The expansion ejector, a new cryogenic device

In recent years the need for continuous generation of cold at temperatures between 2 and 4 °K, and for liquid helium, has grown rapidly. In particular, developments in the field of computers, cryogenic stores, masers, superconductors, etc., present a challenge to cryogenic engineers to carry out refrigeration and liquefaction in this temperature range as simply and efficiently as possible.

Ever since interest was aroused in the liquefaction of gases the Joule-Thomson process has played a predominant role. It still is, in fact, the only process of practical importance for continuous refrigeration at temperatures of a few degrees Kelvin. In this process the gas passes through a cycle in which it expands from a high to a low pressure through an expansion valve (throttling). Provided the initial gas temperature is below the “inversion temperature” the expanding gas is cooled.

The Joule-Thomson cycle is sketched in fig. 1. After compression at room temperature by the compressor C, the gas at the high pressure $p_1$ flows through precoolers $P$ and heat exchangers $H$ to the expansion valve $E$. On leaving the expansion valve the gas at the low pressure $p_2$ flows through the heat exchangers back to the compressor. The precoolers cool the gas to below its inversion temperature and the high pressure input gas to the expansion valve is continuously precooled in the heat exchangers by the low pressure exhaust fluid $P_{11}$. Eventually the temperature is reduced below the gas liquefaction temperature and the condensed fraction of liquid is separated out in $V$; it can either be evaporated (for producing cold) or tapped off (liquefaction).

It is inherent in this cycle that the pressure $p_s$ at the suction side of the compressor is equal to $p_2$ or even less, owing to the flow resistance in the heat exchangers. The vapour pressure of helium drops rapidly with temperature, so that a very low suction pressure is required if liquid helium is to be produced at lower temperatures (fig. 2a). If we consider this together with the fact that a compressor for a given delivery will be larger for a lower suction pressure, while the input power increases with decreasing suction pressure, it becomes evident (see fig. 2b) that at temperatures of 3.5 °K or below, an excessively large compressor is required. The compressor required to achieve a given refrigerating capacity at 2.5 °K is ten times as large as at 4.2 °K.

Investigations carried out in this laboratory have shown that this problem can be solved by a simple modification of the Joule-Thomson cycle. The central element of the modification is a device which we have called an expansion ejector.

First of all, we note that the conventional throttling...
Fig. 2. a) The vapour pressure curve of helium, i.e. the pressure \( P_2 \) as a function of \( T_2 \) when there is liquid in \( V \) (fig. 1). \( P_s \) suction pressure of the compressor in fig. 1. It is assumed that the pressure drop \( P_2 - P_s \) across the heat exchanger is constant at 0.1 bar for all temperatures. b) Input power (curve 1) and the dimensions (curve 2) of the compressor as a function of the required temperature \( T_2 \) in \( V \), compared with the values at 4.2 °K.

The process is not really very efficient. This may be seen by considering throttling through a small aperture (fig. 3). The high-grade energy which the gas has as a result of the high pressure \( P_1 \) is then first converted into directed kinetic energy (a "jet"). This directed kinetic energy is not however utilized as work or tapped off, but dissipated (converted into non-directed kinetic energy, i.e. heat). This cancels out a substantial amount of the expansion cooling in the gas, and it is only on account of certain specific properties of the gas that any cooling effect below the inversion temperature remains. The great advantage of the expansion valve, however, is its extreme simplicity. In this it is unlike isentropic expansion which, although in principle much more effective, requires an expansion machine with moving parts. (With an ideal gas throttling would have no cooling effect, but there would be a cooling effect with isentropic expansion.)

The principle of the expansion ejector is the making use of this directed kinetic energy, which was previously wasted, to create suction power by jet action, rather like the action of a water jet pump. This suction power can then be utilized to achieve a lower temperature using the same compressor.

The modified cycle is sketched in fig. 4. Part of the

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\text{Fig. 3. Illustrating expansion through a small orifice.}
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\text{Fig. 4. The modified Joule-Thomson cycle. In addition to the primary cycle I there is a secondary cycle II. The expansion ejector EE throttles the fluid in the primary cycle and at the same time compresses the fluid in the secondary cycle from } p_{1} \text{ to } p_{2}. \text{ In } V' \text{ the fluid is throttled in the secondary cycle. The pressure } p_{2} \text{ in } V' \text{ can now be substantially lower than the suction pressure } p_{s} \text{ of the compressor.}
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Fluid in the vessel $V$ is fed into a second vessel $V'$ through an expansion valve $E'$. The action of the expansion ejector then reduces the pressure in $V'$ to $P_3$, which is much lower than $P_2$ in $V$, so that the temperature $T_3$ is likewise considerably lower than $T_2$. This permits the suction pressure $P_s$ of the compressor to differ from the vapour pressure $P_3$ at the required low temperature $T_3$. The parts of the expansion ejector can be seen in fig. 5. Here 1 is the jet nozzle, 2 is the suction region, 3 is the mixing zone and 4 the diffuser. The expansion ejector thus acts at the same time as an expansion valve (between $P_1$ and $P_2$) and as a "jet compressor" (between $P_3$ and $P_2$).

The principle described can be used in two ways:

a) In a machine for continuous refrigeration at extremely low temperatures. A machine of this kind operates with a closed cycle: no liquid helium is tapped off, and so helium has to be supplied. In an experimental arrangement with a pump suction pressure of 1 bar an expansion ejector suction pressure of about 50 torr has been achieved, which corresponds to a temperature $T_3$ of 2.3 K.

b) In a liquefier. The liquid helium is tapped off and in the compressor gaseous helium has to be supplied to the system. The helium is tapped off at $P_3 = 1$ bar. The suction pressure $P_2$ can now be 2.5 to 3 bar, so that at $P_1 = 20$ bar the compressor need only have a compression ratio of $20/3$ instead of 20, as required in the conventional cycle. A helium liquefier based on this principle is now being marketed by Philips[1].

The expansion ejector can not only be put to use in systems like that of fig. 4, but in all refrigerating processes employing an expansion valve, for example in processes where the refrigeration is produced partly by expansion machines.

It is interesting to note that any positive effect of the expansion ejector means pure gain with respect to a normal expansion valve, as the ejector cannot perform less efficiently than such a valve. Studies aimed at deriving the optimum design of expansion ejector are being pursued in this laboratory.

The advantage of the expansion ejector can be summarized as follows. A required amount of cold can be produced at a given temperature more efficiently and with simpler means (i.e. a smaller compressor) than when only an expansion valve is used. The expansion ejector itself is an extremely simple device; it has no moving parts and is no larger than a matchbox.

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[*] A description of this helium liquefier is to appear later in this journal. Ed.