Development of a Miniature Fast Cool Down J-T Cryocooler

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ABSTRACT

One major advantage of Joule-Thomson (J-T) cryocoolers over other cryocoolers is the ability to achieve a very fast cool-down, in the range of only a few seconds. The main fluid is chosen according to the desired cooling temperature and the fast cool-down is usually obtained by allowing high flow rates during this transient process. A primary cooling stage may be added in order to cool the main fluid and reduce the cool-down time, but it has the price of two pressure vessels and a more complex, and bigger, cryocooler.

Fast cool-down is usually required when the total cooling time is relatively short, a few seconds up to a few minutes. Thus, fixed-orifice cryocoolers are preferable, according to manufacturing and reliability aspects. However, the flow rate of a fixed-orifice cryocooler is determined by the pressure in the vessel. Thus, the reduction of the pressure in the vessel during operation reduces the flow rate, the pressure in the evaporator varies, and the cooling temperature changes as well. In order to reduce the flow rate immediately after cool-down for depressing the cold temperature variations during the steady operation, a regulation system is required.

In this paper we describe the development of a new flow controller, patent pending, for fast cool down cryocoolers that is a benefit of practical considerations. The new flow controller is designed for miniature cryocoolers, has high reliability, is maintenance friendly, and provides fast reduction of the flow rate after cool down.

INTRODUCTION

J-T cryocoolers are widely used for fast cool-down applications. These applications are usually coupled with miniaturization requirements and short missions. Therefore, J-T cryocoolers for fast cool-down applications have different characteristics than J-T cryocoolers designed for long missions. Bonney and Stubbs describe some fundamental considerations referring to the development of rapid J-T cryocoolers [1]. Among other things, they discuss the trade off between a smaller cooler and dewar size to gain less thermal weight versus a longer heat exchanger with higher efficiency.

There are several options to attain fast cool-down—for example, mixed-refrigerants and multistage cryocoolers. However, this work concentrates on single stage cryocoolers with pure refrigerants. In this case, the means for achieving fast cool-down are in the optimization of operation conditions, flow rate controlling, and heat exchanger adjustments. Hong et al. have

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investigated the cool-down characteristics of a miniature J-T cryocooler for different initial pressures and several volumes of the pressure vessel [2]. Hong et al. have also investigated the flow rates of fixed-orifices and demand-flow cryocoolers [3].

Increasing the flow rate is essential for fast cool-down, but once the cold temperature is achieved the high flow rate leads to a short total cooling duration. In addition, the pressure drop in the vessel during operation changes the flow rate and the back pressure, thus, the cold temperature drops slightly during operation. Therefore, a reduction of the flow rate at the end of the cool-down process is essential. This may be achieved with demand-flow or double-action cryocoolers.

In this work we investigate the performance of a double-action cryocooler and suggest a novel fast response flow controller.

FLOW RATES DURING COOL-DOWN

Fast cool-down is obtained by having a high flow rate, which is achieved with a large orifice, as shown in the following equation that calculates the mass flow rate through an orifice for a chocked flow.

$$\dot{m} = A\frac{C_1 \cdot C_2 \cdot p}{\sqrt{R \cdot T}} \tag{1}$$

where $\dot{m}$ is the mass flow rate, A is the cross section area of the orifice, p and T are the pressure and temperature of the fluid at the orifice inlet, respectively. C_1 is a coefficient that depends on p, T, and the fluid, while C_2 is a coefficient that depends on the fluid only. Equation 1 shows that there is a linear relation between the cross section area of the orifice and the mass flow rate. The cooling power of the cryocooler is given by:

$$\dot{q} = \dot{m} \cdot \Delta h \cdot \eta \tag{2}$$

where $\dot{q}$ is the cooling power of the cryocooler, Δh is the enthalpy difference between the outgoing and the incoming fluid streams of the cryocooler, and η is the cryocooler efficiency, which is mainly governed by the efficiency of the recuperative heat exchanger. From Equations 1 and 2, one might assume that the cooling power of the cryocooler depends linearly on the cross section area of the orifice, and therefore, increasing the flow rate increases the cooling power. However, the cryocooler efficiency depends on the flow rate as well: it is reduced while the flow rate increases, thus, one should not expect a linear dependence between the flow rate and the cooling power. Performing an experimental investigation, previously reported by Tzabar et al. [4], we have found the fastest cool-down at FFR=5 (where FFR –Free Flow Rate - is a parameter indicating the size of the orifice), for a case study. Increasing the flow rate beyond this value only harms the cool-down time. In that research we found the following dependence between the flow rate, $\dot{m}$, and the cool-down time, $t_{cool\text{-}down}$:

$$t_{cool-down} \propto \dot{m}^{-0.58} \tag{3}$$

COOLING TEMPERATURE STABILITY

Cool-down time has to be defined according to the temperature in which the transient process is complete and the load has reached its operation temperature. This operation temperature has to be maintained within a required stability during the mission in order to allow the load functionality. Using a fixed-orifice J-T cryocooler has an inherent problem that contradicts the demand for a stable cold temperature. The flow rate of a fixed-orifice J-T cryocooler is governed by the pressure of the incoming gas (see Equation 1). Thus, when the pressure drops during the pressure vessel discharge, the flow rate decreases. The reduction of the flow rate reduces the pressure at the evaporator (usually called the back-pressure) and leads to a reduction of the refrigerant boiling temperature, which is the cooling temperature. This phenomenon is more severe for small pressure vessels in which the pressure drop during operation is more rapid. Unfortunately, fast cool-down is usually required in conjunction with short missions which dictates small pressure vessels.

Stabilizing the cold temperature after the cool-down process is complete may be obtained by reducing the orifice size with a flow regulation system. Demand-flow cryocoolers provide the optimal flow rate, however, they usually have a slow response which means that the flow rate reduces slowly and the cold temperature changes accordingly. Fast response regulation systems provide fast reduction of the flow rate and cold temperature at the end of the cool-down process. The fast response is at the expense of the regulated flow rate sensitivity, which means, a double-action flow controller that has a more aggressive response but doesn't meet the precise desired flow rate for the steady state cooling. These double-action flow controllers have a large fixed orifice for the cool-down process and a smaller fixed orifice for the steady cooling. A few fast response (double- action) flow controllers are reported: Longsworth et al. demonstrate the idea of using two orifices in a cryocooler while they both open during cool-down and a regulation system closes one of them after the cold temperature is achieved [5]. Buelow et al. have achieved a fast response with a snap disk that actuates a needle valve [6] while Mangano et al. use a snap disk in another configuration for the same purpose [7]. Albagnac suggests fast response regulating systems that are based on two materials with different thermal expansion coefficient that close a gap between them at the desired temperature [8, 9]. Several configurations of flow controllers based on bimaterials are suggested by Longsworth [10] and Herrington et al. [11].

Figure 1 shows a comparison of the cool-down process for three types of cryocoolers: a fixed-orifice, a demand-flow, and a double-action, all operating with argon. As mentioned before, the flow rate of the fixed-orifice cryocooler is limited by the overall cooling duration, which in this example is 220 sec. On the other hand, the flow rate of the double-action cryocooler during cool-down is higher and the temperature reduction rate is increased. The cold temperature is achieved with the high flow rate, and afterwards the flow rate is reduced followed by a reduction of the cold temperature. Figure 1 also demonstrates the slow response of the demand flow cryocooler and the slow temperature reduction. Figure 1 convinces one that a double-action cryocooler reaches cold temperature faster than both of the other two cryocoolers.

While investigating the entire cooling duration of the three cryocoolers, the fixed-orifice cryocooler has a constant slow reduction of the cold temperature during the entire mission when the double-action cryocooler keeps a fairly constant temperature. The temperature stability of the demand-flow cryocooler is about ±½°, according to the demand-flow regulation system performance. The cooling durations in the discussed example are 220, 520, and 2200 sec for the fixed-orifice, double-action, and demand-flow cryocoolers, respectively.

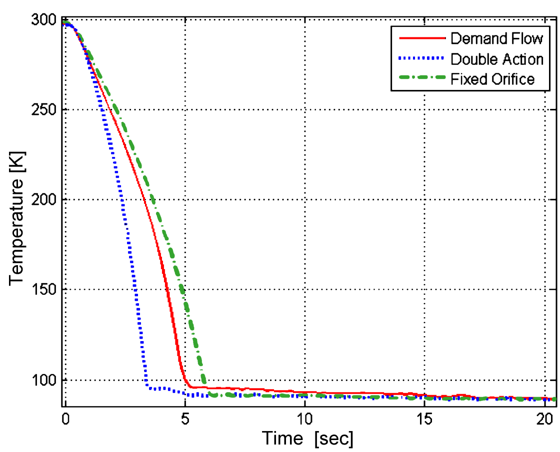

Figure 1. Cool-down performance of a fixed-orifice cryocooler (dash dotted line), a demand-flow cryocooler (continuous line), and a double-action cryocooler (dotted line).

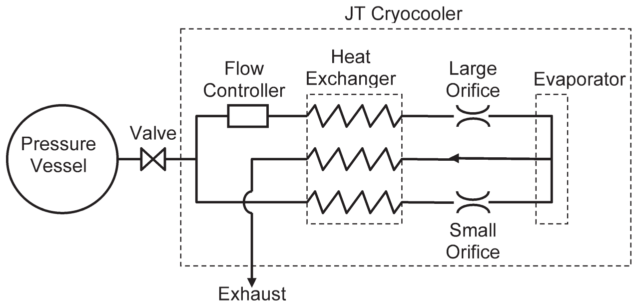

Figure 2. A schematic view of a double-action cryocooler with the TDPAFC.

NOVEL DOUBLE-ACTION CRYOCOOLER

All of the regulation systems that are mentioned above are located in the cold end of the cryocooler. Adding them causes an increase of the thermal mass which contradicts the ambition for fast cool-down. Campbell et al. suggest a regulation system where part of it is located in the warm side of the cryocooler, according to compactness considerations, while some of the components are still in the cold end [12].

In order to position the entire regulation system at the warm end it isn't possible to rely on cold temperature sensing for the regulation action. Thus, regulation on the basis of the inlet pressure is expected. In this case, a preliminary study has to yield the exact inlet pressure in which the flow rate has to be reduced. The idea of a pressure actuated flow controller is introduced by Mangano et al. [13], but the flow controller still has components at the cold end. In addition, the flow controller suggested by Mangano et al. changes the flow rate of the cryocooler when the inlet pressure reaches a constant pre-calculated value, using a spring. Unfortunately, the pressure in which the flow has to be switched depends on the ambient temperature.

In this work we introduce a Temperature Dependent Pressure Actuated Flow Controller (TDPAFC), patent pending, that has no components at the cold end at all. This flow controller concept relies on the assumption that the heat exchanger efficiency of a double-action cryocooler during the steady cooling process might be depressed, since the actual flow rate is much larger than the one required for cooling the heat load. A justification for this assumption is given by the difference between the total cooling duration of the demand-flow and the double-action cryocoolers mentioned in accordance with Figure 1. A schematic view of the novel cooler concept is described in Figure 2. The incoming high pressure stream splits at the cryocooler into two streams, one has a large orifice and the other has a small orifice. When the valve is opened the flow controller is open as well and the pressure vessel is discharged through both streams with high flow rate. At the end of the cool-down process, according to the pressure in the vessel, the flow controller shuts the flow through it and the rest of the cooling operation is obtained with a single stream through the small orifice only.

An important practical advantage of the suggested TDPAFC is that it does not have parts in the cold end. As a consequence, a double-action cryocooler that includes the TDPAFC has the same thermal mass as a fixed-orifice cryocooler. In addition, in case of a failure, the flow controller can be replaced without damaging the cryocooler, and in some cases, even without disassembling the cryocooler from the Dewar.

Temperature Dependent Pressure Actuated Flow Controller (TDPAFC)

The suggested TDPAFC, shown in details in Figure 3, is based on a bellows valve that is filled with a gas at pressure $p_{bellows}$. The function of the TDPAFC is to shut the flow through the large orifice when the cold temperature is achieved. The TDPAFC is activated by the incoming pressure according to the following balance:

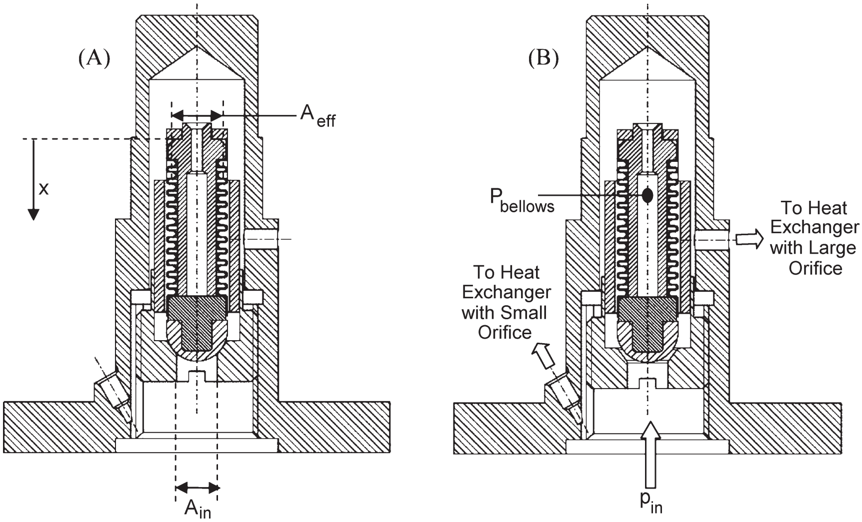

Figure 3. Detailed description of the TDPAFC: (A) "closed" state and (B) "open" state.

$$p_{in} \cdot A_{in} + K \cdot x = p_{bellows} \cdot A_{eff} \quad (4)$$

where p_{in} and A_{in} are the pressure of the gas and the cross section area at the TDPAFC inlet, respectively. K, x, and A_{eff} are the spring rate, axial movement, and effective area of the bellows, respectively. When the left side of equation 4 is larger than its right side the TDPAFC is "open" and gas may flow though it. When the right side of equation 4 is larger than the left side the TDPAFC is "closed". Figure 3 (A) shows the "closed" state while Figure 3 (B) shows the "open" state of the TDPAFC.

Figure 4 shows the operation of the double-action cryocooler with argon at room temperature. The initial drop of the pressure, to about 55.2 MPa, is due to the volume of the tubing between the pressure vessel and the cryocooler, which is at ambient pressure before operation. Cool-down is achieved after 4 sec while the pressure of the argon in the vessel is about 52.5 MPa. The change in flow rate at that moment is well observed by the change in pressure reduction rate. After cool-

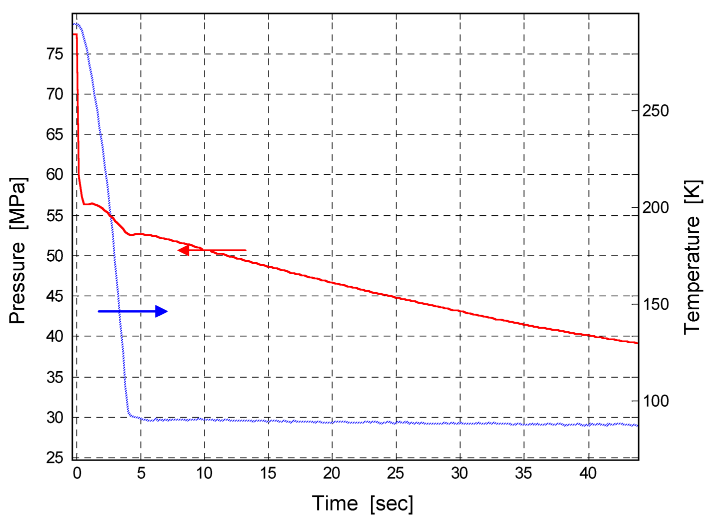

Figure 4. Double-action cryocooler performance at room temperature.

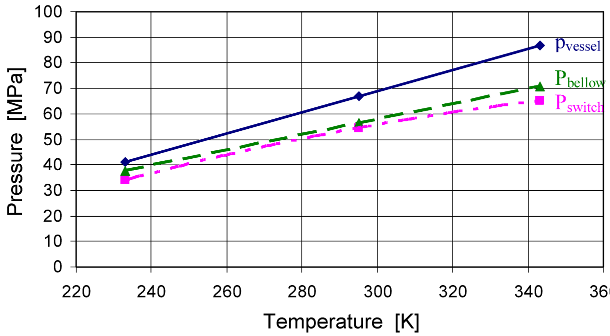

Figure 5. Ambient temperature influence on the pressure in the vessel (continuous line), switching pressures (dashed dotted line) and bellows pressures (dashed line) for a case study with argon.

down, the pressure curve still has characteristics of a fixed-orifice cryocooler but with a smaller orifice size.

While operating at different ambient temperatures many parameters change (assuming that the pressure vessel and the cryocooler have the same ambient temperature): The initial pressure in the vessel, the properties of the refrigerant, the pressure in the bellows, the flow rate during cool-down, and the thermal mass that has to be cooled. Thus, the cool down time and the value of the pressure in which the flow has to be changed, p_{switch}, depend on the ambient temperature. The dependences of the pressure in the vessel, the pressure in the bellows, and the switching pressure on the ambient temperature are described in Figure 5, for a case study with argon. Both vessel and bellows pressures are linear with temperature, according to argon characteristics, while the switching pressure is polynomial with temperature. According to equation 4, while $A_{eff} \cong A_{in}$, $p_{bellows}$ as to be slightly above p_{switch} and the spring force of the bellows compensates for the difference. Since the spring force is independent of temperature, its value has to be determined to ensure appropriate operation over the entire ambient temperature range.

Results

A set of experiments were performed with the discussed double-action cryocooler at various ambient temperatures. All experiments are with argon filled to 67 MPa at room temperature and with a pressure vessel volume of 60 cc. The results are shown in Figure 6 for ambient temperature equal to 60°C, 25°C, and -45°C. As mentioned earlier, the pressure in the bellows and all other parameters of the TDPAFC have to be carefully determined to compensate for the deviation from linearity of p_{switch}. According to experimental results and previous experience, operating at low ambient temperatures provides very fast cool-down. Therefore, we have checked the option of letting the TDPAFC stay closed during cool-down at low ambient temperatures and to use the small orifice only for these cases. The result for such an operation is also shown in Figure 6 for ambient temperature equals -20°C. The cool–down time is about 5.5 sec, longer than for 25°C with double-action cryocooler, but less than for 60°C, which means that it is in the accepted range. One should mention that the total cooling duration is much longer compared to a fixed-orifice cryocooler with the same operation conditions.

SUMMARY

Fast cool-down is obtained with high flow rate of the refrigerant. When the desired cold temperature of the load is achieved there are three main reasons for desiring a rapid reduction in the flow rate: 1) saving refrigerant in order to provide longer cooling duration, 2) rapid reduction of the back pressure at the evaporator in order to reduce its boiling temperature and thus reducing the load temperature, and 3) improving the cold temperature stability during the mission as a consequence

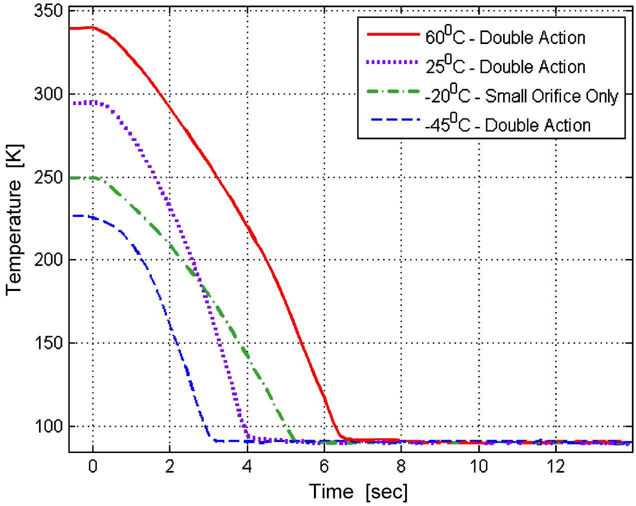

Figure 6. Experimental cool-down results of a double-action cryocooler at different ambient temperature: continuous line for 60°C, dotted line for 25°C, and dashed line for -45°C. The dashed dotted line is for operation at -20°C with the small orifice only.

of the reduced flow rate. The double-action cryocoolers satisfy the rapid flow change requirement at the end of the cool-down process, at the expense of cooling duration compared to demand-flow cryocoolers.

In this work we present a novel flow controller (TDPAFC) for rapid reduction of the flow rate that is based on several practical aspects:

- The flow rate of a double-action cryocooler during steady cooling process is higher than the minimal flow rate required to maintain the cold temperature, thus, the heat exchanger efficiency may be inferior.
- The absence of flow controller's components in the cold-end decreases the thermal mass of the cryocooler and contributes to the fast cool-down rate.
- Operating with a known pressure vessel, the switching pressure (the pressure at the end of the cool-down process in which the flow rate has to be reduced) depends on the ambient temperature. The suggested flow controller is pressure activated and temperature dependent in a way that ensures fast cool-down in a wide range of ambient temperatures.

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