Thermoacoustic Expansion Valve: A New Type of Expander to Enhance Performance of Recuperative Cryocooler Systems

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ABSTRACT

The development of a new type of valve-like expander is described. Referred to as a thermoacoustic expansion valve (TEV), the intended application is low-cooling-capacity recuperative cryocooler systems. TEVs use acoustic wave systems created from a pressure drop to extract heat out of the cold region without using any moving parts. They may be used to replace J-T valves in a Joule-Thomson or sorption cryocooler system, or in a variety of hybrid systems that incorporate a J-T cold stage with a regenerative cryocooler. Initial experimental results have shown that miniature TEVs can combine the reliability advantages of a J-T expander with the improved performance merits of turbo-Brayton expansion components. Thus, they can potentially improve the efficiency and reduce mass flow of low cooling capacity recuperative coolers by combining the advantages of no moving parts and energy extraction at the cold end for increased thermodynamic efficiency.

INTRODUCTION

Great progress has been made in the development of reliable, long-life cryocoolers, particularly for military and space missions.[1,2] Cryocoolers are usually used to enable the application of cryogenic instrumentation based on low-temperature detectors, cold optics, thermal shields, and superconductive devices. Under cryogenic conditions these technologies obtain higher sensitivity and better energy resolution. Space applications such as communication, remote sensing, and weather monitoring benefit from additional subsystems using other cryogenic technologies including superconducting electronics, high data rate signal processors, and high speed/low power analog-to-digital converters. Cryocoolers also have many diverse applications in civil, medical and scientific fields, both existing and prospective. Cryogenic coolers for space and military instrumentation are generally small, light, and very reliable. By reducing the weight of cooled instruments and providing refrigeration for more than 10 years without servicing, active closed cycle cryocoolers have become attractive for many space applications.

Closed-cycle cryocoolers may be broadly classified into two types: recuperative and regenerative cryocoolers. There are three typical recuperative cryocoolers widely used in the applications of cryogenic instrumentation: Turbo-Brayton coolers[3-6], Joule-Thomson (J-T) coolers[7], and sorption coolers[8-10], which are a form of J-T cooler.

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- Turbo-Brayton coolers use high speed turbines for compression and expansion of the cryogen working gas. The advantages of these coolers is their extremely low induced vibration, the remote location of the cold head from the ambient-temperature compressor, and their capacity to lift high heat loads (>5W). Their disadvantage is lower efficiency for smaller heat loads.
- J-T coolers employ a Joule-Thomson (J-T) expansion or isenthalpic expansion of the working gas to achieve cryogenic temperatures. Actually, there are many cycles that use J-T expansion, such as Linde-Hampson, Claude, Joule-Brayton, and sorption cycles. Their advantages are inherent thermal capacity and load leveling, remote location of the cold end from the compressor, and negligible electromagnetic interference or vibration at the cold end. Their disadvantages include a very high pressure ratio of compression or requiring another cryocooler for precooling. Sorption coolers utilize a heat driven sorbent bed to pressurize, circulate, and adsorb the gas in the Joule-Thomson cycle. As a stand-alone cryocooler, J-Ts have a relative low efficiency.

The major challenges faced in cryocooler development are the reduction of mass and power input to cryocooler components, and the improvement of their performance without sacrificing their reliability and simplicity. This requires that a high performance cryocooler must be compact, lightweight, have low input power, operate reliably for 5-10 years, and produce no disturbance that would affect the pointing accuracy of the instruments. Since reliability is a critical concern for cryocoolers, cryocoolers that have less or no moving cold parts, such as pulse tube and J-T based coolers, have excellent prospects to satisfy long-term mission targets and possess a compelling advantage for many applications where maintenance and replacement are difficult or impossible.

However, the stringent requirements on reliability, performance, and freedom from vibration can detract from one's ability to build cryocoolers that run efficiently. Improving the performance of a recuperative cryocooler system operated in the temperature range below 80 K requires reducing the input power to the compressor at the warm end of the system. A common focus of attention is the performance efficiency of the recuperative heat exchanger used at the cold end of the system. In general, less attention is paid to improving the performance efficiency of the expansion component.

As is well known, recuperative cryocooler systems intrinsically rely on the expander at the cold stage to produce refrigeration by reducing the pressure of the cycle refrigerant gas. The expansion components available to miniature recuperative coolers are J-T valves and turbo expanders. The former has no moving parts and the worst efficiency, yet it has high reliability and simplicity. The latter can reach higher efficiency—approaching isentropic processes by precise moving structures—but can sacrifice its reliability and efficiency advantage if in miniature scale.

Thermoacoustic expansion valves (TEVs) provide a new solution to effectively producing refrigeration by making use of part of the pressure drop that is normally wasted by a conventional J-T expansion valve. CryoWave Advanced Technology (CWAT) has developed thermoacoustic expanders since 1998.[11,12,13] The miniature type of TEVs are targeted at low cooling capacity recuperative coolers and feature absolutely no moving parts, useful efficiency, and remarkable reliability. They may provide an alternative solution to enhance the performance of the cold expansion stage of existing recuperative cryocoolers. The unique features of TEVs are

- Absolutely no moving parts
- Heat extraction and energy efficiency in expansion
- High reliability and simplicity
- Feasible in a wide range of operating conditions (flow rate and pressure drop ratio)

OPERATING MECHANICS OF A TEV EXPANDER

TEVs use high-intensity acoustic wave systems to extract heat out of the cold stage and to accomplish a quasi-isentropic expansion without involving any mechanical moving parts. This operating characteristic can make TEVs preferable to J-T expanders by reducing energy loss and mass flow without sacrificing the reliability and simplicity of the recuperative cryocooler system.

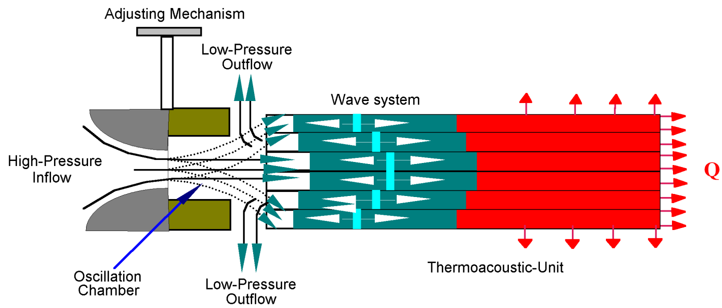

Figure 1. Operating Mechanism and Prototype of miniature TEVs

Distinguished from existing pulse tube coolers, which act as stand-along systems, TEVs are easily used in various recuperative systems as an expander.

Basically, as illustrated in Fig. 1, a TEV consists of a nozzle, an oscillation chamber, and a thermoacoustic unit. The operation of a TEV is described as follows: as cryogen working gases flow into the TEV device, the DC-pressurized stream first enters a nozzle that generates a high-speed jet that rushes into the oscillation chamber. Here the jet encounters a thermoacoustic unit where it impinges on the inlet of resonator elements and drives the oscillation of gaseous columns in the thermoacoustic unit where the wave energy is directly converted into heat due to friction, dissipation, and compression of the gas columns. As a consequence, the temperature of the gas columns is raised as gaseous wave systems move back and forth, analogous to the motion of mechanical reciprocating pistons. In doing so, energy is extracted in the form of heat from pressure expansion and is released to the ambient or other mediums surrounding the hot end of the thermoacoustic unit. On the other hand, the periodic gaseous wave system also sustains the motion of the jet to maintain the TEV operation. A photograph of a representative miniature TEV device is shown in Fig. 2.

THERMODYNAMICS OF TEVS

TEVs differ thermodynamically compared to more conventional expanders and J-T valves. As indicated in the Fig. 3, the energy extracted by TEVs in expansion shows up first in the form of acoustic power streaming $<\dot{H}>_c$ at the cold end of the expander. The acoustic power $<\dot{H}>_c$ is then dissipated at the warm end of the thermoacoustic unit in the form of heat. By the first law of thermodynamics, the cooling power $\dot{Q}_c$ of a recuperative cryocooler at a temperature T_c is generally given by

$$\dot{Q}_c = <\dot{E}>_c + \dot{m}[h_e(T_{out}, P_L) - h_i(T_{in}, P_H)] \quad (1)$$

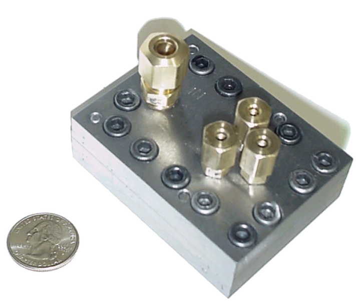

Figure 2. Prototype of miniature TEV.

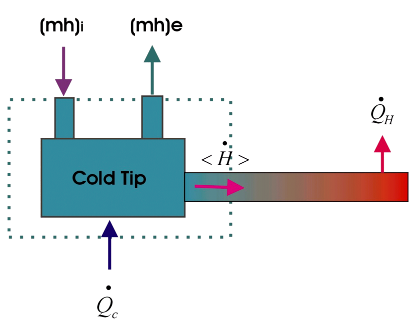

Figure 3. Schematic showing energy streaming.

where $<\dot{E}>_c$ is the energy stream extracted from the cold end by the expansion engine, $\dot{m}$ is the steady mass flowrate, h_e is the specific enthalpy of the outflow at the temperature T_c and low pressure P_L, and h_i is the specific enthalpy of the inflow at the temperature T_{in} and high pressure P_H. For a J-T system there is no expansion engine or heat transfer, so $\dot{E}_c = 0$. In that case, a finite refrigeration power only occurs with a real gas where h is constant and temperature (internal energy) is a function of pressure.

The enthalpy change with pressure can be enhanced with mixed gases[14] as compared to a pure gas. The maximum power that can be extracted from expansion is the work recovered from a reversible isentropic expansion. This maximum work recovered is given by Eqs. (2) and (3):

$$\dot{W}_{c,\max} = \dot{m}[h_{in}(T_{in}, P_h) - h_{e,S}(T_c, P_L)]_S \tag{2}$$

$$\dot{W}_{c,\max} = \dot{m}\frac{\gamma}{\gamma - 1} RT_c[(P_H / P_L)^{\frac{\gamma-1}{\gamma}} - 1] \tag{3}$$

where R is the specific gas constant, and γ is the specific heat ratio of the working gases. For any real expansion device, the actual power extracted will be some fraction of the maximum work due to inefficiencies. In the operation of a TEV, energy is extracted in the form of acoustic power. Because no mechanical power is extracted with the acoustic wave, $\dot{E}_c$ in Eq. (1) is heat $\dot{E}_c = \dot{Q}_h$. As shown in the thermodynamic model represented in Fig. 3, the acoustic wave in the TEV can transport a time average enthalpy flow $\dot{Q}_h = <\dot{H}>_c$ traveling from the cold end to the hot end. The refrigeration power is then given by

$$\dot{Q}_c = \langle \dot{H} \rangle_c + \dot{m}[h_o(T_c, P_L) - h_i(T_c, P_H)] \tag{4}$$

For the TEV device $<\dot{H}>_c$ will also be some fraction of $\dot{W}_{c,\max}$ just as with the Brayton expansion device. With a well-insulated resonance tube, the first law of thermodynamics can be used to show that the time averaged enthalpy flow along the length of the TEV resonance tube under steady operation. Thus, the heat dissipated at the hot end is given by

$$\dot{Q}_h = \langle \dot{H} \rangle_c \tag{5}$$

The efficiency of the TEV can then be expressed as

$$\varepsilon_{TEV} = \frac{< H >_c}{\dot{W}_{c,\max}} = \frac{\dot{Q}_h}{\dot{W}_{c,\max}} \tag{6}$$

The TEV efficiency can be determined by measuring or modeling the heat rejected at the hot end of the thermoacoustic unit. In practice this efficiency will be somewhere between zero, for a normal J-T valve, and the efficiency of a real expansion turbine. Maximizing the efficiency also maximizes the refrigeration power that would be incurred by the enhancement of heat generation at the hot end.

RECUPERATIVE SYSTEM ADAPTING TEVS

Two typical cycles of recuperative cryocoolers, Joule-Thomson and reverse Brayton cycles, are compared in Fig. 4 to a recuperative system that uses a TEV as the expansion component. The Joule-Thomson (J-T) cycle is represented in the left side of Fig. 4 and the reverse-Brayton (RB) cycle is represented in the center of the figure. The assumptions made for the analysis of the performance of the three cycles are that identical compressors and heat exchangers are installed, and the same mass flow rate and thermal properties are required before entering the cold stages of the cycles. As seen, the J-T system uses a J-T expander at its cold stage to generate refrigeration by isenthalpic expansion which has no heat and work being extracted from the pressure drop. In contrast, the Brayton and TEV systems use a turbine and TEV expander, respectively, to extract

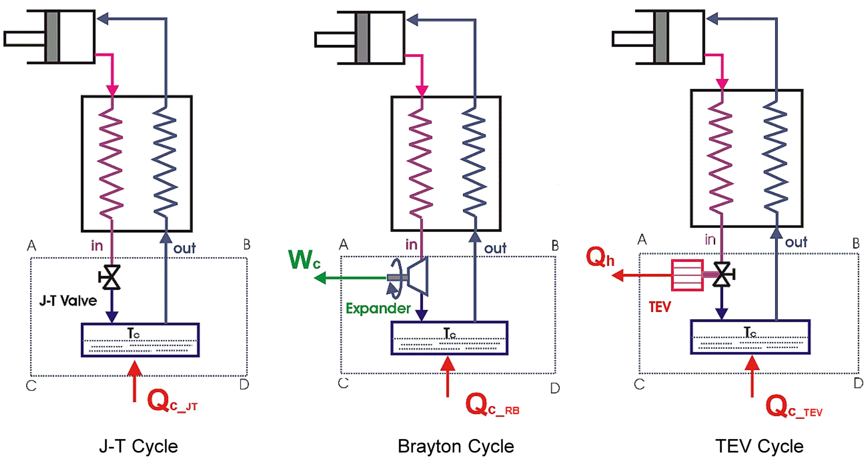

Figure 4. Typical Recuperative Cryocooler Cycles vs. TEV System

energy from the pressure drop. The cooling powers from the three cycles can be determined by Eq. (1), and are given by

$$\dot{Q}_{c\_JT} = \dot{m}[h_e(T_{out}, P_L) - h_i(T_{in}, P_H)] \tag{7}$$

$$\dot{Q}_{c\_RB} = <\dot{W}>_c + \dot{m}[h_e(T_{out}, P_L) - h_i(T_{in}, P_H)] \tag{8}$$

$$\dot{Q}_{c\_TEV} = <\dot{Q}>_H + \dot{m}[h_e(T_{out}, P_L) - h_i(T_{in}, P_H)] \tag{9}$$

where $<\dot{W}>_c$ represents the mechanical work extracted by the piston or turbine Brayton expander, and $<\dot{Q}>_H$ represents the acoustic power extracted by the TEV expander. The subscripts of the term $\dot{Q}_c$ in Eqs. (7), (8), and (9) represent the cooling power generated by J-T, reverse-Brayton (RB), and TEV cycles, respectively. Comparing Eqs. (7) to (8), it is seen that with the Brayton cycle there is an additional term $(\dot{Q}_{c\_RB})$ appearing in the cooling power because the Brayton expansion engine extracts mechanical power $\dot{W}_c$ at the cold end, where $\dot{E}_c = \dot{W}_c$. If the same flow rate $\dot{m}$ is specified from the compressor, the Brayton system apparently produces more cooling power according to Eq. (8) than does the J-T system as given in Eq. (7). It can also produce refrigeration even with an ideal gas, where the enthalpy is independent of pressure. The disadvantage of the Brayton system is that it requires a moving part at the cold end to extract the mechanical power. In addition, when scaling laws are applied to miniature Brayton systems, the parasitic losses inside the Brayton expander increase as cycle cooling capacity and size are reduced. This can result in a significant drop in efficiency when operating at low flowrates.

A similar conclusion can be drawn when the TEV system is compared to the J-T system using Eqs. (7) and (9). There is an extra term $<\dot{Q}>_H$ appearing in the cooling power term $\dot{Q}_{c\_TEV}$ because a TEV extracts heat $<\dot{Q}>_H$ at the cold end, where $\dot{E}_c = <\dot{Q}>_H$. Notice that the disadvantage incurred by a cold moving part is eliminated with the TEV. This is attributed to the fact that the TEV has no cold moving parts and is a simple structure. Consequently the Brayton and TEV systems can provide more cooling power than that of a J-T system in low cooling capacity systems; this is due to the energy extracted from the cold stage by the different expanders.

PERFORMANCE

The technical progress that has been achieved on TEV expanders builds on several inventions and extensive pressure wave energy conversion technologies developed since 1998 by CryoWave Advanced Technology for the oil and gas industry.[12-15] A successful product prototype TEV device has been designed for a 4.2 g/s airflow volume and has shown significant improvement over the cooling performance of a conventional J-T valve. An isentropic efficiency of 17 % has been reached with the TEV device in contrast to the zero efficiency incurred with the J-T valve. The

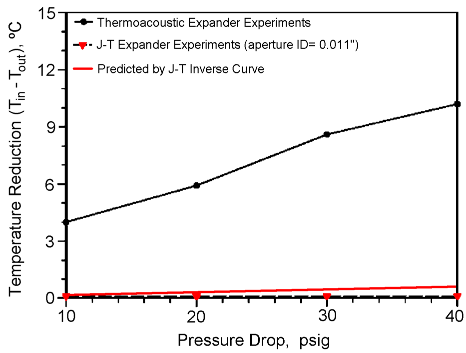

Figure 5. Temperature drop: TEV vs. J-T expander.

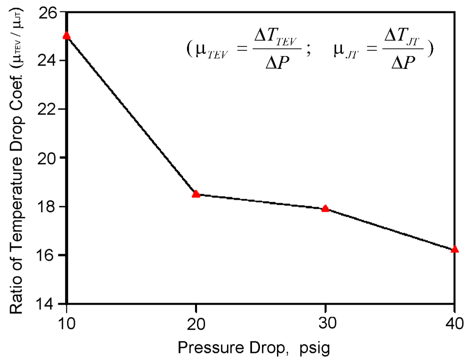

Figure 6. Ratio of Temperature Drop Coef: TEV vs. J-T.

difference of the temperature drop between the TEV expander and the J-T valve is compared in Fig. 5. The experimental results were obtained using pressurized air. There is no efficiency drop observed when working gases are changed from air to natural gases except for the fluctuation related to thermal properties of the tested gases. The temperature drop coefficient indicated by temperature drop per unit pressure drop (per psig) within the TEV versus the J-T expander is presented in Fig. 6. The ratio of the temperature drop coefficient, expressed as (μ_{TEV}/μ_{JT}), shows that the cooling performance of the TEV system surpasses that of the J-T system under identical operating conditions.

A miniature TEV prototype was fabricated and tested in the specified conditions and compared to a small J-T expander that handles the same flow rate. The J-T expander used in the tests is a globe type of control valve (made by DELTROL – Model N25BK) with the aperture opening equivalent to a capillary tube of 0.011-inch internal diameter. The tested miniature TEV has an interior channel capable of handling a flow volume equivalent to a 0.010” ~ 0.011” diameter capillary tube (0.05 g/s air). This interior scale will meet the requirement of many applications in infrared sensing.

The main objective of the experiment of the miniature TEV was to examine the existence of the thermoacoustic mechanism in a miniature scale of chamber and its energy conversion capacity. In the tests, the inlet pressure of the miniature TEV was set at 60 psig, and the outlet pressure of the device was equal to ambient. The temperature of the inlet pressurized gases was controlled at 20°C. The temperature difference through the miniature TEV device was measured by thermocouples. Five different gases (N_2, CO_2, Air, CH_4, and He) were tested, covering the range of thermal properties anticipated that could impact the behavior of the acoustic wave systems inside the TEV. Stable temperature drops were measured with the different gases. Typical experimental results with the five different gases are given in Table 1 versus the temperature drop of the J-T expander.

Table 1. Temperature Drop through the Miniature TEV Tested by Different Gases.

	Air	N_2	CO_2	CH_4	He
P_{in} (psig)	60	60	60	60	60
P_{out} (psig)	0.0	0.0	0.0	0.0	0.0
ΔT (C) tested by MTEV	7.8	7.8	7.5	7.0	9.8
ΔT tested by J-T Expander (C)	<0.3	<0.2	<0.1	<0.1	0.0

Worth noting is the fact that helium gas, when expanded from room temperature, undergoes a temperature rise with the J-T expander, in contrast to a significant temperature drop created by the miniature TEV. The initial tests of the miniature TEV have proven

- Operability of the miniature TEV in ambient
- Existence of thermoacoustic mechanism in macron-scale channels
- Feasibility of miniature TEV operation in different gases

Further tests of miniature TEVs at cryogenic temperatures below 77 K have been scheduled after prototype body leakage tests at 77 K are successfully conducted.

POTENTIAL APPLICATIONS

J-T systems have been well proven for use in space and military applications where the compressor can be located remotely from the cold head to reduce induced sensor vibration and to facilitate heat rejection. Since the cold head has no moving parts, it eliminates vibration, minimizes electromagnetic interference, and promotes high reliability. The J-T system can also provide multiple cooling loads at different locations and different temperatures. The J-T uses a recuperative cycle that exchanges heat directly between counter-flowing gas streams and does not rely on the heat capacity of an intermediate material as required in regenerative cryocoolers such as pulse tube coolers. Thus, the recuperative cycle has advantages for cooling at temperature of 10 K and below.

Miniature TEVs can be used in a variety of J-T systems where the TEV expander can improve the performance by simply replacing the J-T valve in the cold end. It is expected that after replacing the J-T expander with a TEV, the pressure ratio and mass flow could be reduced due to the increased cooling efficiency of the miniature TEV. Miniature TEVs also have the potential of improving the performance of Stirling/J-T hybrid coolers, pulse tube/J-T hybrid coolers, and GM/J-T coolers by simply replacing the J-T valve in the cold stage with a miniature TEV.

The miniature TEV technology is equally applicable to mixed-gas J-T cryocoolers. In this approach, miniature TEVs can eliminate the limit that the expansion occur below the inversion temperature of the mixed gases. Mixed gas J-T cryocoolers have the potential to achieve better cooling performance. Thus, by applying miniature TEV, these coolers will be more flexible and efficient.

Miniature TEVs can also be used in sorption cooler systems to enhance their cooling power. An attractive alternative is the use of a sorption compressor that drives a J-T cold stage in combination with passive radiative precooling below 50 K. Such a sorption cooler has no moving parts and is, therefore, essentially vibration-free. In addition, the absence of moving parts also simplifies scaling down of the cooler to small sizes, and it contributes to achieving a long life time. With a TEV, instead of throttling through a J-T valve, hydrogen would be expanded through the miniature TEV where its partial pressure energy would be recovered and released to 50 K passive radiators. In doing so, the yield of the hydrogen liquid fraction would increase, thereby enhancing the cooling power of the sorption cooler.

In addition, miniature TEVs will allow reverse-Brayton systems to replace the turbo-expanders in low cooling capacity applications. In our approach, miniature TEVs could deliver a compelling isentropic expansion efficiency without using moving parts, and thus would be free of reliability issues.

CONCLUSIONS

In the present study, the operating mechanism of TEVs and the cooling performance have been reported in comparison to existing expansion components available for recuperative cryocooler systems. From the thermodynamic analysis and experiments on TEVs, the following conclusions can be drawn:

- TEVs are a new type of expansion component that can improve the performance of recuperative cooling systems, such as J-T cooler, sorption coolers, and other types of hybrid J-T cooler systems, replacing J-T expanders.

- TEVs feature no moving parts, heat extraction at the expansion stage, and flexible operating conditions that can benefit recuperative cryocooler systems—adding high reliability, efficiency, and simplicity.
- The TEV cycle can be run over an extended temperature range without the limit on the temperature of the working gases as required by the J-T cycle; this can eliminate or simplify the precooling stage required for J-T systems.
- The operating feasibility of miniature TEV in the micron scale channel and small flow rate (0.05g/s) have been experimentally demonstrated.
- TEVs have exhibited stable performance with various working gases and operating conditions.

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