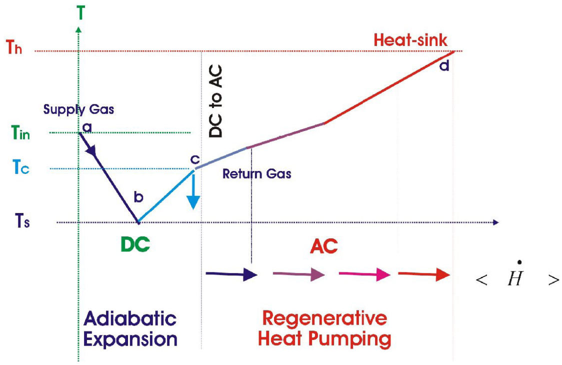

Figure 2. Illustration of temperature distribution through MTAE operation

to spontaneously trigger the oscillating flow by pressure drop from various types of supply gases under different pressure conditions. In contrast to conventional J-T and mechanical expanders, MTAEs are able to accomplish a quasi-isentropic reversible expansion without the scale-rule-limit of miniaturization and without involving any mechanical moving parts at the cold-stage.

EXPERIMENT SETUP

Our testing system and apparatus for the MRCS tests is schematically illustrated in Fig. 3. The system consists basically of a helium supply and circulation setup (not included in Fig. 3), a primary precooling chamber (135K cryo-refrigerator chamber), a liquid nitrogen tank installed inside the primary precooling chamber, and a 77 K vacuum chamber where the tested MRCS is installed. The system is designed to provide a range of precooling powers at different temperature levels in response to the various mass flow rates required by the MRCS tests. The main portion of the pre-

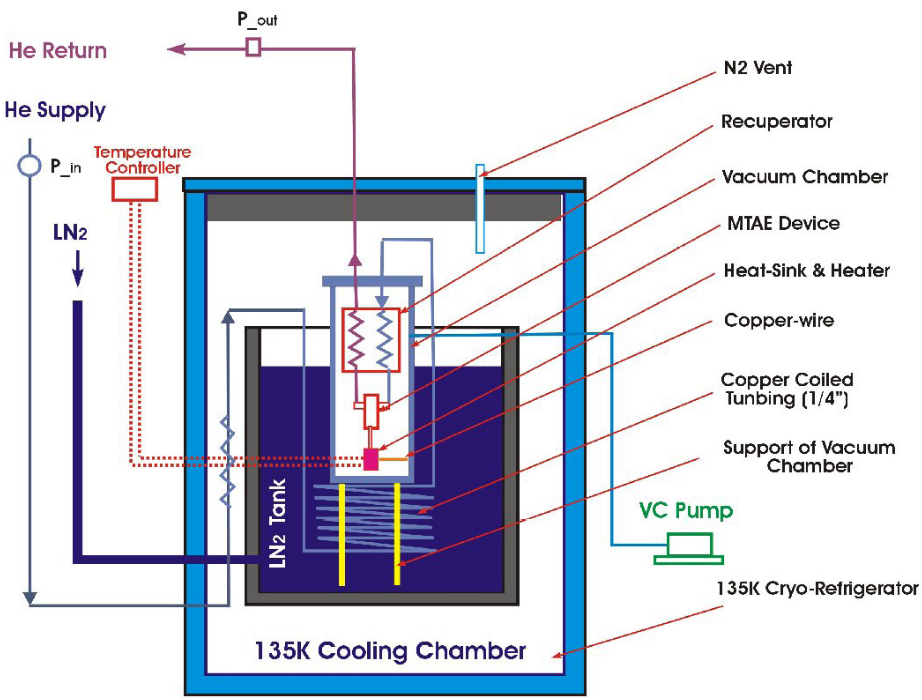

Figure 3. Illustration of MTAE recuperative cooling experimental setup in 77K temperature range

cooling power required to precool the supply helium is provided by this primary cooling chamber (135 K cryo-refrigerator). The supply helium is cooled from 293 K to 135 K through the copper tubing coiled inside the 135 K chamber before entering the liquid nitrogen tank (LN2). The LN2 tank provides the additional refrigeration to cool the supply helium from 135 K to 77 K before it flows into the 77 K vacuum chamber.

After the LN2 tank, the precooled supply helium is led to the warm end of a recuperator through the sealing flange of the 77 K vacuum chamber. The supply helium experiences its recuperative cooling step to heat up the returning helium stream in the return gas side of the recuperator. After the recuperative cooling, the supply helium gas is cooled further to (~79K) and expanded through the MTAE to reduce its temperature and pressure to 4.0 psig before it returns to the warm end of the recuperator.

In the initial recuperative cooling tests, a commercial off-the-shelf (COTS) miniature recuperator fabricated by Polycold was used to demonstrate the feasibility of the MRCS with a basic configuration of recuperative cooling system. The recuperator was originally designed for a coldhead that utilized a mixed hydrocarbon refrigerant with a phase-change at 77 K following a J-T expansion; it has a tube-in-tube structure. The MTAE prototype device is connected on the cold-end of the recuperator as seen in Fig. 3. The heat sink for the MTAE prototype, where the heat extracted from expansion is rejected, is attached to the 77 K vacuum chamber wall by a copper wire (OD = 0.060”) which supports a constant heat rejection by conduction. The heat sink temperature can be adjusted and controlled by a LakeShore temperature controller Model 331 in addition to an electrical heater as shown in Fig. 3. A vacuum pump station also is installed on the system to pump the 77 K vacuum chamber down to 4.0×10^{-5} mbar. Two types of temperature sensors (K-type thermocouples and LakeShore DT470-SD-12 diodes) are used to measure the temperature variations in the 77 K vacuum chamber and in the 135 K chamber, respectively. Two DT470 diode sensors are installed on the outside walls of the supply and return gas conduit tubing of the MTAE so as to detect the temperature drop on the solid wall across the MTAE device. Additionally, two K-type thermocouples are inserted into the inlet and outlet conduit tubing to detect the temperatures of internal streams before and after expansion. These two temperature readings give a fair estimation of the cooling power output from the recuperative cooling system tests. Because the stable cold-stage temperatures reached represents the cooling effectiveness of the MTAE in the fundamental recuperative cooling system, the current experiments enable us to examine the MTAE figure of merit under variable supply gas temperatures below 78 K.

The setup of the MRCS inside the 77 K chamber is pictured in Fig. 4. As seen, the copper heatsink is on the top of the MTAE device, and the Polycold recuperator is on the bottom of the picture, just above the sealing flange.

TEST PROCEDURES

The following test procedure was followed for the experiments:

- Start the 135 K cryo-refrigerator to cool down the whole 77 K vacuum chamber (77 K-VC) and LN2 tank to 135 K.
- Pump the vacuum chamber to a level of 5×10^{-5} *mbar* ;
- Fill LN2 into the LN2 tank inside the 135 K chamber so as to precool down the 77K-VC body and the MRCS to a temperature close to 77 K;
- Take temperature data from the system to monitor the temperature stability as thermal balance is reached between 135 K and 77 K-VC before the supply helium gas is pumped into the system;
- Set up the heatsink temperature in the 77 K-VC until thermal equilibrium is reached in MRCS;
- Drive the system using a supply of helium gas with a supply pressure of 80 psig and a return gas pressure of 4.0 psig;
- Measure the temperatures of the temperature sensors after temperatures have stabilized on the cold stage of the system;

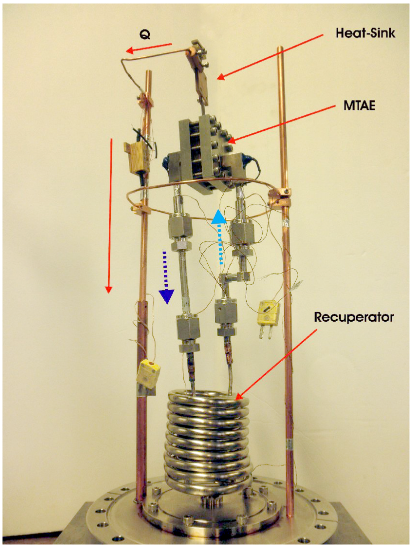

Figure 4. Experimental setup of MTAE integrated with a recuperator for testing in the range of 77 K.

In the tests, the shortfall of the precooling system design inside the 135 K cryorefrigeration chamber was explored. Because the top portion of the 77 K vacuum chamber extended out from the LN2 tank, this portion of the body could not be cooled directly by the LN2. The exposure of the 77 K-VC body and helium gas supply line inside the 135 K chamber resulted in a significant amount of thermal losses. Thus, the temperature of the precooled supply helium was significantly warmed before entering the 77 K vacuum chamber. The temperature before entering the warm end of the recuperator increased from 78 K to 93 K, which degraded the cold-stage temperature reached after the recuperator. The experiments took more than six hours to reach thermal equilibrium with the circulating supply helium in the MRCS test system.

TEST RESULTS

The cooling power of recuperative cooling systems is solely dependent on the effectiveness of the expansion device on the cold-stage of the MRCS. To evaluate the cooling effectiveness of the MTAE in the MRCS, the maximum theoretical cooling power produced by the MTAE at the mass flow rate through the testing system was estimated. The total cooling power created by the MTAE on the cold stage of the MRCS is calculated by the following formulas: $Q = \dot{m} C_p \Delta T$, where Q is the cooling power produced by the MTAE device, $\dot{m}$ is the mass flow rate through the device, C_p is the specific heat of helium, and ΔT_w indicates the temperature drop measured between the inlet and outlet conduit exterior walls. If ΔT_g gives the gas temperature difference measured between the inlet and outlet streaming, the maximum cooling power produced can also estimated. Given the specific heat of helium gas at 5.197 kJ/(kg·K) at a temperature of 77 K, the measured temperature drop in the stream ΔT=3.5 K , and the measured mass flow rate in the tested MRCS $\dot{m}$=0.180 (g/s), the cooling powers provided by the MTAE in the cold stage are calculated in Table 1. Here Q_w is the actual cooling power output from the external solid wall of the MTAE outlet where the heat load is attached at the down stream side of the cold stage; and Q_g gives the nominal cooling power output from the cold stream of the MTAE device after expansion. The differentiation between the

Table 1. MRCS Performance Calculations

C_p $kJ/(kg \cdot K)$	$\overset{*}{m}$ (kg/s)	ΔT_w (K)	Q_w (J/s)	ΔT_g (K)	Q_g (J/s)
5.197	0.180×10^{-3}	1.5	1.40	3.5	3.27

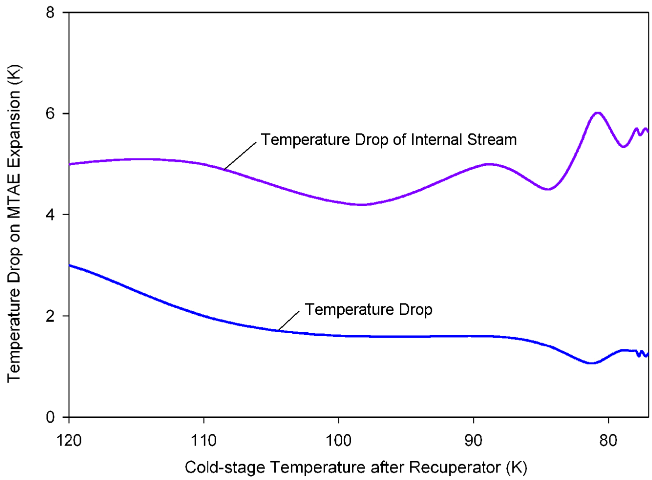

Figure 5. Temperature Drop Tracking cross MTAE during MRCS Recuperative Cooling Procedure

two cooling power outputs indicates the serious thermal shuttle loss across the solid body of the MTAE. The ratio of actual cooling power to the nominal cooling power enables one to measure the thermal losses of the device body structure in the cold stage of the MRCS (*pure cooling power loss*).

The temperature drop across the MTAE is the critical benchmark checked to evaluate the cooling power produced, and the stability of the cooling performance of the device through the recuperative cooling procedure. As the recuperator is introduced between the supply gas line and the MTAE on the cold-stage of the system, only the cooling power to pull down the cold-stage temperature is produced by the MTAE. All thermal shuttle losses are segregated to the MTAE device. Holding the temperature or continuously walking down with the cold-stage temperature is attributed to the heat pumping capacity of the MTAE. The heat extracted by expansion only has a single way to be conducted out through the heatsink on the MTAE body, which is usually attached on the warm-end of the MRCS. The temperature drop created by the MTAE expansion is plotted in Fig. 5. The lower "Temperature Drop" line indicates the temperature drop across the MTAE exterior conduit walls, while the upper line gives the temperature drop in the supply helium stream. It is seen that the stream temperature drop shows some fluctuations, and the solid wall temperature drop becomes small due to the strong thermal shuttle across the MTAE body.

The mass flow rate varies during the recuperative cooling, which directly affects the cooling power produced by the MRCS cold stage. The mass flow rate variations are tracked as the cold-stage is cooled down and are given in Fig. 6. The x-axis represents the cold-stage temperature descending value which starts from 120 K to 76 K. The y-axis gives the mass flow rate through the MTAE. The steady mass-flow-rate increment is detected by the flow meter installed outside of the 135 K cryo-refrigerator chamber. This mass flow change is brought about by the temperature drop, which reduces the speed of sound and increases the density of the supply helium during the MTAE expansion process. There is about a 25% mass flow increase (He, 138 mg/s to 178 mg/s) as the cold-stage temperature drops from 120 K to 76 K under the overall pressure drop ratio of 4.67 at the warm end of the recuperator (from the supply side to return side).

The temperature variations measured at several positions in the MRCS are plotted in Fig. 7. These temperature descending tracks are important benchmarks indicating the MTAE working state and output of cooling power. The x-axis in Fig. 7 indicates the testing time duration in minutes, and the y-axis shows the temperature readings measured by the thermocouples and LakeShore DT470 diode sensors. As indicated, the top solid line gives the temperature of the MTAE heatsink surface where the heat is pumped from the MTAE.

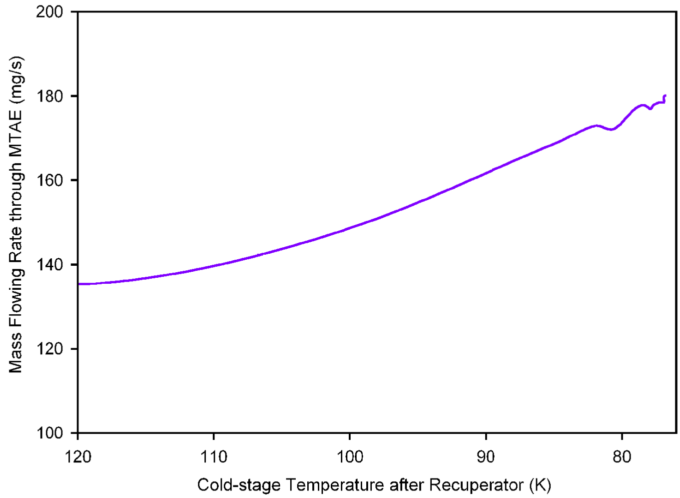

Figure 6. Variation of mass volume rate along with cold-stage temperature descending in MRCS (*Helium, 80.0 psig/4.0 psig*)

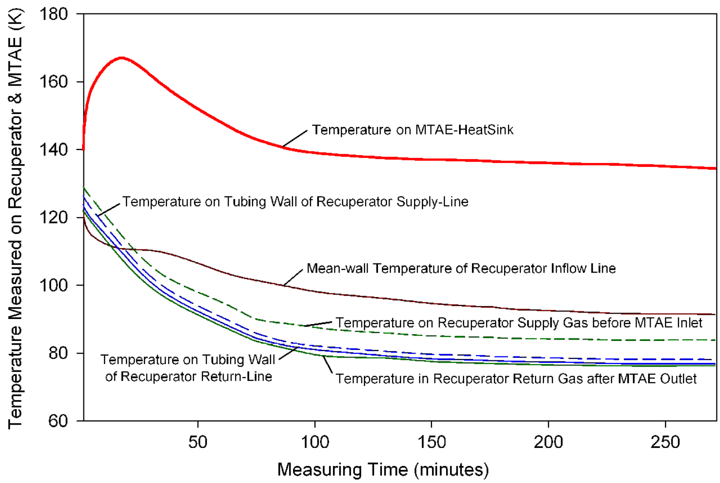

Figure 7. Temperature tracking histories on MRCS system (*He: 80 psig/4.0 psig*)

The thermal shunt (shuttle) losses and pressure losses related to the MTAE body structure and the recuperator operating parameters were identified in the tests. There are two major losses that result in the significant cooling power degradation identified in the tests. They are the pressure losses in the recuperator, which resulted in significant reductions in the ideal available work across the expansion, and heat shuttle flow across the device solid body. The cooling power loss due to pressure losses within the recuperator channels is estimated in comparison to the cooling performance given by a stand-alone MTAE device without the installation of a recuperator. The heat shunt on the MTAE body is estimated by a simple conduction model in combination with measured temperature data on the exterior surface of the device body. Because the MTEA cooling performance is purely dependent on pressure drop and the state of the supply helium before expansion, both losses must be evaluated.

The pressure loss between the warm-end and the cold-end of the recuperator in the expansion was measured in ambient tests before the cryogenic tests were started. The initial pressure drop tests showed that the supply channel pressure losses costs about <5% cooling power loss over the

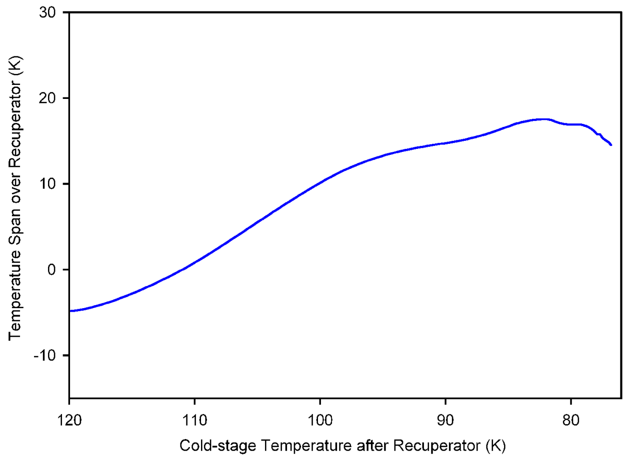

Figure 8. Temperature span tracking between warm-end of MRCS recuperator and MTAE cold-stage (He: *80~85 psig/4.2~5.7 psig*)

testing pressure conditions (80 psig/4.0 psig), and the return-channel flow resistance after expanded gas contributes about 35% cooling power losses (8.4 K/12.9 K @ 293 K with helium). As the mass flow rate increases 190% (from 60 mg/s @ 293 K to 178 mg/s @ 77 K) the pressure drop losses change due to viscosity and density in the flow channel. The pressure loss on the MTAE cold stage at 77 K was estimated in the slightly reduced versus the ambient tests.

Thermal shuttle due to heat conduction across the contacting surfaces among the covers of the MTAE chamber was also examined. Significant heat conduction occurs due to the large cross-section of the contacting body covers to the flow channel cross-section in the current version of the prototype (which was designed for tuning up the acoustic wave system). If the body dimensions are reduced, this type of heat shuttle can be limited to a smaller value, but it still exists and becomes a key limitation of the MTAE when the shuttle heat is balanced by the cooling power produced at small mass flow rates.

In summary, the MRCS cold-stage temperature is mainly degraded and limited by the two loesses: 1) pressure loss in the return gas channels of the recuperator (which reduces the cooling power being produced), and 2) heat shuttle loss, which reduces the cooling power to the returning gas stream on the low pressure side. Both problems can be fixed by reducing the MTAE body size and opening the return gas channels.

CONCLUSIONS

The preliminary experiments of the MRCS successfully demonstrated the recuperative cooling feasibility of the MTAE with a simple configuration of a fundamental recuperative cooling system at a cryogenic temperature of 76 K. A commercial off-the-shelf recuperator (Polycold-cryoTiger) was used to integrate with the MTAE so as to segregate the thermal shuttle to the MRCS cold-stage from external precooling resources. The MRCS prototype was designed to handle a mass rate of 84 mg/s @ 290 K and 180 mg/s @ 77 K and be driven by a helium supply gas at a pressure of 80~85 psig with the return line pressure around 4.0~5.5 psig. With the given operating pressure conditions, the pressure drop ratio through the recuperative cooling system remains near a constant value of 4.67; this provides a stable ideal expansion work from the compressor side of the MRCS during the recuperative cooling tests. At thermal equilibrium in the test system, the cold stage temperature of the MRCS stabilized at a temperature of 76 K and provided 1.40W of cooling power output from the MTAE (*cooling power estimated by external wall temperature drop across the MRCS cold-end*) and 3.27 W idea cooling power output (*estimated by measured stream temperature drop across the MTAE expansion*) with a heat reject temperature of 136 K on the heatsink. The experiments also exposed serious thermal shuttle losses through the MTAE body and pressure losses in the return flow side of the recuperator. These losses significantly limited the achieved cold-stage temperature and created a great amount of cooling power leakage and degraded the expansion work output in the MRCS tested.

Based on the results of the preliminary experiments from the MRCS tested, the following conclusions are drawn:

- The MRCS enables the removal of heat effectively from cryogenic loads at temperatures around 77 K with the functionality of a stand-alone miniature cryocooler system;
- The cooling feasibility of the MRCS was demonstrated with helium supply gases for cryogenic temperatures close to 77 K;
- Operability of the MTAE integrated within a simple recuperative cooling configuration was demonstrated with helium supply gases;
- Stable cooling performance was verified for the MTAE with variable supply temperatures as the MRCS cold-stage walked down in cryogenic temperature close to 77 K
- Stable cooling power output and heat rejection capability was verified for the MTAE prototype in the MRCS with helium supply gas at 77 K cold-stage temperature;

REFERENCE

1. Zhimin Hu, "Thermoacoustic Expansion Valve: A New Type of Expander to Enhance Performance of Recuperative Cryocooler Systems," *Cryocoolers 14*, ICC Press, Boulder, CO (2007), p. 429.
2. Zhimin Hu, "Cooling Performance of Miniaturized Thermoacoustic Expanders Operated at 133 K," *Cryocoolers 15*, ICC Press, Boulder, CO (2009), p. 429.
3. Zhimin Hu and T. Roberts, "Heat Rejection Capacity in Miniature Thermoacoustic Expanders at Cryogenic Temperature 77K," *Cryocoolers 16*, ICC Press, Boulder, CO (2011), p. 497.
4. P.E. Bradley, R. Radebaugh, M. Huber, and M.-H. Lin, "Development of a Mixed-Refrigerant Joule-Thomson Microcryocooler," *Cryocoolers 15*, ICC Press, Boulder, CO (2009), p. 425.
5. W. Chen and M. Zagarola, "Vibration-Free Joule-Thomson Cryocoolers for Distributed Microcooling," *Cryocoolers 15*, ICC Press, Boulder, CO (2009), p. 433.
6. M.J. Simon, C. Deluca, V.M. Bright, Y.C. Lee, P.E. Bradley and R. Radebaugh, "Development of a Piezoelectric Microcompressor for a Joule-Thomson Microcryocooler," *Cryocoolers 15*, ICC Press, Boulder, CO (2009), p. 441.
7. F. Roush and T. Roberts, "AFRL Space Cryogenic Technology Research Initiatives," *Cryocoolers 14*, ICC Press, Boulder, CO (2007), p. 11.
8. T. Nast, J. Olson, E.Roth, and B. Evtimov, "Development of Remote Cooling System for Low-Temperature Space-Borne Systems," *Cryocoolers 14*, ICC Press, Boulder, CO (2007), p. 33.
9. M.V. Zagarola, W.L. Swift, H. Sixsmith, J.A. McCormick and M.G. Izenson, "Development of a Turbo-Brayton Cooler for 6K Space Applications," *Cryocoolers 12*, Kluwer Academic/Plenum Publishers, New York (2003), p. 571.
10. C. Knokel and W. Bradley, "Design and Qualification of Flight Electronics for the HST NICMOS Reverse Brayton Crycooler," *Cryocoolers 10*, Plenum Publishing Corp., New York (1999), p. 439.