

## PERFORMANCE OF A VERY LOW TEMPERATURE REFRIGERATION SYSTEM OPERATING WITH NATURAL FLUIDS

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**Abstract** - This paper presents the development and testing of a multistage mixed refrigerant cascade refrigerator for achieving very low temperatures. The main advantage with these systems is the use of natural fluids such as nitrogen, argon, helium, neon, and hydrocarbon fluids such as methane, ethane, propane, butanes and pentane, which, unlike the HFCs and their mixtures, are environment friendly. The system cools down to 100 K in about 60 minutes. A load of 7 Watts could be met at 100 K.

### Introduction

Single stage refrigeration systems can be used for meeting refrigeration loads down to  $-40\text{ }^{\circ}\text{C}$ . Two stage systems are needed for applications operating at temperatures below  $-40\text{ }^{\circ}\text{C}$  and down to  $-75\text{ }^{\circ}\text{C}$ . Three or more stages are needed for temperatures below  $-100\text{ }^{\circ}\text{C}$ . Ozone depleting substances such as CFC13/CFC12 and CFC14/CFC13/CFC12 were widely used in two and three stage cascade systems. However, after the Montreal Protocol ban on the ozone depleting substances, CFC13 has now been replaced by HFC23 and CFC12 by HCFC22 or HFC134a. Under the Kyoto Protocol on Green House gases, HFCs have been included. Hence, there has been a quest for alternate environment friendly fluids / mixtures for obtaining very low temperatures.

Refrigeration systems known as "Auto Refrigerant Cascade (ARC)" or "Mixed Refrigerant Cascade (MRC)" which can reach temperatures as low as  $-200\text{ }^{\circ}\text{C}$  are under development in many parts of the world. The MRC systems were studied extensively in the former Soviet Union (Alexeev *et al*, 2000; Boiarskii *et al*, 1998) and were also patented in the United States by Missimer (1972, 1973). The use of a single compressor in a MRC cycle compared to multiple compressors in traditional cascade cycles results in reduction of cost and complexity. The efficiency of the MRC cycle can be as high as the traditional cascade cycles because of the low exergy efficiency of the small compressors, typically between 30 to 45%, depending on the construction (reciprocating or rotary) and working pressures.

Figure 1 shows the schematic of a single stage MRC refrigerator. In this cycle a mixture of refrigerants is compressed from state point 1 to state point 2. The heat of compression is rejected in the after-cooler (state point 3). Then the refrigerant and the lubricating oil are separated, before the high pressure refrigerant is introduced into the cryostat (state point 4). The high pressure refrigerant is condensed and sub-cooled using the low pressure refrigerant

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leaving the evaporator in a counter current heat exchanger (state point 5). The sub-cooled refrigerant is expanded from state point 5 to state point 6, and is evaporated in the evaporator to state point 7.

With appropriate mixtures, the refrigeration temperature can be varied from 245 K to as low as 70 K with a working pressure less than 20 bar. The theoretical exergy efficiency ( $COP/COP_{Carnot}$ ) of these refrigerators ranges from 20 to 40% depending on the refrigeration temperatures and mixtures used. The practical exergy efficiency of refrigerators operating at 80 to 100 K varies typically between 2 to 7%.

At the Refrigeration & Airconditioning Laboratory of Indian Institute of Technology Madras, MRC refrigerators have been studied by the authors theoretically for the last 10 years and prototypes have been built and tested since 1998. Different types of heat exchangers have been fabricated, and the systems have been tested with different compressors and mixtures. In this paper, the results obtained on a MRC system with phase separators using nitrogen-hydrocarbon mixtures are presented.

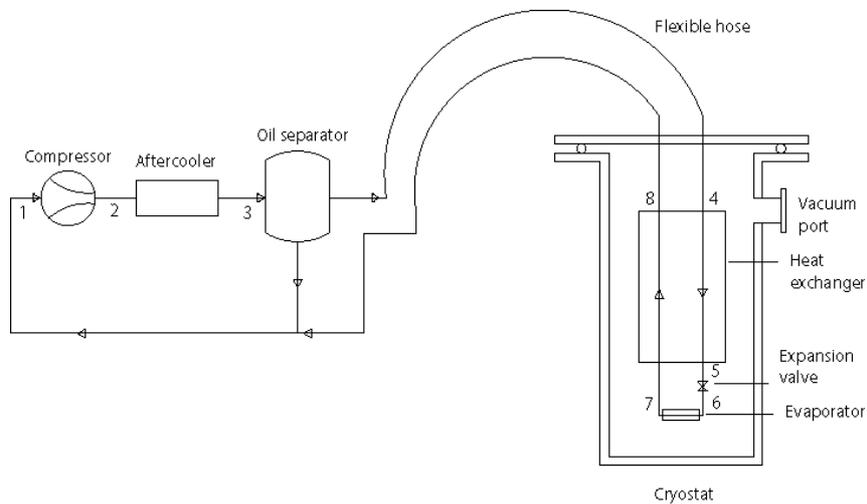


Figure 1: Schematic of the single stage MRC refrigerator

### Performance of the Multi-Stage MRC Cycle

One of the problems with the single stage cycle shown in Fig. 1 is the possibility of carry over of the compressor lubricating oil, which can freeze in the expansion capillary tubes. In order to avoid the freezing, a phase separator cycle (Fig. 2), also known as the multistage cycle is under development in our laboratory. In this cycle (Fig. 2), a phase separator is employed to remove some of the high boiling point components such as butanes and pentanes and the lubricating oil carried over from the compressor from reaching low temperatures where they may freeze. In the phase separators, the liquid consists mostly of the high boiling point components, and the vapour phase preferably does not contain any high boiling components. The liquid is expanded to a lower pressure, mixed with the low pressure refrigerant returning from the evaporator at an intermediate temperature and returned to the compressor. The expanded liquid also provides the necessary cooling to cool and condense the vapour stream leaving the phase separator. The use of phase separator also allows balancing the refrigeration needed to cool the high pressure refrigerant at different temperatures. When no liquid phase is

present, the phase separator simply acts as a bypass valve to decrease the flow rate through the heat exchangers.

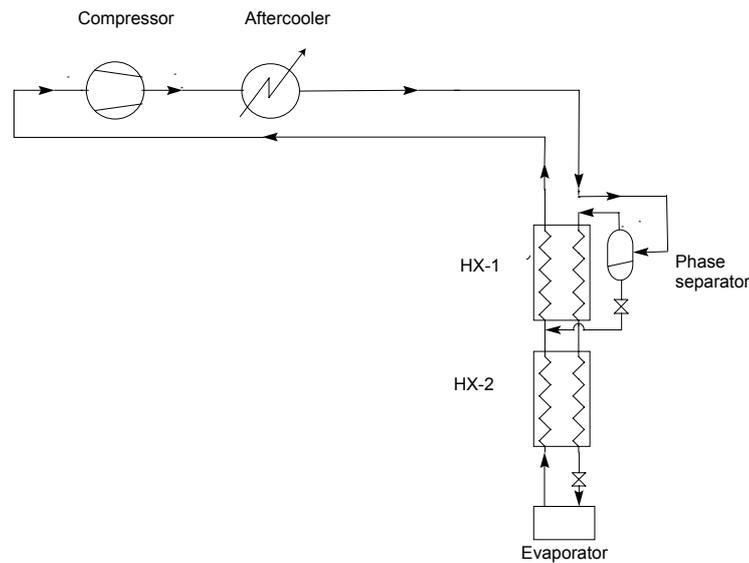


Figure 2 : Schematic of the multistage MRC refrigerator

### Test Setup

In the MRC refrigerator test rig, a rotary piston R22 compressor of 3.8 m<sup>3</sup>/hr capacity has been used. Capillary tubes are employed for expanding the refrigerant at room temperature as well as at low temperature. A coiled heat exchanger of 6.5 metres total length was used. A vacuum level of less than 10<sup>-4</sup> mbar was maintained in the cryostat. Ten layers of aluminized mylar separated by paper spacers was applied as insulation. A conventional commercial oil separator used in R22 systems was employed. The test rig is extensively instrumented for measurement of temperatures, pressures, flow rates, etc.

### Results and Discussion

The system was charged with the following mixture: N<sub>2</sub>/CH<sub>4</sub>/C<sub>2</sub>H<sub>6</sub>/C<sub>3</sub>H<sub>8</sub>/I-C<sub>4</sub>H<sub>10</sub>: 36/14/07/22/21 mol%. Figure 3 shows the cool down curve of the multistage refrigeration system shown in Fig.2. It can be seen that a temperature of 100 K can be reached in about 56 minutes. The cool down time compares well with the 40-45 minutes required in the single stage cycle tested by the authors (Venkatarathnam et al, 2003).

Figure 4 shows the heat load and exergy efficiency of the refrigerator with the mixture at different evaporator outlet temperatures. The exergy efficiency of a refrigerator is the ratio of the minimum work required with a reversible (Carnot) refrigerator and the actual work required to meet the same heat load, and is given by

$$\eta_{\text{ex}} = \frac{W_{\text{rev}}}{W} = \frac{Q \left( \frac{T_a}{T} - 1 \right)}{W} \quad (1)$$

In the above expression Q is the refrigeration load, T<sub>a</sub> is the ambient temperature, T is the refrigeration temperature and W is the compressor power. The exergy efficiency is termed as

the external exergy efficiency when  $T$  is the temperature of the load, and internal exergy efficiency when  $T$  is the temperature of the refrigerant leaving the evaporator. The evaporator

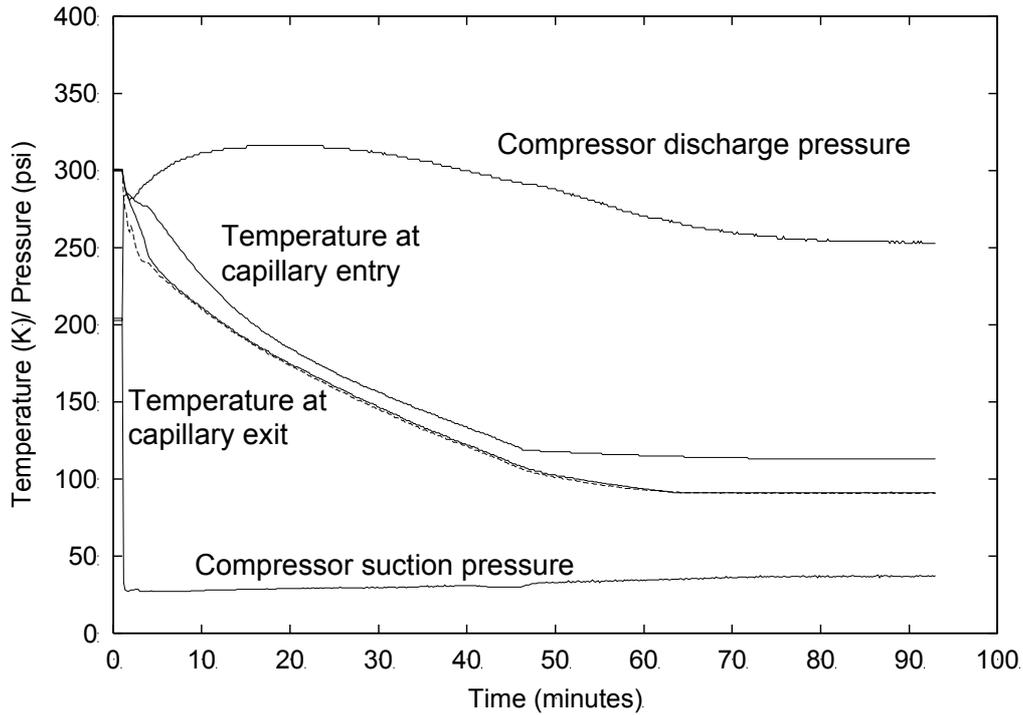


Figure 3: Cool down characteristic of the refrigerator with a mixture of nitrogen, methane, ethane, propane and iso-butane

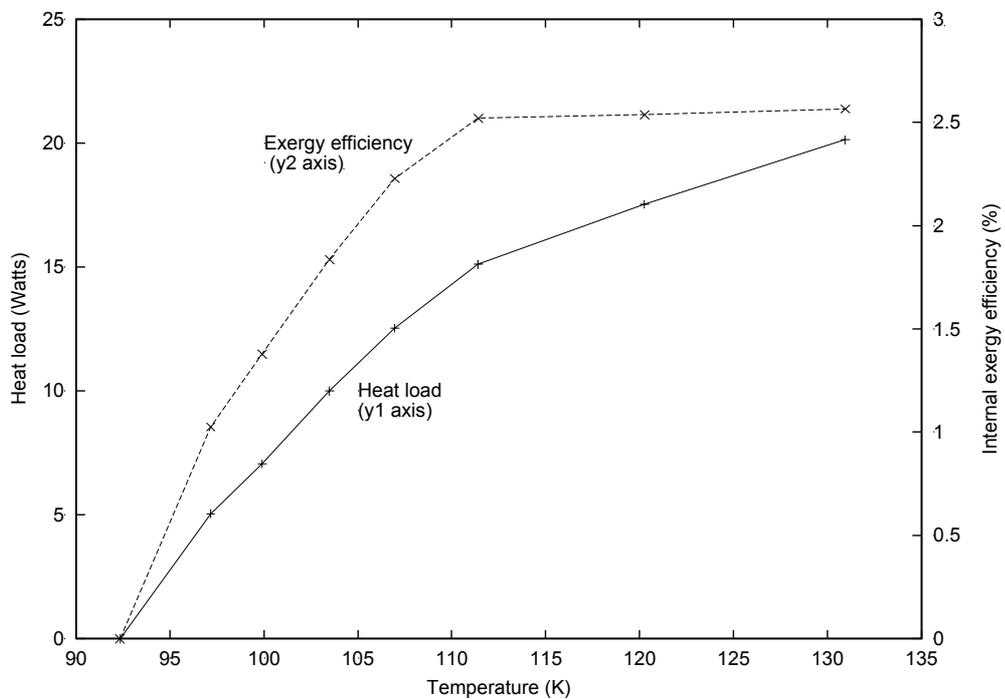


Figure 4 : Heat load characteristics and internal exergy efficiency with a nitrogen, methane, ethane, propane, iso-butane mixture

used in this work has not been optimized for the system. Hence we have chosen to present the results in terms of internal exergy efficiency.

With the present mixture, a load of 7 Watts could be met at a temperature of 100 K, and a maximum load of 20 Watts at 130 K. A maximum internal exergy efficiency of 2.5% could be achieved at about 110 K.

Figure 5 shows the heat load and internal exergy variation with a mixture of nitrogen, methane, ethane, iso-butane and n-pentane. A maximum exergy efficiency of 4.1% could be obtained with this mixture and a heat load of 30 Watts could be met at a refrigerant temperature of 122 K. The higher refrigerating temperature obtained in this mixture is due to the higher evaporating pressure applied. With an appropriate throttle and evaporator, it is possible to improve the capacity and exergy efficiency with the n-pentane based mixture even further.

The results presented above are the preliminary results obtained with the system, and there's much scope for improvement in the refrigeration capacity as well as the exergy efficiency by matching the components of the system, and using an optimized mixture. This work is under progress.

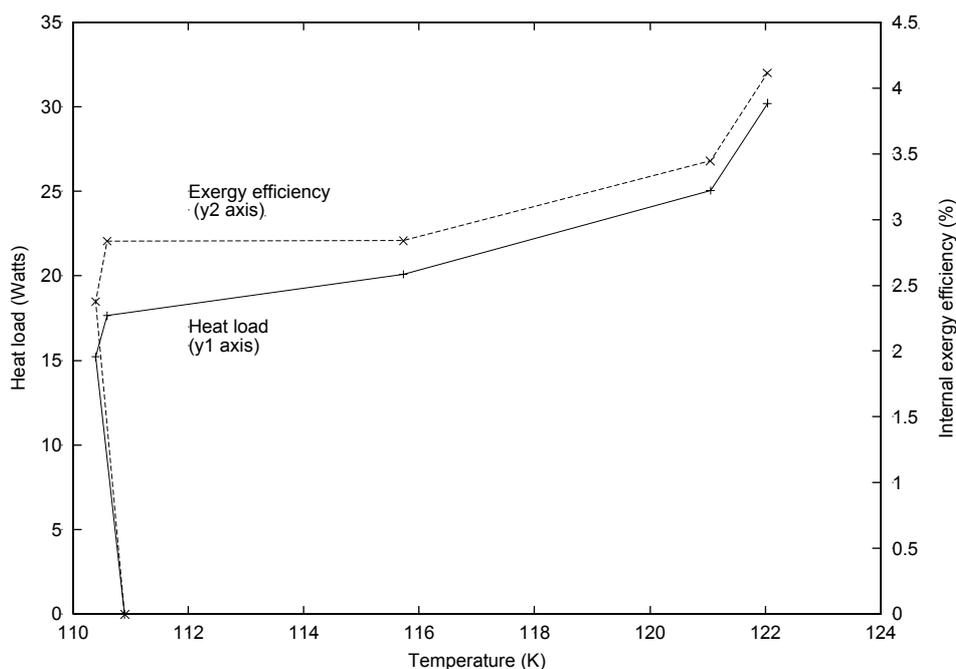


Figure 5: Heat load characteristics and internal exergy efficiency with a nitrogen, methane, ethane, iso-butane, n-pentane mixture

## Conclusions

A multistage mixed refrigerant cascade refrigerator has been built and tested. The main advantage with these systems is the use of environment friendly natural fluids such as nitrogen, argon, helium, neon, and hydrocarbon fluids such as methane, ethane, propane, butanes and pentane. The system cools down to 100 K in about 60 minutes. A load of 7 Watts could be met at 100 K.

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