CASCADE JOULE-THOMSON REFRIGERATORS*

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ABSTRACT

The design criteria for cascade Joule-Thomson refrigerators for cooling in the temperature range from 300K to 4.2K have been studied. The systems considered use three or four refrigeration stages with various working gases to achieve the low temperatures. Each stage results in cooling to a progressively lower temperature and provides cooling at intermediate temperatures to remove the substantial amount of parasitic heat load encountered in a typical dewar. With careful dewar design considerable cooling can be achieved with moderate gas flows. For many applications, e.g., in the cooling of sensitive sensors, the fact that the refrigerator contains no moving parts and may be remotely located from the gas source is of considerable advantage. A small compressor suitable for providing the gas flows required has been constructed and tested. Performance of the system is described.

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* This paper represents one phase of research carried out at the Jet Propulsion Laboratory, California Institute of Technology, under NASA Contract NAS7-918.

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INTRODUCTION

The applications for electronics operating at cryogenic temperatures are continually expanding, particularly for military applications. Examples include infrared detectors, Josephson junction computers, communication receivers, precise navigation devices and magnetic sensors. With the advent of nuclear magnetic resonance imaging systems, the production of liquid helium temperatures even in medical instrumentation will soon be routine. Unfortunately, the actual use of cryogenic electronics has been hampered by the expense, complexity, size, and power requirements of the cryogenic refrigerators. In addition, cryogenic refrigerators, in most circumstances, require highly trained maintenance personnel to keep them operating.

The Joule-Thomson (J-T) refrigerator is extremely simple and has no moving parts at cryogenic temperature. In a small J-T refrigerator very high pressure gas flows through a capillary sized tube to a valve or flow restriction where it expands to a lower pressure and cools. This, now cool, gas is used both to provide the required refrigeration and to precool the high pressure gas moving in the capillary tube. This very simple refrigeration method is based entirely on simple energy conservation and requires no intricate or speculative design. Apparently, two factors have limited the use of J-T refrigerators for cryogenic applications. First, very high pressure gas and very clean gas is required, and second, J-T refrigerators are theoretically not as efficient as other types of refrigerators. In order to provide clean high pressure gas researchers have been trying for several years to develop a compressor to meet the very exacting requirements of J-T refrigerators. At the Jet Propulsion Laboratory, a need for long-lived refrigerators (up to 10 years) for use on spacecraft has resulted in a considerable effort to develop non-mechanical adsorption and absorption compressors [1] for use with J-T refrigerators. It is anticipated that such systems could deliver the long lifetime required because of the absence of motion induced wear which is the chief performance degradation mechanism in conventional refrigerators.

In the meantime, W. A. Little, at Stanford, has developed a method of producing tiny J-T refrigerators for electronics applications on small glass slides using photolithographic techniques.[2] These small refrigerators are now produced commercially [3] and are very promising for high volume, inexpensive mass production. Currently, these refrigerators are run "open cycle" from a compressed gas cylinder with the exhaust gas being vented to the atmosphere. The development of a small reliable compressor would open up many more applications for use of small J-T systems. Cross, Lawless, and Steyert have designed, but not built, a J-T compressor which uses new electrostrictive materials developed at Pennsylvania State University. In addition, a prototype small mechanical compressor which appears to meet the exacting requirements of J-T systems has been built and tested at the Jet Propulsion Laboratory.

There are two important features of J-T systems which are of particular importance for many applications and should be emphasized. The first is that the J-T refrigerator itself can be made very small. This means, that for the cooling of devices such as sensors the dewar can also be made small. For many sensor applications the major load on the cooling system is due to parasitic heat leaks which scale with the size of the dewar system. Therefore, one often would require smaller cooling powers for a J-T system than if either a mechanical refrigerator system or a stored cryogen system is chosen. Secondly, for sensors that are vibration sensitive, the J-T cooler itself has no moving parts and the compressor can be remotely sited. This leads to potentially very low vibration at the sensor for J-T refrigerators with small gas flows [4].

JOULE-THOMSON REFRIGERATION

J-T refrigerators operate on a simple conservation of energy principle. This is illustrated with the aid of Figure 1. High pressure gas of enthalpy h_h with mass flow rate $\dot{m}$ enters the high pressure side of the heat exchanger where it is precooled before it expands through the J-T valve to a low pressure and cools. The gas then picks up the heat load $\dot{Q}$ and exits through the low pressure side of the heat exchanger so that it precools the incoming high pressure gas. The gas exits the heat exchanger with an enthalpy h_l. From energy conservation,

$$\dot{Q} = \dot{m}\,(h_h - h_l) \tag{1}$$

if there are no additional parasitic heat loads.

This simple expression is valid independent of the quality of the heat exchanger, although, obviously the better the heat exchanger the larger is $(h_h - h_l)$ and therefore the larger the cooling power. Many gases can be used to provide J-T cooling over a wide temperature range. The primary physical constraint on the cooler is that for a particular gas which is to be used, the inlet temperature to the heat exchanger must below the inversion temperature of that gas. It is this constraint that limits use of a single working fluid design for an all J-T cooler operating to liquid helium temperatures and at room temperature. He^4 has an inversion temperature of 51K and therefore to reach temperatures around 4K requires upper stage refrigeration to well below 51K in order to precool the high pressure He gas. Therefore, in order to reach ~4K with an all J-T cooler design one requires a cascade process in which one has a few stages of cooling using appropriate working gases. For example, in order to reach 4.2K starting at room temperature one could design a three-stage J-T system using the working gases N_2, H_2 and He.

A N_2 gas source provides high pressure gas to a N_2 J-T cooler which reaches 77K. A H_2 gas source provides high pressure gas which is precooled by heat exchange with the N_2 J-T cooler before it enters the H_2 J-T cooler and provides cooling to approximately 20K. The last cooling stage uses He gas precooled by both the N_2 and H_2 refrigerators before entering the He J-T refrigerator and achieving the 4.2K low temperature. For each cooling stage one must include additional cooling power in order to handle the inevitable parasitic heat loads encountered in a real system. However, nature is kind to the designer in the following way. For a given flow rate, the cooling power available from a N_2 cooler is far larger than that available from the H_2 which is in turn far larger than that available from a He cooler. This means that per unit of cooling power less is demanded of the compressor for the higher temprature stages.

In a related paper at this conference [5] we give an example of a cascade J-T refrigerator which is designed for a very long lifetime. In this system non-mechanical adsorption compressors are used as the high pressure gas sources. The long lifetime is expected because of the absence of moving parts in the refrigerator. A feature of these compressors is that they must also be precooled to their appropriate operating temperatures. Therefore, for this design an upper stage refrigerator has to provide, in addition, cooling for the lower stage compressor. This differs from the example given later in this paper, where room temperature gas sources are assumed. Therefore, for adsorption J-T systems, the upper refrigeration stages would require larger cooling power than a comparable cascade J-T refrigerator using a room temperature compressor. In some applications, however, such as for a long space mission where the cooler is inaccessible for maintenance, cascade J-T refrigerators using adsorption compressors are very promising, especially given the history of lifetime problems with mechanical cryocoolers.

CASCADE J-T REFRIGERATOR

To illustrate the performance requirements of a cascade J-T refrigerator, we consider for simplicity a two-stage design operating between 300K and 84K rather than a four-stage design operating down to 4.5K. A schematic of the cascaded J-T system is shown in Fig. 2. The upper temperature CF_4 stage is used for precooling the gas to the lower temperature N_2 stage. In addition, the CF_4 stage is used to trap parasitic heat leaks into the dewar system. If required, sufficient additional cooling capacity may be included for a specific cooled instrument. In Table I we show some performance characteristics for a two-stage system. The available cooling power is calculated conservatively, assuming that the heat exchangers are not perfect resulting in 85% of ideal efficiency for each J-T heat exchanger system. As well, the heat load on the CF_4 refrigerator for precooling the N_2 gas has been included. Therefore, the available cooling power represents the cooling which can be used for both dewar parasitics and instrument heat loads. Note that even with these modest flow rates we have quite reasonable cooling powers available.

Table I

Two-stage Refrigerator Performance

	CF_4 stage	N_2 stage
Input pressure (atm)	68	68
Output pressure (atm)	3	2
Flow rate STP cm^3/sec	15	15
Precool temperature (K)	300	165
J-T temperature (K)	163	84
Total cooling power (W)	2.0	1.0
Precool power (W)	0.8	---
Available cooling power (W)	1.2	1.0

Such a refrigerator can be run either open or closed cycle and additional cooling stages to lower temperatures could be added. The addition of H_2 and He stages would provide temperatures down to <5K with cooling powers at the lowest temperature approximately 25mW.

A real closed cycle refrigerator requires a small high pressure compressor for the gas source. We have built such a small mechanical compressor which is oilless and provides almost isothermal compression. This single-stage compressor is capable of providing compression ratios of 40:1 with flow rates larger than those used in the previous example. We have operated this compressor for periods of weeks as a gas source for a small J-T refrigerator using argon as the working fluid. In that period we had no failure or blockage in the small refrigerator. From data taken with the cooler we can make the following estimates on its performance. Because of the low flow rates a simple parallel capillary tube heat exchanger can easily be made to give refrigerator efficiency of at least 85% relative to ideal values. The compressor and drive combined are 60% efficient and a motor of at least 70% efficiency can be used. Therefore, the refrigerator of the example for an 85% efficient J-T and heat exchanger would have available cooling powers of 1.2W at 165K and 1.0W at 84K with an input power of 19W.

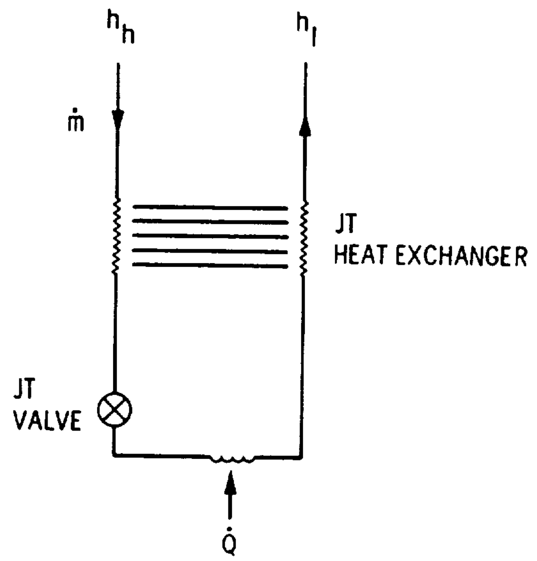
h_h
h_l
$\dot{m}$
JT
HEAT EXCHANGER
JT
VALVE
$\dot{Q}$

Fig. 1

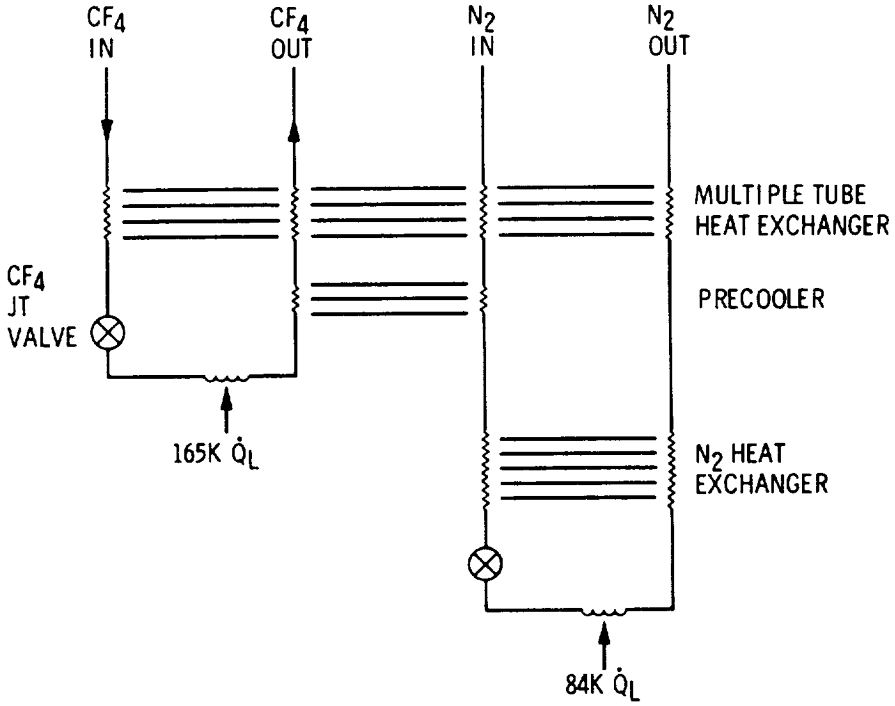
CF_4 IN
CF_4 OUT
N_2 IN
N_2 OUT
MULTIPLE TUBE
HEAT EXCHANGER
CF_4
JT
VALVE
PRECOOLER
165K $\dot{Q}_L$
N_2 HEAT
EXCHANGER
84K $\dot{Q}_L$

Fig. 2

QUESTIONS

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1. For a 4.2K, .01W, 4-stage cascaded J-T refrigerator, is 18W input power the total required for all 4 compressors?

Author's reply:

Yes. The calculation assumes the same efficiencies as given in the two-stage example of the text, a particular dewar design whose small parasitic heat loads are handled by the refrigerator, and no excess cooling capacity at the upper stages.

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