DEVELOPMENT OF EXPERIMENTAL TEST FACILITIES FOR VALIDATION OF MULTISTREAM PLATE FIN HEAT EXCHANGER DESIGN CODES WITH INITIAL RESULTS

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Compact plate-fin heat exchangers (PFHE) having very high effectiveness (>0.95) are key equipment of modern helium liquefaction / refrigeration systems. Effectiveness (ε) of these heat exchangers strongly influences the overall system performance. Apart from basic fluid film resistances, various secondary parameters such as axial heat conduction (AHC) through the heat exchanger metal matrix, parasitic heat in-leak from surroundings, variation in fluid/ metal properties and flow mal-distribution etc need to be considered while sizing/ rating such high effectiveness PFHE. Need of multiple streams in a single heat exchanger further complicates thermal designs. In-house codes are developed at BARC/ IIT Bombay for rating of such high effectiveness PFHEs. For experimental performance evaluation of PFHEs, their characterization at various operating conditions and validation of in-house developed numerical codes, a dedicated closed loop experimental test facility is developed. Development of the dedicated closed loop experimental test facility is presented in this paper along with initial test results.

Key words: Plate-fin heat exchanger, heat exchanger experimental test facility.

INTRODUCTION

Modern helium liquefaction/ refrigeration systems employ compact plate fin heat exchangers (PFHE) as their key equipment to recover the cold of return low temperature streams in the cryogenic process cycle. Since the overall system performance is a strong function of the effectiveness of the heat exchangers employed, generally effectiveness of these heat exchangers is greater than 0.95 [1]. Apart from basic fluid film resistances, various secondary parameters such as axial heat conduction (AHC) through the heat exchanger metal matrix, parasitic heat in-leak from surroundings, variation in fluid/ metal properties and flow mal-distribution influence performance of such high effectiveness PFHEs [2-3]. To study these combined effects, numerical methods become unavoidable, even for two-stream PFHEs. Need of multiple streams in a single heat exchanger further complicates thermal designs. In-house codes are developed at BARC for rating of such high effectiveness PFHEs [4-5]. However, the numerical studies need to be backed up with detailed experimentation at cryogenic temperatures.

Open literature on experimental code validation of PFHEs at cryogenic temperatures is very sparse. Hence, a full-fledged experimental set-up is required for the purpose.

The objective of such a set-up is to characterise the performance of cryogenic PFHEs of various types (up to 4 streams) and a range of sizes (height up to 1.5m) at different pressure, temperature and flow conditions. The studies include steady state characterisation of the PFHEs with a scope to extend the same to understand the transient behaviour. Other different studies include those related to determination of temperature profiles along the length of a typical PFHE. The in-house codes developed for numerical studies of cryogenic heat exchangers can thus be validated through experiments conducted on the set-up.

The present paper details the development of a dedicated closed loop experimental test facility to meet the above objectives.

PROCESS SCHEMATIC

The test facility uses helium as process gas. Liquid nitrogen (LN_2) is used for cooling of incoming helium stream. Figure.1 gives the schematic of the test facility. Helium gas is used for initial trials in all the three streams, however, in the actual case, He/ N_2/ He can also be used at different flow rates and pressures.

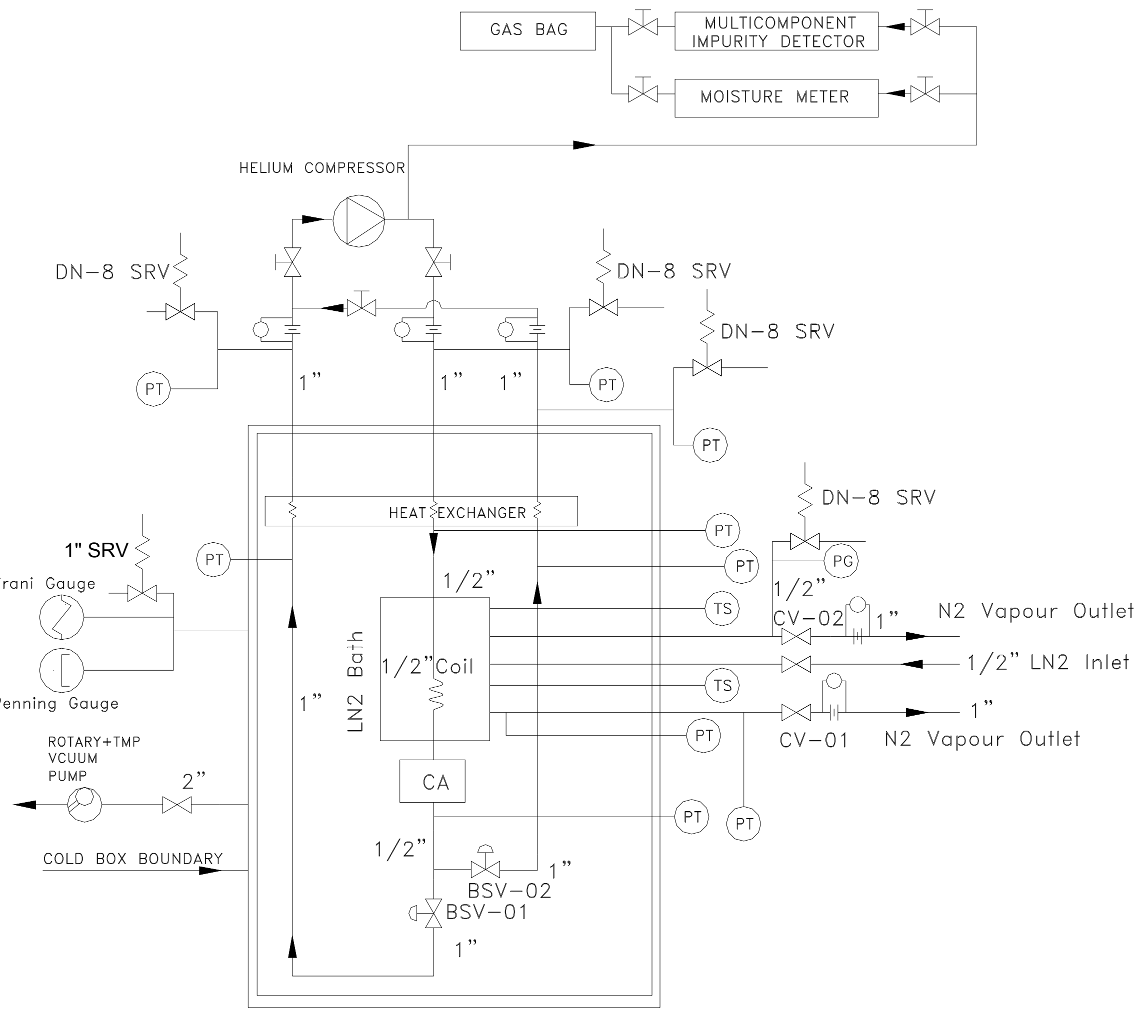

Figure.1 Schematic of the test facility

Effectiveness of the heat exchanger is evaluated using terminal temperature measurements with Platinum Resistance Sensors (PT-100) mounted on the surface of end connections of the heat exchanger. Temperature profile along the length of the heat exchanger is found with the help of a series of PT-100 sensors mounted on the end plates of each side of the heat exchanger. Various types of PFHEs like two-stream (He-He), three-stream (He-He-He), three-stream (He-He-N_2), and four-stream (He-He-He-N_2) PFHEs can be tested in the developed facility.

Sample PFHEs with 2 layers and 3 layers are developed for validation of in-house developed multistream PFHE thermal design codes. In two layers PFHE, each stream will have only one layer so that temperature of the fluid flowing in that layer will be closer to the temperature measured by Pt-100 sensors mounted on the end plate of that layer. Capacity rate ratio between the two streams is controlled with the help of bypass valve (BSV-02) as given in the Figure 1. Flow measurement system is provided for both the streams as well as bypass flow. Pressure of the low pressure (LP) stream is controlled using pressure control valve (BSV-01) as given in the Figure 1. Temperature profile along the length is used for validation of the theoretical models. For multistream design model verification, PFHE with three streams, each having only one layer is used. Heat capacity rate ratios between the streams are controlled using bypass flow control valve. In three-stream (He-He-N_2) PFHE case, two helium streams (HP and LP) and one N_2 stream (Vapour of the LN2 used for cooling of HP helium stream) is used. N_2 flow rate is regulated using bypass flow valve (CV-02) as shown in Figure 1. Flow measurement system is provided for both N_2 flowing through the heat exchanger and by-pass N_2 flow.

DESIGN AND FABRICATION OF MAJOR COMPONENTS

Plate fin heat exchangers (PFHEs)

Four numbers vacuum brazed aluminium PFHEs are developed for model validation experiments. Out of the four PFHEs, two have two layers and remaining two have three layers. All of the four PFHEs have similar heat exchanger core as described in Table 1. Schematic of the offset strip fins (OSF) used in the PFHE is shown in Figure 2. The PFHEs are fabricated using vacuum brazing technique. The PFHE core including fins are made of Al-3003, separating plates are made of Al-3003 coated with Al-4104, headers, pipes and other pressure containing parts are made of Al-5052. Pneumatic testing of the PFHEs is done as per the ASME Boiler and Pressure Vessel Code Section VIII, Div I [6]. Leak testing is done by soap bubble test and helium mass spectrometric leak detector (MSLD), where leak tightness of the PFHEs was found to be better than specified value of 10^{-6}mbar.litre/sec for inter-stream leakages and external leakages. Above mentioned tests are performed at 15 bar (g) pressure. Figure. 3 shows photograph of the developed PFHEs. Pneumatic testing and MSLD (sniffer probe method) of the developed two stream PFHEs is shown in Figure 4. Figure 5 shows the same heat exchanger being leak tested for global leak-tightness with sniffer probe (hood) method.

Table 1 Details of Heat Exchanger Core

Description	Value
Heat Exchanger Matrix Metal	Aluminium (3003)
Core Length	1200mm
Core Width	184mm
Side Bar Width	8mm
Total Width	200mm
Separating Plate Thickness	0.8mm
End Plate Thickness	3.8mm
Fin Type	Serrated
Fin Metal Thickness	0.2mm
Fin Height	6.3mm
Serration Length	3mm
Fin Pitch	1.4mm

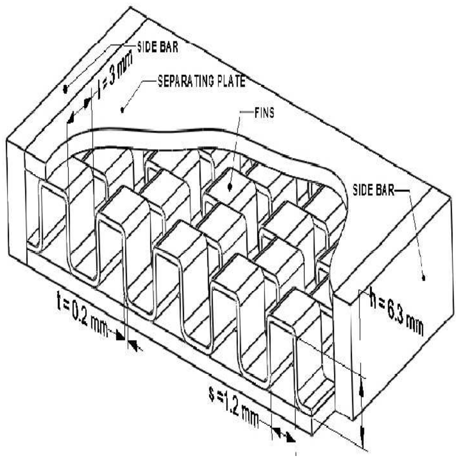

Figure 2 Schematic of OSF used in the developed PFHEs

Figure 3 Developed PFHEs for Model Validation

Figure 4 PFHE Being Leak Tested with Sniffer Probe Method of MSLD

Figure 5 PFHE Being Leak Tested for Global External Leak Using Sniffer Probe (Hood Method) Method of MSLD

Cold box and evacuation system

In the cryogenic systems, cold box is used to house all the cold components. High vacuum and multi-layer super-insulation are generally used to reduce heat in-leaks from surroundings. A cold box is designed and fabricated for the experimental test facility. The fabricated cold box is a cylindrical vessel with 800 mm OD, 4 mm thickness and 1700 mm height. It has 25 mm thick flat bottom head, 25 mm thick top ring flange with 800 mm ID and 900 mm OD, top flat head with 25 mm thickness, 900 mm OD and appropriate holes for various openings. It has lugs support suitable for fork lift. The cold box is designed for both internal and external pressures. Under normal working conditions cold box is under vacuum, therefore, it is designed for 1 bar external pressure. To avoid damage due to accidental pressurization, it is designed for 1 bar internal pressure. Mechanical design and testing such as pneumatic testing is done as per ASME Boiler and Pressure Vessel Code Section VIII, Div I [6]. A turbo molecular pump (TMP) backed up by a rotary vane pump (RVP) is used for evacuating the cold box. Charcoal packets in contact with LN_2 bath are kept in the vacuum space for long term vacuum retention. A Pirani gauge and a Penning gauge are used for vacuum measurement of the cold box. 1” safety plate is used for accidental pressurization of cold box. This safety plate remains open under positive pressure inside the cold box and becomes leak-tight when there is vacuum inside the cold box.

LN_2 bath and charcoal adsorber
A LN_2 bath with approx. capacity of 40L (Φ273mm OD, 800mm cylindrical height, 2mm thick shell with 2mm thick torispherical heads) is used for cooling of helium stream. To attain near LN_2 temperatures, helium stream flows through a SS-304L helical coil made from ½" schedule-10 pipe (Φ200mm PCD X 8 turns) and housed inside the LN_2 bath. The helical coil being leak-tested is shown in Figure 6.

At low temperatures, fine passage of PFHE may get choked and its heat transfer characteristic may get affected by solidification of impurities in the surfaces. A charcoal adsorber is used in the test facility to remove impurities in the helium gas. The helium stream passes through the charcoal adsorber after getting cooled by LN_2.

Figure 6 The Helical Coil Being Leak Tested

Instrumentation and Accessories
33 numbers PT-100 temperature sensors (Make: Heraeus sensor technology, C-220 series, thin-film, Class B PRTDs) are used for temperature measurements at the inlet and exit of the PFHE as well as along the length of PFHE. 112 channel datalogger (Make: Masibus, model-8040) with universal inputs and data logging software with PC communication is used to log all process parameters like pressures and temperatures. Three numbers multi-pin ceramic feed-thoughs (each having 48 pins) are used to take out temperature sensor leads from cold-box to outside. Leak-tightness of the feed-throughs is better than 10^{-9} mbar.ltr/sec. Absolute pressure transmitters (GEMS make, 0-20 bar (a) range, 0.25% FS accuracy) are used to measure inlet, exit pressures of helium streams and N_2 stream. Orifice meters with ABB make differential pressure transmitters are used for flow rate measurement of helium and N_2 vapour streams. Alcatel make MSLD is used for leak testing of PFHEs, cold box and piping. Linde make multi-component impurity detector and moisture meter are used to measure impurities in the helium streams. Two numbers long stem bellow sealed valves (BSV) are used for pressure control and bypass flow control of helium streams. ½" transfer line with flow control valve is used for LN_2 feed. 1" line with control valve, pressure gauge, flow meter and safety relief valve is used for N_2 vapour exit. In case of N_2 vapour as one of the streams, 1" line with control valve and flow meter is used for controlling the flow of N_2 stream through the PFHE. Flexible hoses suitable for high pressure and vacuum are used for interconnection of PFHE with BSVs and LN_2 bath. Figure 7 shows the cold box piping in which a sample PFHE with 3 layers is mounted. Charcoal adsorber and LN_2 are wrapped with multilayer super-insulation and PT-100 sensors are mounted on the sample PFHE. Complete set-up with cold box, evacuation system, LN_2 filling system, data logging and instrumentation system, etc is shown in Figure 8

Figure 7 The Cold Box Piping

Figure 8 The Closed Loop Heat Exchanger Experimental Test Facility

FIRST RUNS USING THE EXPERIMENTAL TEST FACILITY

Experiments have been initiated with the developed closed loop experimental test facility. A sample PFHE with 3 layers and heat exchanger core as described in Table 1 is mounted inside the cold box. Initial evacuation and LN_2 filling show good over-all system integrity and vacuum hold. At room temperature $1x10^{-5}$ mbar vacuum was achieved with TMP backed with RVP. After filling LN_2, the vacuum pump was isolated with a gate valve and good vacuum retention was observed even without active pumping (activated charcoal connected to the LN2 bath acts as a cryo-pump). At room temperature, a total flow of around 15 g/s was directed to the sample PFHE and pressure drops of the order of 0.2 bar was observed in the HP/LP lines. The sample PFHE gave around 10K temperature approach when cooled down to 80K. Detailed experiments are being conducted.

CONCLUSION

A dedicated closed loop experimental test facility is developed. This facility is being used to characterise the performance of PFHEs of different types and sizes at cryogenic temperatures. Experimental validation of the design codes will pave the way for further advancement in the high effectiveness PFHEs essential for helium liquefaction/ refrigeration systems.

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