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PERFORMANCE OF THE COLD EJECTOR OF THE JET CRYOPLANT

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ABSTRACT

A cold ejector is used to pump the helium inside 3 large operational cryopump systems at JET to a pressure below the suction pressure of the cryoplant compressor (160 gs^{-1}/1.3 b absolute) down to 250 mb below atmospheric pressure. The cold ejector has been successfully operated for over 2 years and successfully copes with stringent dynamic conditions encountered during cooldown and cryopump regeneration. The performance characteristic of the cold ejector has been analysed by calorimetric measurements with a power of up to 300 W and for flow rates of up to 60 gs^{-1}. The pumping of gas, vapor and liquid have been compared. The results are presented and operational aspects discussed.

INTRODUCTION

Cryosystems operating below the suction pressure of the refrigerator compressor require a pumping unit between the cryostat and the compressor. An ideal solution is a cold ejector - a unit which uses the suction capacity of the Joule Thompson expansion nozzle (similar to that of a water jet pump). Its advantage is the lack of moving parts, no sealing requirements and operation at cryo-temperatures practically without maintenance problems.

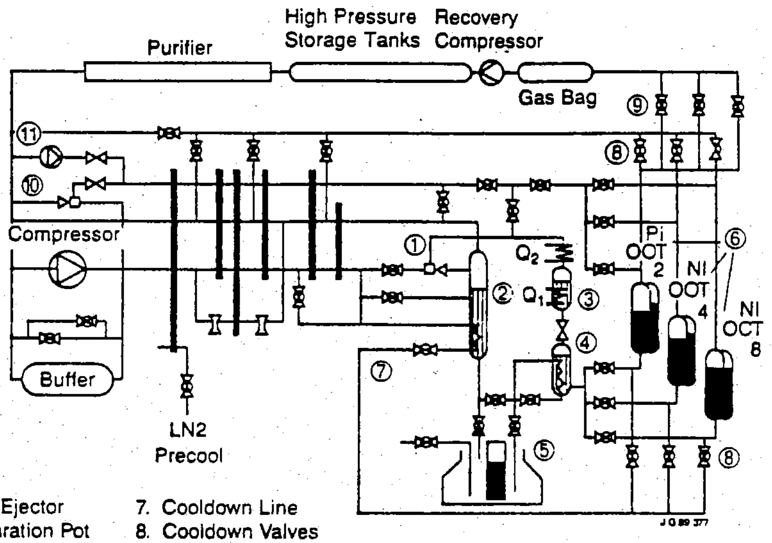
Pumping by fluid or vapor jets is widely used in process engineering due to their virtues of simple configuration and minimum investment costs but there is only limited experience available for cryogenic applications. At JET (Joint European Torus) a cold ejector is used to lower the pressure of the 3 large scale injector cryopumps. The Joule Thompson expansion of the He refrigerator provides free pumping capacity without additional power or external pumping sets. The performance of the ejector has been analysed in order to evaluate further potential pump capacity for future applications.

THE JET CRYOSYSTEM

The JET cryosystem consists mainly of a He refrigerator with a capacity of 800 W refrigeration or 250 l/h liquifaction which supplies LHe to 3 large cryopump systems. The layout of the cryoplant, its data and the cryopumps are described elsewhere [1] [2].

In order to minimise the thermal load of the cryopump system and to guarantee the pressure drop for the LHe supply over the upto 80m long cryolines [3], the exhaust of the cryopump has to be below the 1.3 bar compressor suction pressure and has to be ≤1 bar if Hydrogen is being pumped by the cryopump otherwise the thermal transpiration from the vapor-pressure of the condensed gas will contribute a considerable heat load to the cryopump and hence the refrigerator.

The basic flow diagram for the cryosystem is shown in Fig 1, Fig 2 gives an overview over the actual JET cryosystem.



1. Cold Ejector
2. Separation Pot
3. Calorimeter
4. Subcooler
5. LHe Tank
6. Cryopumps
7. Cooldown Line
8. Cooldown Valves
9. Bypass Valves to balloon
10. warm ejector
11. Roots Blower

Fig.1 JET He-plant flow diagram

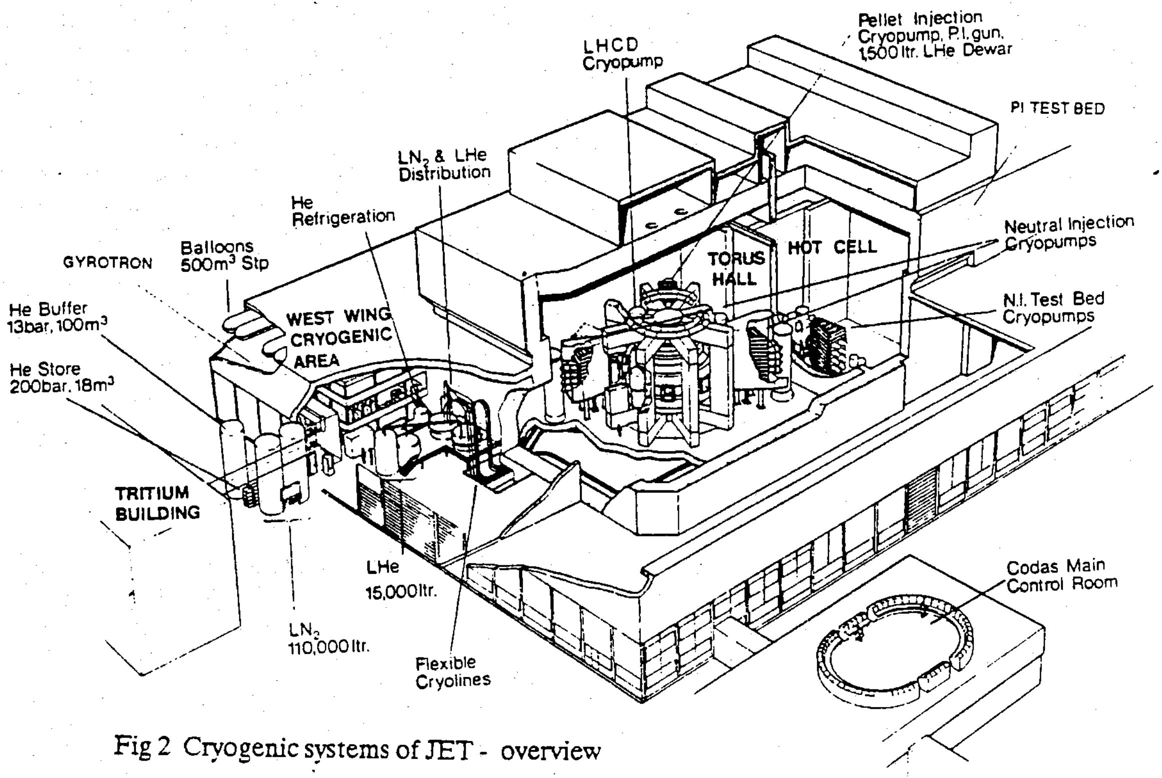


Fig 2 Cryogenic systems of JET - overview

LHe cryoplant	800 W / 250 l/h	3 Injector cryopumps		
He labyrinth compressor	160 g/s	pumping speed, each		8×10^6 l/s
		heat load, each	LHe	< 80 W
			LN2	< 250 l/h

Three different possibilities exist to pump the boil-off He gas from the cryopumps at pressures below the compressor suction pressure:

- mechanical vacuum pump, roots blower with interspace pumping in order to stop any oil contamination: Due to severe oil leakage problem this loop has never been used.

- warm ejector which is driven by a partial flow from the main compressor flow: This unit has been used when only a single cryopump was operational and the loss in refrigeration power due to the reduced flow through the plant was acceptable. In the stage of operation, the full refrigeration/liquifaction power is required and the use of the warm ejector was therefore abandoned.

- cold ejector which is driven by the expansion flow through the Joule Thompson nozzle: The operation of the JET cryosystem relies on this unit and it worked without problems over the last 2 years.

THE JET COLD EJECTOR AND THE TEST SET UP

Fig.3 shows the cross-section of the JET ejector with the main dimensions together with the experimental set-up and the used notation.

The He plant conditions for the tests are listed in Table 1. The ejector driving flow has been calculated from the inlet pressure and temperature to be approx $60 gs^{-1}$.

The high pressure He driving flow from the plant enters the ejector with the pressure P_{in} and temperature T_{in}, pumps the suction flow with the pressure P_{ej} and leaves the ejector with the pressure P_{out}. The two-phase flow from the ejector is separated in a separation-pot. The gas is routed back to the plant, a control valve on this flow keeps the pressure in the separation-pot constant and this pressure is practically the same as the ejector outlet pressure p_{out}. The liquid level in the separation pot is kept constant, any excess goes into the LHe tank which is kept at 1.5 bar pressure.

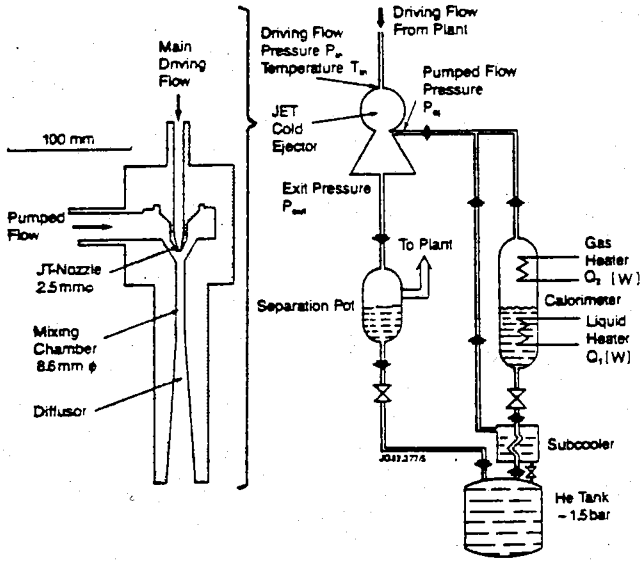


Fig.3 JET cold ejector and ejector measurement loop

Table 1 He - Plant conditions for ejector tests

compressor pressure out	12.5 bar
compressor pressure suction	1.25 bar
driving flow pressure p_{in}	12.1bar - 12.2 bar
driving flow temperature T_{in}	6.5K - 7 K
driving flow rate	appr. 60 g/s
ejector outlet pressure p_{out}	1.6 bar (...2.2 bar)
LN2 cooling	off (on)
Turbine speed	2700 - 3500 rpm
Heating power Q_1 (liquid)	0 - 300 W
Heating power Q_2 (gas)	0 - 200 W
suction mass flow m_{ej}	0 - 60 g/s
ejector driving flow m_{in}	appr. 60 g/s

For the experiments to measure the performance of the cold ejector, liquid helium is taken from the tank to a calorimeter via a subcooler and is evaporated by electrical heaters. The evaporated vapour can be further heated up with another set of heaters. The pressure at the ejector pump inlet is measured as a function of the heating power. Four different ejector suction flow conditions can be established:

vapour: keeping level in calorimeter constant at const. heater power Q_1

gas: as vapour but additional heating of the vapour by gas heater Q_2

liquid: keeping the supply valve to calorimeter at fixed opening without heating Q_1 or Q_2 such sending pure liquid plus flash to the ejector

liquid + vapour: as liquid but with heater Q_1 or Q_2 on.

TEST RESULTS

Effect of Outlet Pressure. Fig 4 shows the suction pressure of the ejector P_{ej} at constant heating power (for 50 W and 200 W) as a function of the outlet pressure of the ejector p_{out} which was varied from 1.6 bar to 2.2 bar. All other conditions were kept constant and were as in Table 1.

The suction pressure increases linearily with the ejector output pressure and the corresponding compression ration (P_{out}/P_{ej}) decreases accordingly from 3 to 2 for the 50 W case and from 1.9 to 1.7 for the 200 W case.

Vapour pumping. Fig.5. shows the measured suction pressure P_{je} as a function of the electrical heating power into the liquid of the calorimeter which was kept at 65%. All other parameters were the same as above and p_{out} was kept to 1.6 bar.

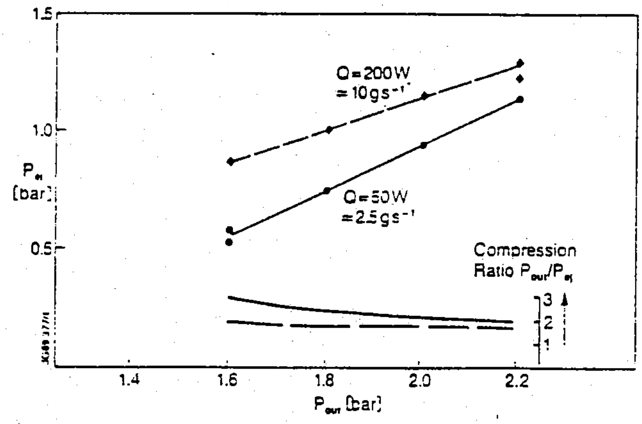


Fig.4
Ejector suction pressure and compression ratio as a function of the outlet pressure for two different vapour flow rates (different heating power)

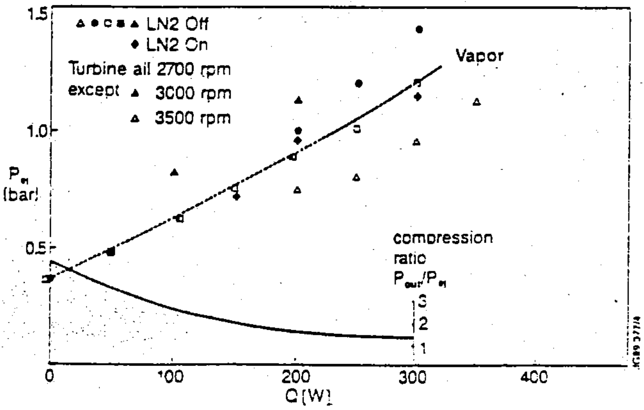


Fig.5
Ejector suction pressure as a function of the heating power of the vaporiser under different plant conditions

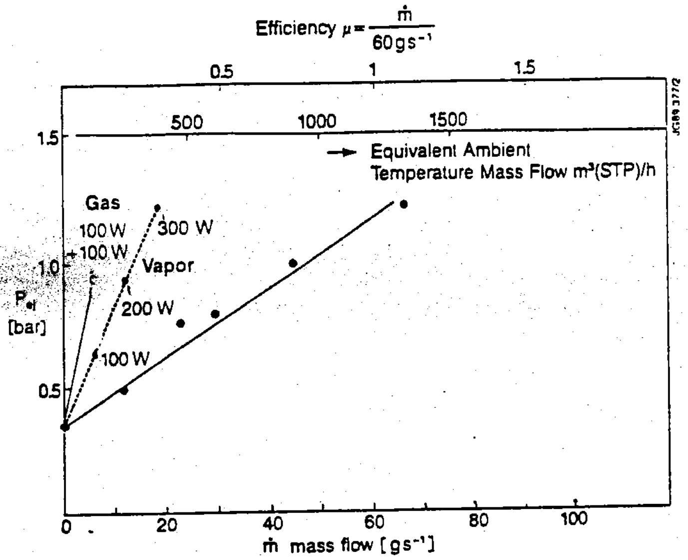


Fig 6
Ejector suction pressure as a function of the pumped mass flow for different suction flow conditions (gas, vapor, liquid, liquid/vapour) and pump efficiency

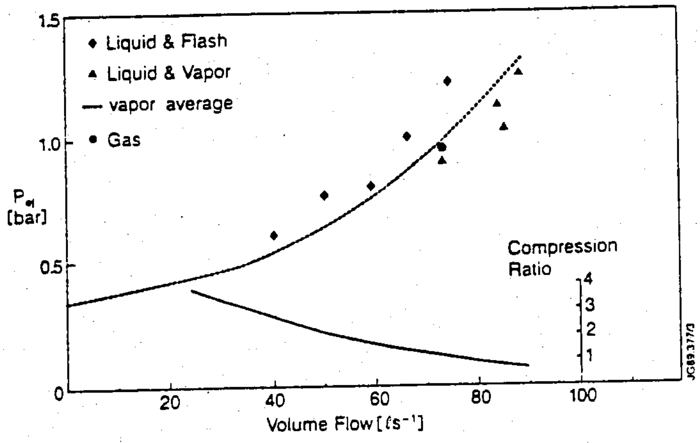


Fig 7
Ejector suction pressure and compression ratio as function of the pumped volume flow rate in litres/seconds

The ejector pressure increases linearily with the calorimeter power which is basically proportional to the flow rate plus a correction for the expansion losses from the 1.5 bar He of the tank to the ejector suction pressure.

The ultimate ejector suction pressure (at zero suction flow) is between 350 mbar and 450 mbar and the value increases to typically 1.2 bar for 300 W heating power. The figures show sets of data which were obtained over a period of 2-3 weeks whereas each set was recorded within a few hours with good reproductibility. It indicates the effects of the changes of plant conditions (liquifaction/refrigeration and others) on to the ejector performance.

The compression ratio shown in the same picture falls from 4.5 (no load) to 1.4 (300 W).

- LN2 Precooling: Switching from LN2 precooling to no precooling gave nearly the same results (allowing the system to settle for 2-3 hours before the measurements and after switchover).
- Subcooler: No difference in the ejector pressure could be observed whether the LHe was subcooled or not before entering the calorimeter.

Gas pumping. In another set of experiments, the boil off from the calorimeter was heated up by a second heater in the gas stream for various combinations of heat input into liquid and heat input into gas. The results show that the ejector pressure remains practically the same if the total power is kept constant.

Liquid pumping. For otherwise constant plant conditions, the supply valve to the calorimeter was set to a fixed opening, such supplying the ejector with liquid plus the unavoidable flash losses due to the expansion from the He tank pressure to the ejector suction pressure.

The mass flow was calculated from the valve manufacturers data sheet and found within 20% of the mass flow evaluated from the vapourization measurements (see above).

In Fig.6. the measured suction pressure p_{ej} is shown versus the mass flow $\dot{m}$ (g/s). It shows a linear increase of p_{ej} with $\dot{m}$. The same figure also shows the average valve for p_{ej} for the vapour and gas measurements from Fig.5. The mass flow is translated in the same figure into a pumping efficiency μ = suction flow/driving flow (60g/s) and also into an equivalent ambient temperature flow rate (m^3(STP)/h).

One can see that the pumping efficiency is the highest for the pumping of liquid and a value of over 1 could be achieved which represents a pumping capacity of 60 gs^{-1} at 1.1 bar. This pumped mass flow represents in terms of an equivalent ambient temperature flow, a flow rate of over $100m^3$ (STP)/h which would be the required size of a corresponding mechanical pump with the same performance.

Liquid and vapour pumping. Under the same conditions as above, the liquid flow was partially evaporated by heater Q_1 and/or Q_2 and no difference was found as long as the total power was the same.

With increasing heating, the ejector suction pressure p_{ej} increased. In order to obtain a consistent graph, the measured p_{ej} was plotted in Fig.7 for the liquid and liquid/vapour mixtures as a function of the volume flow (ℓ/s).

The measurements for the vapour and for the gas are also shown in Fig.7 (for easier analysis, only the average data is shown - dotted line).

The plot of p_{ej} versus the volume flow shows that practically for all flow conditions (gas, liquid, vapour, liquid/vapour) the same suction pressure is obtained as long as the volume flow is the same.

DISCUSSION

The performance of an ejector pump can be theoretically described by analysing the balance of the momentum energy and flow under the prevailing condition in the expanding flow (for more details see [4] [5]). However, the results of such theoretical approaches are not always satisfactory and most ejectors are rated by scaling from existing ejector data.

The measurements confirm the expected scaling of the ejector suction pressure with the volume flow of the pumped medium (gas, vapour, liquid, liquid vapour). This e.g. explains that p_{ej} remains practically the same whether the same heating power is used to vapourize fully liquid or vapourize only partially liquid and to warm up this vapor. In both cases (high mass flow/low temperature or small mass flow/high temperature) the resulting density and hence the volume flow is similar.

The results from Fig 4-7 allow to scale the existing ejector performance for further cryostats at JET which are planned for the near future.

OPERATIONAL ASPECTS EXPERIENCE WITH THE COLD EJECTOR

The three large cryopump systems have been running continuously with the cold ejector for more than 2 years. No repair or maintenance has been necessary so far on the cold ejector and no problems with the operation of the ejector have occurred apart from one blockage on the suction filter due to icing up. This was due to insufficient purging of the cryoplant after a shutdown.

For the various different operation conditions of the JET cryopumps such as cooldown, regeneration, warm up and continuous operation the cold ejector is used as follows:

Continuous Operation. The flow from the 3 large cryopump systems is approximately 3 gs^{-1} per pump (including the sub-cooler flow) and about 80 W per pump has to be taken into account for the heat inleak including the supply and transfer system.

With 3 cryopumps running the ejector suction pressure is typically between 700-800 mbars absolute depending on the actual conditions in particular the actual opening of the LHe supply valves to the cryopump but also on the actual condition of the cryoplant. With 1 and 2 cryopumps we find approximately 500 mbars and 600 mbars respectively, the ultimate pressure with no load is approximately 350 mbars.

The pressure of the cryopumps is usually kept to just above atmosphere by a controlled return valve. This is in order to minimise the risk of an air inleak into the close LHe loop of the cryopumps.

Cooldown and Fill. For the cooldown of a cryopump from ambient the cold ejector is not involved. Most of the cooldown (down to ∿100K) is usually, but not necessary, achieved by radiation exchange with the LN2 cooled radiation screen which can be enhanced by admitting some gas into the vacuum chamber as contact gas (typically 10^{-1} mbar). The cooldown to 4K is then achieved by a dedicated high pressure cooldown loop as shown in the flow diagram (Fig.3) where the return gas goes directly back to the main compressor at 1.3 bar. The valve between the separation pot to the LHe tank is closed hence the full power of the plant for the cooldown. The operational cryopumps are supplied direct from the LHe tank during the cooldown. The cryopump can also be filled with this loop. After filling the LHe supply is switched to the LHe tank (1.5 bar) the return is sent for approximately 10 minutes to the recovery system (balloons at atmospheric pressure). After this settling time, the return is connected to the cold ejector hence guaranteeing that the inlet pressure does not get spoiled and that the operation of the other cryopumps is not jeopardized.

<u>Regeneration</u>. The regeneration process runs through 4 phases:

Emptying cryopump
Desorption of condensed gas
Pumpdown of desorbed gas
Cooldown and refill with LHe

The routine operation is to start the regeneration by closing the LHe supply valve. The system is left under this condition with the He boil off to the cold ejector until the pressure falls to a pre-set level (usually 20% - a level where the pump is still stable). This allows recovery of most of the LHe inventory back into the clean He loop of the cryoplant. Subsequently the return valve is closed and the cryopump is pressurised to typically 2 bar. This decouples the regenerating cryopump from the others and it also increases the temperature of the cryopump resulting in a rapid release of the gas condensed on the pump. The He return goes to the balloon if the pressure exceeds 2 bar.

After desorption of the cryopumped gas the vacuum vessel is pumped down by conventional mechanical pumps to approximately 10^{-1} mbar and the loop of the cryopump which is in the meantime close to LN2 temperature is cooled down and refilled as described above.

<u>Emergency Pressure/Flow Peaks</u>. Under certain fault conditions the boil off or return pressure of a particular cryopump can increase substantially which could spoil the operation of one of the other cryopumps. To avoid any cross talk each cryopump has an individual pressure control valve between the return and the cold ejector and also a non-return valve which prevents any back pressurisation. Any pressure increase is released via a separate bypass valve to the recovery system (balloons at atmospheric pressure).

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