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Design and component development of a 17 l/d liquefier for helium recondensation

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Abstract. This paper describes the design and component development of a 17 l/d liquefier for helium recondensation. The liquefier uses an oil-free linear motor compressor with suction and discharge pressures at 1 and 22 bar respectively. The liquefier is a hybrid cryocooler consisting of an interchanging component made up of recuperative heat exchangers, an 80 K pulse tube cooler (PTC) and a 25 K two stage PTC. The cooling powers required of the PTC's are 14.2 W at 80 K and 1.6 W at 25 K. The primary cooling mechanism is two stage J-T expansion at 22 bar and 11 bar resulting in liquefaction with a liquid fraction of 0.19. This corresponds to a cooling power of 0.54 W at 4.2 K and a liquefaction rate of 17.8 litres per day. An overview of the design and development of the PTC's, heat exchangers and JT valves is presented.

1 Introduction

A zero-loss helium cryostat can be realized by recondensing the boil-off generated during the cryostat's operation. A novel recondensation system is envisaged using a hybrid cryocooler consisting of Stirling-type pulse tube coolers and Joule-Thomson expansion. Such hybrid cryocoolers are also being investigated to provide cooling near 4 K for space applications [1, 2, 3]. This paper describes the design and component development of a 17 l/d hybrid cryocooler(liquefier) for helium recondensation. First, the process flow is described, followed by a discussion of the development of recondensation system components.

2 Process flow diagram

The recondensation system (Fig. 1) includes a heat exchanger called the recondenser that is interfaced to the cryostat. In the recondenser, a thin film of liquid helium at appropriate temperature is formed to absorb the heat from the boil-off vapours, thus recondensing them back to liquid phase. The liquid film is obtained by precooling helium in a network of six recuperative heat exchangers along with two stages of Joule-Thomson expansion. The inlet and outlet temperatures of both the high-pressure forward stream and low-pressure return stream of the heat exchangers are also shown in the Fig. 1.



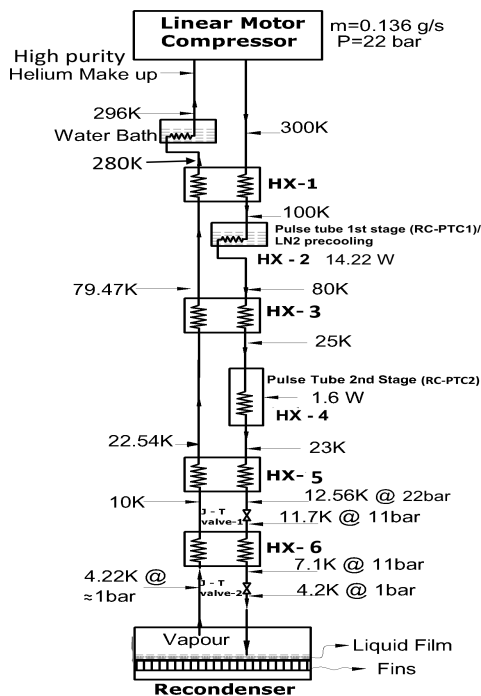


Figure 1: Schematic flow diagram of the recondensation system.

A linear motor driven compressor supplies pressurized oil-free helium gas to the heat exchanger network. The compressor sucks in the low-pressure helium gas from the return path of the heat exchanger network and discharges high-pressure helium gas at 22 bar, at a mass flow rate of 0.136 g/s. This high-pressure helium gas forms the forward path as it flows in the tube side of heat exchangers 1 to 5. Heat exchangers HX-2,4 are interfaced to pulse tube cryocoolers. This results in precooling the gas to a temperature of 12.56 K, which is below the inversion temperature of helium at 22 bar. Then, the gas undergoes isenthalpic expansion to 11 bar and flows to heat exchanger HX-6. The second isenthalpic expansion to 1 bar results in liquefaction and liquid helium film at 4.2 K is formed in the recondenser. As a result of the heat exchange with the boil-off from the cryostat, the liquid film evaporates and flows back as low-pressure return stream to the compressor, thus completing the helium refrigeration loop.

3 Recondensation system thermodynamics

The pressure-enthalpy diagram of the recondensation system is shown in Fig.2. Before the first JT expansion the helium stream is at 12.56 K and a pressure of 22 bar. As a result of JT expansion the helium gas is cooled to 11.7 K. This is followed by cooling to 7.1 K and JT expansion 2 resulting in condensation of helium with a liquid fraction of 0.19[4]. If a single JT expansion was done from 12.56 K and 22 bar to the recondenser pressure of close to 1 bar, it would not have resulted in condensation.

The total pressure drop in the return path of the heat exchangers plays an important role in determining the recondensation pressure. If the pressure drop is high the recondenser pressure has to be high to drive the helium gas to the compressor suction port. Higher recondenser pressure results in an increase recondenser temperature as shown in Fig. 3, thus determining the final temperature of the cryostat.

As the system flow rate is 0.136 g/s the liquefaction rate will be $0.136 \times 0.19 = 0.02584$ g/s or 17.86 liter per day equivalent to a cooling power of 0.5 W at 4.2 K.

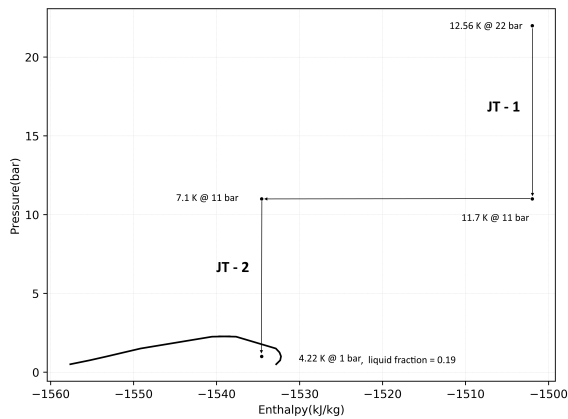


Figure 2: Pressure-Enthalpy diagram of the recondensation system

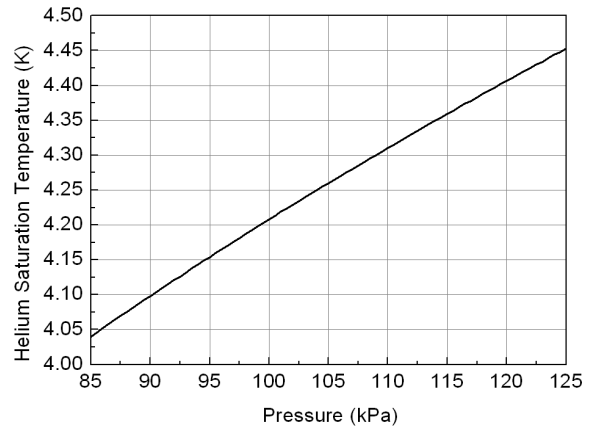


Figure 3: Variation of recondenser temperature with pressure

4 Recondensation system components

4.1 Compressor for the helium gas

The compressor was custom built for the recondensation system by CFIC Qdrive(Fig.4). Flexure bearing technology was used in the compressor for oil-free operation. The compressor consists of two linear motors driven by STAR motor drives in a dual opposed balanced configuration to reduce vibration. Figure 5 shows the compressor characteristic curve. The best operation conditions are 22 bar and 55 slm. The compressor is strong and stable. It delivers repeatable performance over long periods on the order of many hours during test and parameter validation studies.

4.2 Pulse tube coolers

The recondensation system uses two pulse tube coolers denoted as RC-PTC1 and RC-PTC2 in the Fig. 1 to precool the helium gas. The cooling powers required of RC-PTC1 and RC-PTC2 are 14.22 W at 80 K and 1.6 W at 25 K respectively. Alternatively liquid nitrogen can be used instead of RC-PTC1. Development of RC-PTC1 is discussed in Ref. [5].



Figure 4: Oil free compressor for the Recondensation system.

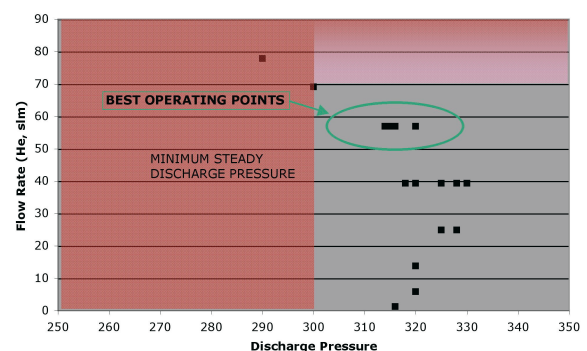


Figure 5: Compressor performance.

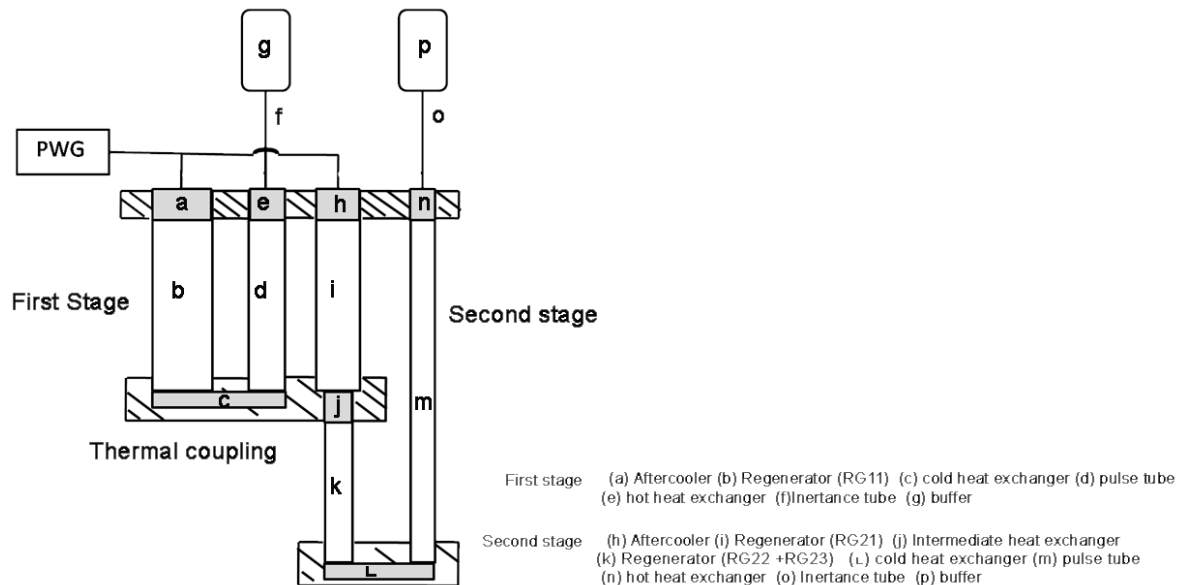


Figure 6: Twin pulse tube cooler.

A twin pulse tube cooler (RC-PTC2), shown schematically in Fig.6, was designed using SAGE software to provide the cooling at 25 K [6, 7]. It is a thermally-coupled cooler where two cooling stages are driven by the same pressure wave generator (PWG). Using 900 W of maximum deliverable PV power from the PWG (CFIC 2S175W), the twin cooler design cooling powers are 2 W at 25 K and 11.5 W at 80 K. The cooling power at 80 K can be used to complement RC-PTC1 in supplying the recondensation system requirement.

4.3 Heat exchangers and Joule-Thomson valves

Heat exchangers are crucial to the recondensation system and need to be compact and highly effective. Also, it is imperative that the pressure drop in the low-pressure side is as small as possible in view of the discussion in Sec.3. The heat exchangers were designed using the NTU-Effectiveness method. A custom FORTRAN code was developed for calculating the heat transfer and pressure drop [5]. The heat exchangers were of a tube in tube design with a nylon string used to achieve uniform spacing between the tubes. The inner tube along with the spacer string was inserted into the outer tube. Then the tubes were coiled to the particular mandrel diameter chosen to facilitate concentric arrangement of the heat exchangers. The thermal and physical parameters of the heat exchangers are summarized in Tab.1 and the heat exchangers are shown in Fig.7.

The JT valves were designed and built in-house (Fig.8). Using the formula given by [8], the orifice sizes required for JT expansion from 22 bar to 11 bar and from 11 bar to 1 bar were estimated to be 150 and 135 μm respectively. Details of internal construction are given in Ref. [5].

5 Conclusion

A novel helium recondensation system has been designed with a liquefaction rate of 17.8 liters per day. This corresponds to a cooling power of 0.53 W at 4.2 K. The recondensation system

Table 1: Summary of the thermal and physical parameters of the heat exchangers.

	HX1	HX3	HX5	HX6
High pressure stream				
Inlet temperature (K)	300.0	80.0	23.0	11.7
Outlet temperature (K)	100.0	25.0	12.6	7.1
Low pressure stream				
Inlet temperature (K)	79.5	22.5	10	4.2
Outlet temperature (K)	279.6	79.5	22.5	10.0
Length of tubes (m)	15	34	14	5
Weight (kg)	3.25	4.00	2.60	1.56
Theoretical effectiveness	90.7	95.7	80.0	61.3

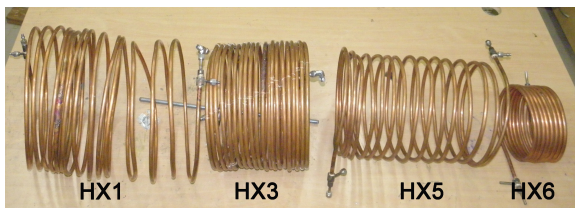


Figure 7: Heat exchangers.

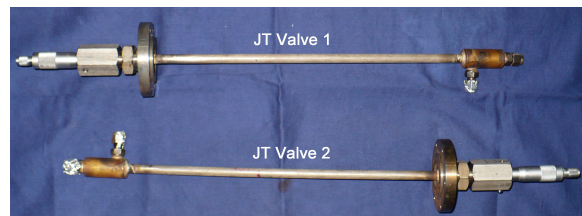


Figure 8: JT valves.

is a hybrid cryocooler with Stirling-type pulse tube cryocoolers and Joule-Thomson expansion. The recondensation system components have been designed and fabricated. The optimization of the twin pulse tube cooler and recondensation system integration is in progress.

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