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Mechanical pumping at low temperature

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This novel concept consist of a mechanical pump able to run at low temperatue (25K). Since gas density varies inversely with temperature, this pump would deliver much higher mass flow rate than at room temperature for a given size. Advantages of this concept are order of magnitude reduction in size, weight, when compared to a conventional pump scaled to perform the same mass flow rate at room temperature. This pump would be a solution to allow continuously tritium extraction and minimize the mass inventory.

1. INTRODUCTION

Next step tokomaks will require the development of large tritium compatible high vacuum pumps. In large tokomak, such as the international tokomak experiment reactor (ITER), the plasma exhaust containing deuterium, tritium and a fraction of 5% helium must be pumped off in the burn and dwell regime.The mass flow is 1000 mbarl/s at a pressure of 5 10^{-3} mbar. To date to meet this requirements the developments are essentially cryopumps [1] and turbomolecular pumps working at room temperature [2].

This paper gives the results obtained at low temperatures (80K and 25K) with a molecular drag pump Holweck type (MDP) of 100 mm diameter and with few stages of a turbomolecular pump (TMP) *running at the same temperatures. It* describes also an engineering solution for ITER which minimizes the scale-up and the tritium inventory.

2. EQUIPMENT

To perform experiments, we used an electrical motor designed to work at T<80 K. This driven unit runs with active magnetic bearings in the range of 15000 to 24000 rpm (250 to 400 Hz). These bearings permit to limit the radial displacement within 0.05 mm, fully compatible with a MDP working with small clearance (0.15 mm) between the wheel and the stator In such a pump a smooth wheel is rotating at high speed (20000 rpm) inside a stator with helicoidal grooves drilled in it.

A MDP seems well adptated for runnig at low temperature in the pressure range of 5 10^{-3} mbar to 5 10^{-2} mbar. The figure 1 gives a schematic draw of the MDP and the main parameters are summarized as follows :

Channels number = 10
Inlet cross section = 10 mm *6.12 mm
Outlet cross section = 10 mm *0.25 mm
Developed length = 286 mm
1st stage gap : 0.23 mm 2nd stage gap : 0.17 mm

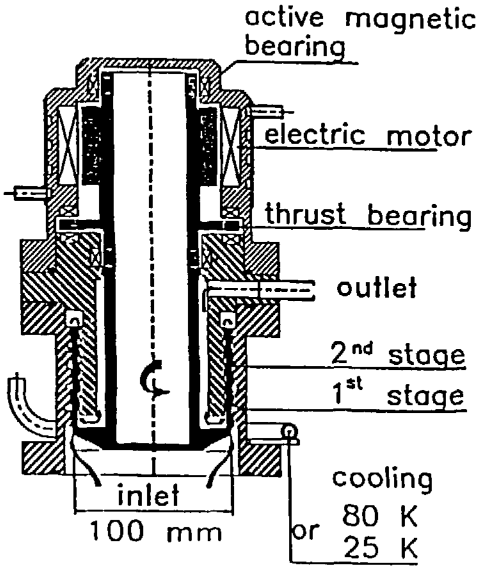

Figure 1 2 stages MDP tested geometry.

On the same driving unit we tested a TMP with 4 compression stages (22° angle blade) and one impeller stage (35° angle blade). The low temperatue running was easier because the axial clearance between the static and movable blades is 0.6 mm, and the radial one for the same piece is 0.6 mm on the radius.

A test facility has been set on to insure the mass flow rate measurement of helium, deuterium, hydrogen, and mixtures He-D_2 at different temperatures (25 K, 80 K, 300 K) and the pressure at the entrance and the exhaust of the pump.The mass flow rate was measured by pressure decrement in a reference volume and the pressures by absolute gauge (Baratron).

The aims of this work were to compare MDP characteristics with results given by a monodimensional computer code and to test few stages of turbomolecular pump at low temperatures.

3. COMPUTER CODE

In a molecular drag pump (MDP) the flow can be described by the superposition of two typical flows Couette flow and Poiseuille flow.

These flows are governed by the Navier-Stokes equations :

$$\vec{Grad}\ P + \nu . \vec{Rot}\left(\vec{Rot}\vec{V}\right) = 0 \qquad (1)$$

where: P is the pressure.

ν is the viscosity which is only temperature dependant.

V is the fluid velocity.

The other hypothesis are : Couette flow is independant of flow regime, compression process is isothermal, gas is perfect (PV=nRT), flow is stationary.

Mass flow rate balance is given by :

$$Q_M = Q_d - Q_c - Q_l \qquad (2)$$

where Q_M is the exhaust flow, Q_d is the Couette flow, Q_c is the Poiseuille countercurrent flow in the channel, Q_l is the Poiseuille countercurrent flow in the gap (annular section). Q_c and Q_l are independant one from the other. The model is one dimensional. The description of gas flow in vacuum systems depends on value of a dimensionless parameter called the 'Knudsen number'(ratio of the mean free path to a characteristc dimension of the channel K = λ/a). Knudsen has established an empirical formula to describe the flow rate from molecular regime to viscous regime.

$$Q = Q_{Viscous} \cdot \left(1 + \frac{64}{3\pi} Z \frac{\lambda}{a}\right) \qquad (3)$$

where Z is Knudsen function [3]. Its value varies between 0.8 and 1. This correlation was used for the countercurrent flow (Q_c) and the leak flow (Q_l). $Q_{viscous}$ is calculated by assuming the real conditions (pressure, temperature, viscosity) [3-4].

4. DISCUSSION OF THE MDP RESULTS

4.1. Comparison : calculations and experiments

The analysis of the results obtained with two stages drag pump shows that the calculations agree very well with the experiments when a pure gas is pumped (margin less than 20%). The figure 2 shows the mass flow rate relation versus inlet pressure and temperature. The rule of flow rate directly proportional to the gas density is verified within the performed experiments in the 5 10^{-3} mbar to 5 10^{-1} mbar range.

$$\frac{Q(T)}{Q(300K)} = \frac{300}{T} \qquad (4)$$

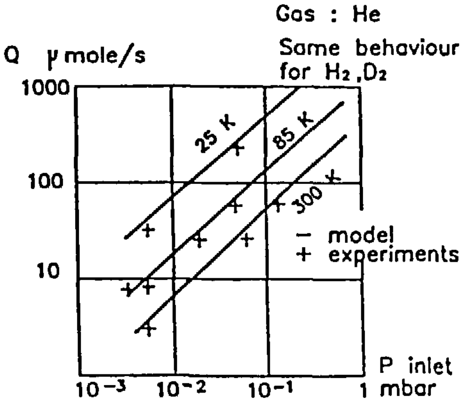

Figure 2 Mass flow rate versus inlet pressure.

4.2. Viscosity influence

Two gases deuterium and helium have the same molar weight (M = 4 g/mole), but their viscosities are very different (at 25K He 4.02 10^{-6} Pa.s and D_2 1.95 10^{-6} Pa.s).

It clearly appears that at the same conditions (T, Q_M, Pinlet) pressure ratio (τ) and maximum mass flow rate are higher for the most viscous gas, as well predicted by the numerical model as shown in table 1.

Table 1

Mass flow rate (Q_M) or pressure ratio (τ) for He and D_2 gases at 5 10^{-2} mbar pressure inlet and 25K

	Q_M µmole/s	τ
helium	70	20
deuterium	70	10
	Q_M µmole/s	τ
helium	160	6
deuterium	100	6

4.3. Available outlet pressure

At low inlet pressure (5 10^{-3} mbar) the outlet pressure is as higher as the temperature is low. On the contrary for higher inlet pressure (e.g. 5 10^{-1} mbar), some optimum temperature level appears. This effect is well predicted by the numerical model and is confirmed by experiments. See figure 3 for helium gas.

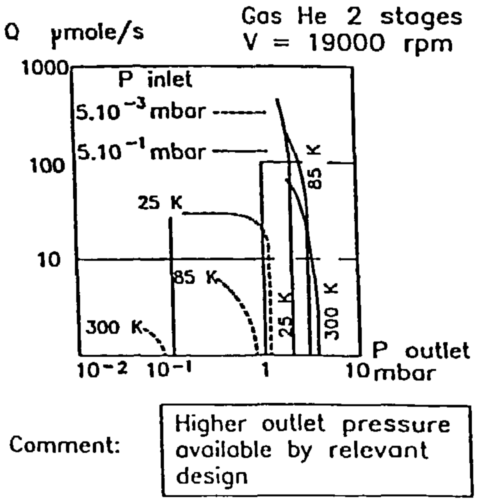

Figure 3. Mass flow rate versus outlet pressure.

5. DISCUSSION OF TMP EXPERIMENTS

For an inlet pressure of 5 10^{-3} mbar and for all tested gases, the mass flow rate or the pressure ratio increment are noticiable at low temperature as shown for He at 21600 rpm on figure 4. The flow rate improvement is difficult to quantify due to the experimental limitation. For this pressure at 300 K the flow regime is molecular and at lower temperatures (85K or 25K) the regime becomes in transition range or viscous.

A pressure ratio improvement is observed for all gases and all investigated inlet pressures when the temperature decreases. Table 2 gives an example for helium gas .

Table.2

Pressure ratio (τ) for helium versus temperature and inlet pressure

Temp. K	25	85	300
P inlet	τ	τ	τ
10^{-3} mbar	32	16	3
5 10^{-3} mbar	12	10	4.6
10^{-2} mbar	6.5	7.2	4

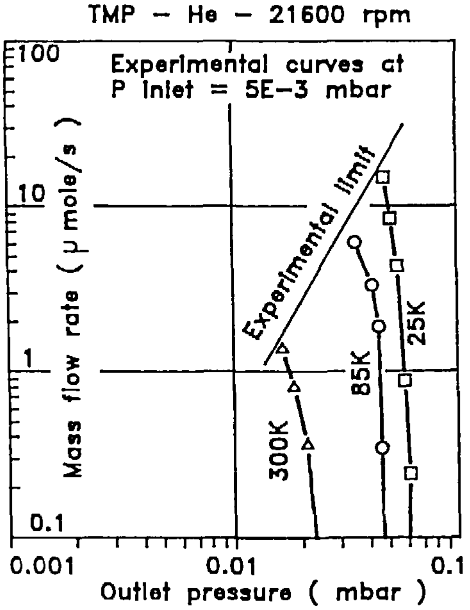

Figure 4. Mass flow rate versus outlet pressure

For TMP working at low temperature is especially helpfull because the mass flow rate and the pressure ratio are both increasing.

6. POSSIBLE APPLICATION

From such very encouraging results, an advanced pump unit can be proposed for the ITER project, it associates a few stages TMP and MDP. By assuming the mass flow rate is proportional to the inverse temperature ratio, a working temperatue of 25K gives an increment by a factor of 12 with respect to 300K operation. In the MDP to reach some optimum for outlet pressure, a temperature gradient has to be associated with the pressure gradient

Such kind of pumps can be assembled in double flux operation (figure 5) to withstand sudden venting. As an example 250 mm diameter set operated between 25 K and 300K running at 24000 rpm would be able to pump 25 mbarl/s mass flow rate from 1 10^{-3} mbar inlet to 10 mbar exhaust pressure. (50 pumps needed for ITER burn and dwell regime). This set is formed with a TMP stage and three MDP stages working at 25, 85, 300K.

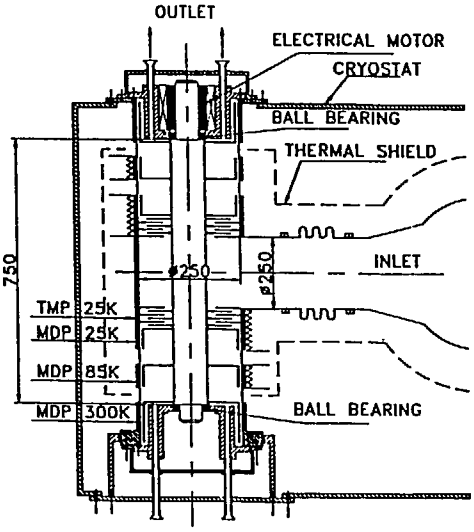

Figure 5 Schematic layout of ITER pump.

7. CONCLUSION

Croymechanical concept has been experimentally demonstrated. Mechanical pumping of predensified gases at low temperature exhibits the possibility to extract plasma light gases mixture with very high flow rate at convenient pressure.

Application to the ITER project seems very attractive by comparison to the previously developed solutions. The last key issue to be demonstrated is the capability to operate running parts (presumably non metallic) at high rotating speed whatever the magnetic field influence around a tokomak machine.

8. ACKNOWLEDGEMENTS

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