Development of Cold Box for Upgradable Helium Refrigerator Plant of 200 W at 4.5 K

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Abstract. The cold box for helium refrigerator plant of cooling power ~200 W at 4.5 K has been developed at IPR, Gandhinagar, India. Helium compressor system, which gives helium flow ~60 g/s at 14 bar, has been used for this plant. The cold box of the plant is made using a vertical vacuum chamber, within which all cold components are assembled. The thermodynamic process used is a modified Claude Cycle. This cold box has 7 plate-fin heat exchangers, 3 turbo-expanders, an 80 K helium purifier and a JT valve. LN2 pre-cooling is used in the cold box to ensure 80 K before the helium purifier. Turbine-1 and 2 are warmer ones and are connected hydraulically in series. The 3rd turbine is colder one and is in series with JT valve. This plant, due to certain reasons, has been developed using components made for other purposes. Later, based on the detailed process analysis and optimization, it was found that if only 7th heat exchanger, the coldest one, is replaced by a higher capacity, cooling power of the plant can be improved significantly. Similarly, there are other possibilities to upgrade it up to cooling power ~1 kW at 4.5 K. Hence, provision was kept for up-gradation to a plant of higher capacity with different modes of cooling. The architecture of this layout has been developed and implemented indigenously. Details of the design concept of the cold box and experiences of initial operations will be discussed in this paper.

1. Introduction

The helium refrigerator (HR) plant being developed at IPR, Gandhinagar, India has initial design target of cooling power 200 W at 4.5 K and 600 W at ~18 K, when operated in respective refrigeration-only mode. Provisions have been kept to upgrade it to higher cooling powers with liquefaction-only mode and simultaneous operation of these 3 different cooling modes.The process flow diagram of Figure 1 shows the arrangement of different process components after inclusion of LHe extraction provisions with original planned HR plant making it helium refrigerator-cum-liquefier (HRL) plant. The picture of assembled vertical cold box is shown in Fig-2. It has one compressor, 7 plate-fin heat exchangers (HE), 3 helium turbines and one helium purifier. Thermodynamic cycle used, is based on the modified Claude Cycle. Due to certain constraints, the refrigerator plant has been made using components, which were originally meant for other purposes. A suitable combination has been made using these, to get maximum cooling power. Turbines were originally procured for HR plant of refrigeration power 1 kW at 4.5 K, Plate-fin HEs and 80 K purifier were made for helium flow rates of 30 g/s as prototype (1/4th scale) components of 1 kW HR plant. Helium compressor, developed by using an open-loop air compressor, can provide helium flow ~60 g/s at 14 bar and it was meant to use for testing prototype cryogenic components. Isentropic expansion efficiency of turbines goes down

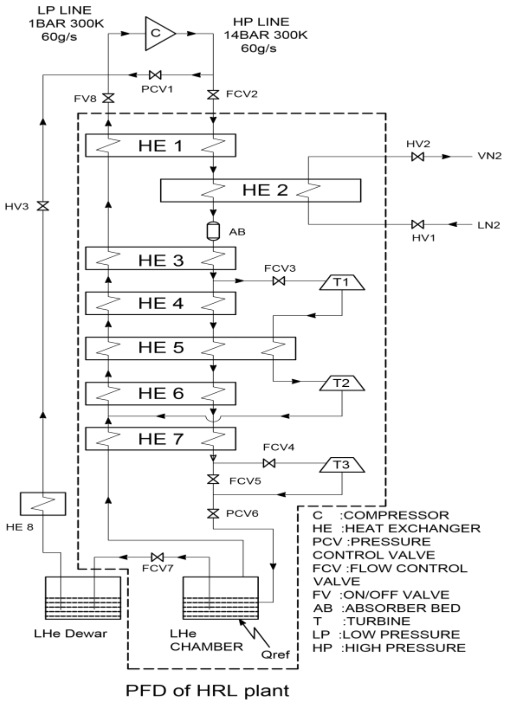

Figure 1: PFD of HRL plant

Figure 2: Picture of assembled cold box

significantly when operating parameters are away from the designed ones. But appropriate P, T and $\dot{m}$ combinations were made to provide good efficiency. For HEs, as the flow rate is ~2 times of the designed ones, heat load is also doubled and hence performance is reduced, although to good extend, it gets compensated due to increase of heat transfer coefficient with increase of flow rate. Pressure drops becomes about 4 times of design values. These prototype HEs and purifier were designed to have low pressure drops and hence it came out to be less problem to use in the helium plant with this higher flow rates. Based on plant process analysis using these components, target cooling power was kept 200 W at 4.5 K. Up-gradation provision to use HEs of higher heat duty for higher cooling power, up to about 1 kW in future has been included. As a 1st step of up-gradation, UA value of HE7 will be doubled (without changing UA values of other HEs) to get higher cooling power of about 270 W. In the subsequent up-gradations, one more compressor will be added to the existing one and UA of other HEs will be increased to get cooling about 1 kW @ 4.5 K. The effect of increase of UA values of HEs have been reported in different literatures [1-2] and improvement requirements in different cryogenic facilities have been reported [3-5]. Hence, to take up the future cooling requirements easily and with less cost, appropriate provisions have been included in this developed helium plant. The details of various component sizes, design parameters, provisions of up-gradations are discussed in the following sections.

2. Design parameters of main components of the cold box

A vertical cylindrical vacuum chamber of diameter 3 m and height 3 m with torispherical heads has been used to make the cold box, within which all cold components are kept at a vacuum of about 5 x10^{-5} mbar during operation. It has sufficient volume to use bigger size HEs in place of

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smaller ones in future to increase the cooling power of the plant up to about 1 kW @4.5 K. One more compressor can be added parallel to the existing one to get flow rate of 120 g/s at 14 bar. With this flow rate, higher cooling power up to ~1 kW at 4.5 K can be achieved, if higher capacity HEs are used. Sizes of HEs for this 1 kW plant have been estimated before deciding the size of the vacuum chamber of the cold box. The overall design parameters of presently used turbines and HEs are given in table 1 and 2 respectively. Cold and hot layers of all HEs have same serrated fins of thickness 0.2 mm and same serration length 5 mm, except the hot layer of HE7, which has serration length 3 mm. HEs were designed for 30g/s helium flow with good margin in heat transfer (UA values) and pressure drops, so that these could be used for helium flow rate of 60 g/s in the present plant. Pressure drops for 60 g/s flow for different streams are between 8 to 30 mbar. It shows that, for flow of 120 g/s, UA values can be about 3 times of presently used values instead of 4 times, for which, in most of the cases, except HE1 (which has considerable axial conduction effect), only cross-sectional area can be increased to ~3 times. Length of HE1, presently placed horizontally inside the cold box, can also be increased to reduce axial conduction problem, as, there is space to accommodate it. Turbines are designed to take up large variation of flow rates, temperature and pressure. Normally, for turbines, efficiency goes down fast, if process flow parameters are away from the design values. To have good efficiency in the off-nominal operation, following equation of state can be used for real gas, which includes

Table 1. Overall design parameters of turbines (Turbine-3 was not operated as flow rate available was only 25 g/s, very low compared to design value.

Name of Turbine	Nominal design parameter : Tested values in operation			
	Ti/To (K)	Pi/Po (bar)	flow rate (g/s)	Speed/isentropic Eff., RPS / %
T1	33/26.4: 33.5/27.1	13.5/6 : 10/4.5	45:35	3750 /72 : 3717 /69.8
T2	15.4/9.9: 13.4/9.6	5.9/1.3: 4.3/1.5	45:35	2800/72: 2753/69.5
T3	7/5.8: --	13.3/4:--	67:--	2066/66 : --

compressibility factor Z.

$$\dot{m} = \dot{V}P/ZRT \tag{1}$$

$$\dot{V} = \dot{m}ZRT/P = R(\dot{m}\,ZT/P) \tag{2}$$

The value of volumetric flow rate ($\dot{V}$) for the design condition can be found from above equation by using the design flow parameters: mass flow rate ($\dot{m}$), pressure (P), temperature (T) and Z from literature or commercial software or NIST webbook [6]. In the off-nominal operating condition, $\dot{V}$ can be made nearer to the design value by manipulating $\dot{m}$, T and P values, where feasible. For only a particular optimum flow velocity, turbines are designed to have best isentropic efficiency. In the present operation, turbines have been operated at off-nominal conditions, but, still, good isentropic efficiencies have been obtained as shown in Table-1.

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Table 2. Overall design parameters of heat exchangers

Name of HE	Dimension (mm) of thermal zone: length /width /depth	Fin dimensions (mm):Density (fins per meter)/ height	Layer pattern: C: Cold str. H: Hot Str.	Mass flow rate (g/s): mh/mc	UA (kW/K)
HE1	965/275/265	709/9.5	(CHC) x 7	60/60	6.64
HE2	645/121/105	709/6.5 (C) and 9.5(H)	(HCH) x 3	60/15	0.7
HE3	965/275/265	709/9.5	(CHC) x 7	60/60	3.12
HE4	645/121/105	787/6.5 (C) and 9.5(H)	(HCH) x 3	25/60	0.7
HE5	940/238/188	709/6.5	CH1CCH2CCH 1CCH2CCH1C CH2CCH1C	35/25/60	2.02
HE6	645/121/105	787/6.5 (C) and 9.5(H)	(HCH) x 3	25/60	0.436
HE7	900/69/98	709 (H) and 560(C)/9.5	HCHCHCHCH	25/25	0.55

Turbine-3 could not be operated as available mass flow rate was only ~25 g/s, which is significantly low compared to the design value.

80 K charcoal-adsorption based helium gas purifier was included in the cold box and was designed to take up air impurities in inlet helium gas up to ~500 PPM with outlet impurity < 10 PPM for flow of 30 g/s. It was designed with good margin, so that, for closed-loop operation in refrigeration and liquefaction mode, helium gas having air impurity up to about 500 PPM and flow rate ~60 g/s could be taken up in the present helium plant. It has diameter ~35 cm and charcoal bed height 45 cm. A bigger size charcoal bed can be installed, in case, quantity of helium fluid in the plant circuit is increased significantly due to up-gradation.

3. Component Layout in the cold box and up-gradation provisions

A support frame is made of C-channels (75 mm x 40 mm x 5 mm) of SS304L material to assemble different cold components, which is hanged from inside of the top dish end of the cold box. The model of assembly is shown in Figure 3. The arrangements have been made in such a way that, pipe routings will have good no. of bends, so that, good flexibility is there and thermal contraction-induced stresses are low. Also in future, HEs and purifier, filters can be upgraded to bigger sizes with less effort. The size of the main support frame is such that, bigger size (for 1 kW plant) can be accommodated. Of course, the mass of the support structure is higher, compared to that is required for 200 W plant, which leads to longer cool down time. Conduction length is more and Teflon insulation material have been used in the hanging support to reduce this heat load. Bigger HEs (HE1, HE3 and HE5) are kept horizontally in the support frame and all other HEs and 80 K purifier are kept around this frame vertically. All cryogenic valves, turbines, instrument feedthroughs have been assembled on the ports of the top dish end. Sizes valves

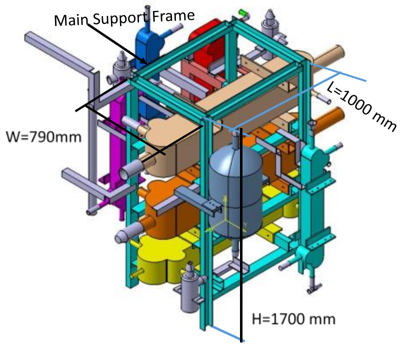

Figure 3 3D model of Assembly of main cold components of cold box of cooling power 200W at 4.5 K

used are also such that, it can be used for higher flow rates. The pressure drops in HEs are high as flow rate is 2 times of design value. The compressor suction pressure is kept at about 1.05 bar to avoid air ingress into the helium loop and LHe chamber should be at pressure about 1.3 bar to generate LHe. To maintain this, pipe sizes in the LP (low pressure) line were chosen to have low pressure drop of about 0.5 mbar/m and no control valve was kept at the outlet of the LHe chamber to manage required pressure drop. 30 layers of MLI were wrapped on all cold components. Vacuum level was ~5 x 10^{-5} mbar during operation.

4. Process analysis and improvement of cooling power of the plant

The plant process cycle has been simulated using commercial ASPEN HYSYS software. All 7 HEs,

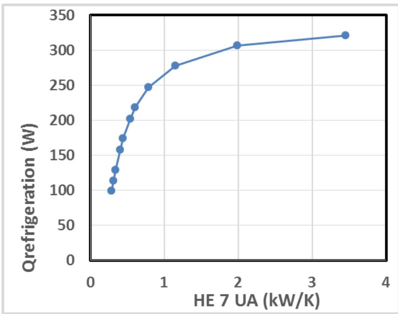

Figure 4 Effect of UA value of HE7 on refrigeration power.

2 turbines, one compressor has been modelled in this software. Variation of UA value of HE7 was done without changing UA values of other HEs. The results are plotted in the graph shown in Fig-4. It says that if the UA values of the presently used HE7 is increased from 0.55 kW/K to

about 1.1 kW/K, then refrigeration power can increase to about 280 W. In all cases, flow of 35 g/s in the Turbine-1 and 2 and flow of 25 g/s in JT path were considered. The tested refrigeration power is 200 W, while the presently used HE7 has UA value 0.55 kW/K.

5. Initial operation results

Operation has been conducted successfully and measured different performances of helium plant. In this operation, liquid helium production, extraction and liquefaction rate measurement in closed loop were included, which is shown in Fig-1. During this operation, measured refrigeration power was 200 W at 4.5 K, while helium inlet pressure to the cold box was 12 bar and flow rate was 60 g/s. The flow to the turbine-1 and 2 was ~35 g/s. An electrical heater was dipped in the LHe bath of the LHe chamber inside the cold box. Operation was stable. Liquid helium could be extracted to the external Dewar and heated up to room temperature to feed to the suction of the compressor and to the plant cycle. The measured liquefaction rate was ~80 ltr/hr. The expected equivalent liquefaction rate, as per thumb rule is 1/3rd of the measured refrigeration power. As this is high, it seems, it is more biased towards liquefaction mode. It means, plant has potential to provide higher refrigeration power. The refrigeration power at 18 K was also measured and was ~600 W. This cooling power can be used for different applications like, high temperature superconductor cooling, cryosorption pumping of hydrogen gas Liquefaction of green hydrogen, etc.

6. Conclusion

The upgradable cold box has been developed and operated successfully down to 4.5 K and in different modes using components made originally for different other purposes. The measured refrigeration power is 200 W at 4.5 K and ~600 W at 18 K, which are same as were the design targets. LHe could also be extracted and measured to have about 80 ltr/hr liquefaction rate. Appropriate up-gradation provisions have been kept in the cold box to increase cooling power. It is found by analysis that, if UA value or size of only HE7 is increased to 1.1 kW/K, then, it can provide ~270 W at 4.5 K. Further, if, one more compressor of similar capacity (60 g/s at 14 bar) is included parallel to existing one and bigger size heat exchangers are used to replace existing small HEs (HE-1 to 6), cooling power can be upgraded to ~1 kW at 4.5 K. It shows that, inclusion of future up gradation possibility is good, which can take up future higher cooling requirements with less cost and time.

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