# Mixed Gas JT Cryocooler with Precooling Stage

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## ABSTRACT

A mixed gas Joule Thomson refrigerator offers decisive advantages for several applications. Requirements such as an extreme long MTBF and long life, low levels of vibration and noise can be satisfied by such a refrigerator. However, the known coolers of this type have a relative low thermodynamic efficiency. An improvement of the efficiency is possible by introducing a precooling stage. This method will be discussed in the paper. A mixed gas JT refrigerator with precooling stage has been tested. The efficiency proved to be 1.5 times better compared with a Gifford-McMahon refrigerator.

## INTRODUCTION

The object under discussion here are coolers with a cooling capacity of more than 50 W at 90-110 K. Mixed gas JT-coolers have a good chance to be introduced to the market in this capacity range, because of their low cost. However, to be really competitive, e.g. compared with Gifford-McMahon refrigerators, an improvement of the efficiency of mixed gas JT coolers is necessary.

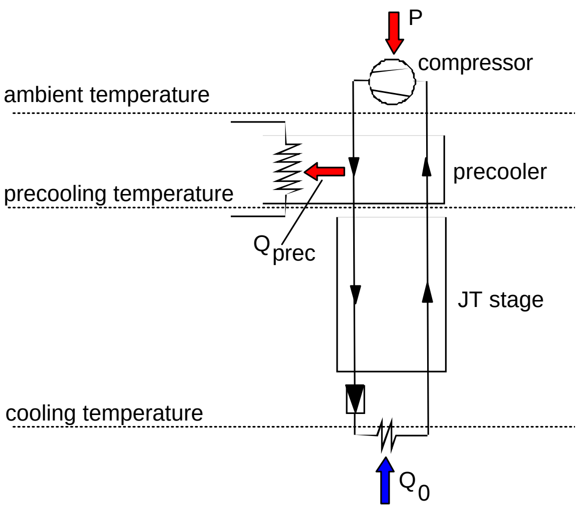
We have tried this by varying of the mixture composition but found that the greatest improvement can be obtained by the introduction of a precooling stage.

In the large scale refrigeration the propane precooled mixed refrigerant process was introduced successfully by Lee.S.Gaumer[1] for natural gas liquefaction.

## MIXED GAS JT COOLER

The main components of a Joule Thomson system are compressor, counterflow heat exchanger (JT heat exchanger), throttle valve and evaporator.

The compressor supplies the high pressure flow of the mixed refrigerant, which flows through the JT heat exchanger, expands through the throttle valve and passes the evaporator, where it absorbs heat from the object to be cooled. The low pressure stream is then circulated back through the counterflow heat exchanger into the compressor. The thermodynamic cycle has been discussed in detail earlier[2,3].



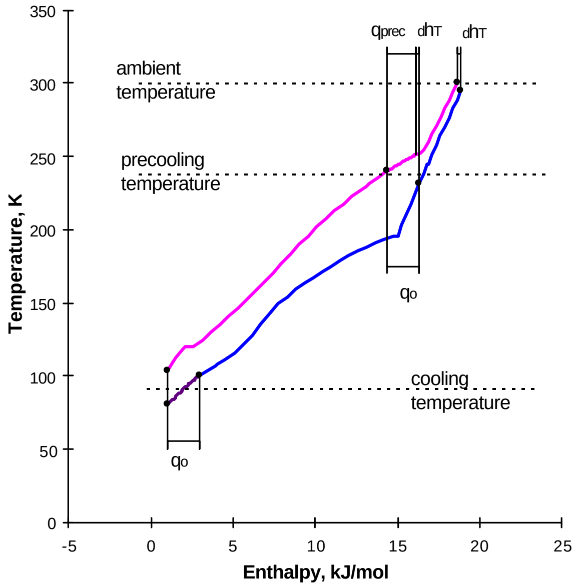




**Figure 1** JT cycle with precooling

**Figure 2** T-h-diagram for the mixed gas JT cycle with precooling

## WHY PRECOOLING?

The refrigeration capacity of a mixed gas JT refrigerator is determined by the enthalpy difference between low and high pressure stream at the pinch point in the heat exchanger. For optimum mixtures the pinch point is situated at the warm end (similar to a JT cycle with pure refrigerant). The pinch point enthalpy difference depends on the temperature. At temperatures of about 240 K it is approximately 1.5...2 times larger than at 300 K. Consequently the cooling capacity of the cooler can be 1.5...2 times higher.

In order to use this effect the „ambient temperature“ should be shifted down to about 240 K. An additional cold source (precooling stage) can be used for that. Fig. 1 illustrates this principle. The cycle consists of compressor, 3-stream heat exchanger (precooler) and the conventional JT-stage. The high pressure stream is cooled by an additional cold stream in the precooler before entering the JT-stage. The cooling capacity of the low pressure stream, which remains after the JT stage, is used in this heat exchanger, too.

The specific cooling capacity $q_0$ of such a cycle is given by:

$$q_0 = \Delta h_T + q_{prec}\text{, with}$$

$\Delta h_T$ - enthalpy difference between high pressure and low pressure stream at ambient temperature,
$q_{prec}$ - specific cooling capacity of the precooling cycle.

Fig. 2 shows a typical temperature-enthalpy diagram for a mixed gas JT cycle with precooling stage. The high pressure mixed refrigerant (optimized for the cycle with precooling stage) is totally gaseous at ambient temperature. Therefore $\Delta h_T$ is relatively small. This value is considerably smaller than $q_0$. Consequently the necessary cooling capacity of the precooling cycle has to be in the same order of magnitude as the cooling capacity of the main cycle:

$$q_{prec} \approx q_0$$

The COP of refrigerators used for temperatures of about 235-245 K is in the order of 1. Therefore the power consumption for the precooling refrigerator is numerically equal to the cooling capacity of the precooling cycle and is about 10 times smaller than the power consumption of the mixed gas compressor.

Thermodynamically this small additional energy investment is profitable, because the cooling capacity of the mixed gas refrigerator is increased by a factor of 1.5-2.

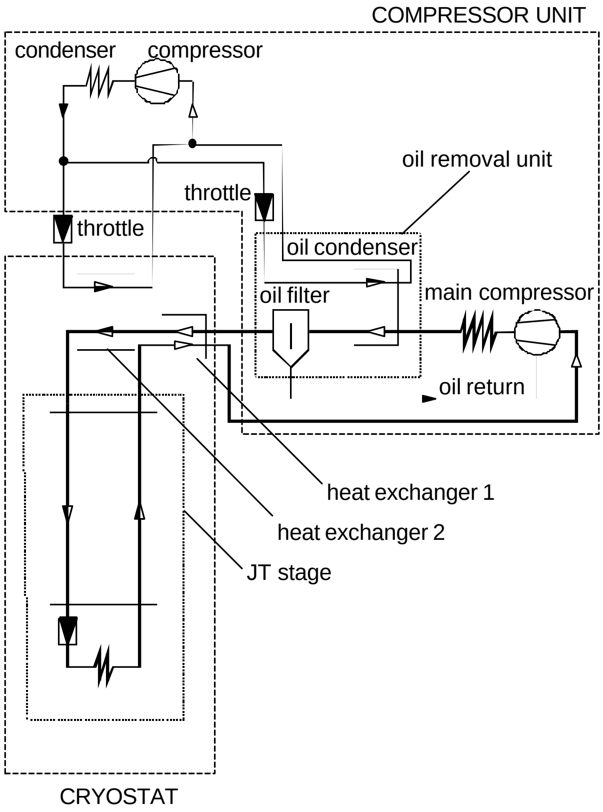



**Fig. 3** Flow diagram of the mixed gas JT refrigerator with precooling stage

## PROCESS DESIGN

A mixed gas JT cooler with precooling stage was developed at the Technische Universitaet Dresden. Fig. 3 shows the flow diagram of this refrigerator. It includes two separate cycles: a mixed gas cycle and a precooling cycle.

### Mixed Gas Cycle

The mixed gas is discharged at high pressure from the main compressor. The gas flows through the aftercooler and the oil separation unit. The separated oil is returned to the main compressor.

Instead of the 3-stream exchanger shown in Fig. 1 two separate counterflow heat exchangers are provided. In the first heat exchanger the high pressure stream is cooled down by the low pressure stream from the JT stage. The further precooling takes place in the second heat exchanger by the cold stream from the precooling cycle. The high pressure stream than flows into the JT-stage to produce the cooling power at the required temperature.

A mixture of nitrogen, methane, ethane and propane is used. The composition was optimized[*] to achieve the maximum specific cooling capacity at 95-100 K.

### Oil Removal

The use of an oil lubricated compressor has the disadvantage of oil contamination in the high pressure stream. If the oil contamination in the mixture exceeds compatible quantities, this would result in clogging in the cold box at low temperatures. Therefore an oil separation for the high pressure gas after the compressor is required.

The required purity of the mixture can not be guarantied by conventional filter technology under all circumstances. In order to overcome this, we condense the vaporous oil by cooling of the high pressure stream to below room temperature[**] . This can be realized by introducing an additional heat exchanger (oil condenser) before entering the oil filter. The high pressure gas is cooled to approximately 0°C, the vaporous oil is condensed and removed from the refrigerant by a conventional oil filter. This way the necessary purity of the refrigerant for failure-free operation can be achieved.

### Precooling Cycle

The precooling cycle has two functions: precooling of the high pressure stream and cooling of the oil containing high pressure stream in order to condense vaporous oil.

We use a simple throttle cycle (similar to domestic refrigerators) for precooling. The refrigerant is discharged at high pressure from the compressor and liquefied in a condenser at ambient temperature. A portion of the liquid refrigerant expands in a first throttling device. The cold refrigerant flows via precooler back to the compressor. The rest of liquid refrigerant expands

[*] Patent pending
[**] Patent pending

in a second throttle valve, producing additional cold. This is used in the oil condenser, and returned to the compressor. Refrigerant R507 was used for the precooling cycle.

**Further Advantages**

The process design with a precooling stage brings additional advantages. The refrigerant mixture can consist of four components only: high-boiling components like butane are not longer needed, the percentage of components like propane can be smaller. Therefore mixture design and composition control are more simple. A further effect is that solidification of these components at the lowest temperatures can be prevented better this way.

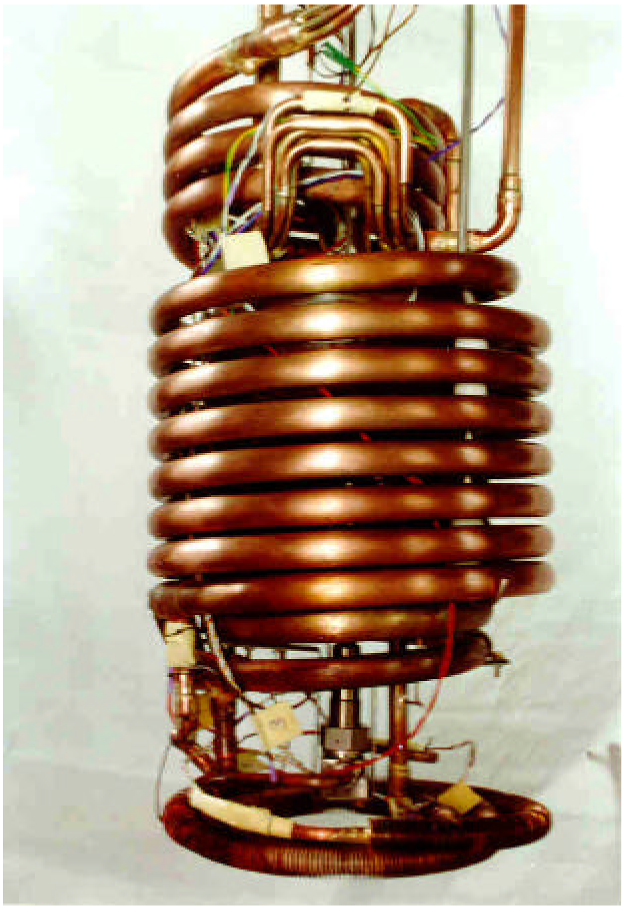


**Figure 4** cryostat interior

## HARDWARE

Our mixed gas JT cooler consists of two separate modules: the compressor unit and the cryostat, which are connected by gas lines.

The compressor unit consists of two compressors. The mixed gas compressor is a single stage oil lubricated rolling piston compressor (power consumption about 1 kW) with aftercooler and oil removal unit. The R507 compressor is a smaller hermetic compressor with a condenser for the precooling loop (standard Danfoss unit).

A multitube heat exchanger was used. For the high pressure stream eight small 4 mm copper tubes are provided, which are placed in a larger 16 mm tube. The low pressure stream flows in the larger tube in the space between the small tubes. The arrangement is wound into two spirals (with approx. 120 mm and 180 mm diameter). Figure 4 shows the cryostat interior.

## TEST RESULTS

The tests of the system started in the end of January 1998. So far more than 400 operating hours of the refrigerator have been accumulated.

The cooling capacity of the system depends on the composition of the mixture. With an optimum mixture composition a cooling capacity of approximately 100 W was found at 100 K (Fig. 5). The energy consumption of the system amounts to approximately 1.1 kW.

With the same mixture a minimum cooling temperature of about 83 K was achieved.

This refrigerator is more effective compared with known mixed gas JT systems. At temperatures above 95 K this unit is more than 1.5 times more effective than a comparable Gifford McMahon refrigerator.

## RELIABILITY

The reliability of the system will be only slightly affected by the introduction of the precooling stage, because all additional components are as reliable as the original components of the mixed gas refrigerator.

## COSTS

The addition of the precooling stage does not cause a considerable increase in costs of the system, because all additional components are „low cost“ elements, available from conventional refrigeration. The costs of the compressor-condenser-unit (used as precooling stage) are less than 200 $. Even including the costs of the necessary periphery (heat exchangers, connection lines and throttling devices) and some additional expenditure for installation of these elements, the excess costs are lower than 1/10 of the cost of the complete system.

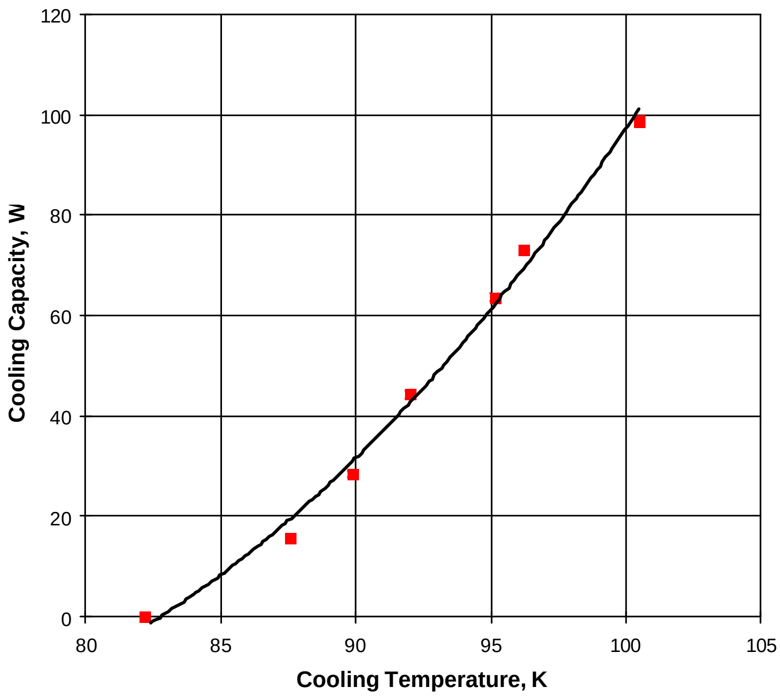



**Figure 5** Cooling capacity of the mixed gas JT refrigerator with precooling stage

## SUMMARY


A mixed gas JT refrigerator with precooling stage was developed, built and tested. This system is more effective (at least 1.5 times) compared with a Gifford McMahon refrigerator. The reliability of the system will not be essentially affected by the introduction of the precooling stage. The additional investment is negligible in comparison to the achieved improvement in efficiency.


## REFERENCES


1. Gaumer L.S., Newton Ch.L., US Patent # 3763658, Oct.9, 1973
2. A.Alexeev, Ch.Haberstroh, H.Quack, Low cost mixture Joule Thomson refrigerator, Proceedings of the 16th International Cryogenic Engineering Conference, Kitakyushu, Japan, 1996
3. A.Alexeev, Ch.Haberstroh, H.Quack, Further development of a mixed gas Joule Thomson refrigerator, presented at the Cryogenic Engineering Conference, Portland, USA, 1997