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Numerical studies on sizing/ rating of plate fin heat exchangers for a modified Claude cycle based helium liquefier/ refrigerator

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Abstract. Performance of modern helium refrigeration/ liquefaction systems depends significantly on the effectiveness of heat exchangers. Generally, compact plate fin heat exchangers (PFHE) having very high effectiveness (>0.95) are used in such systems. Apart from basic fluid film resistances, various secondary parameters influence the sizing/ rating of these heat exchangers. In the present paper, sizing calculations are performed, using in-house developed numerical models/ codes, for a set of high effectiveness PFHE for a modified Claude cycle based helium liquefier/ refrigerator operating in the refrigeration mode without liquid nitrogen (LN_2) pre-cooling. The combined effects of secondary parameters like axial heat conduction through the heat exchanger metal matrix, parasitic heat in-leak from surroundings and variation in the fluid/ metal properties are taken care of in the sizing calculation. Numerical studies are carried out to predict the off-design performance of the PFHEs in the refrigeration mode with LN_2 pre-cooling. Iterative process cycle calculations are also carried out to obtain the inlet/ exit state points of the heat exchangers.

1. Introduction

Most of the modern high capacity helium liquefaction/ refrigeration systems are based on ultrahigh speed cryogenic turboexpanders and compact plate fin heat exchangers (PFHE) having very high effectiveness (>0.95). These systems are required to be operated as a refrigerator or a liquefier with or without LN_2 pre-cooling. PFHE used in the process should be rated properly for these different modes of operations to achieve optimum plant performance. A strong dependence of the helium liquefier performance on the effectiveness of heat exchangers is shown by Atrey [1].

The performance of a PFHE, such as those employed in helium refrigeration/ liquefaction systems, depends on various secondary parameters apart from basic fluid film resistances. These secondary parameters include axial heat conduction (AHC) through the heat exchanger metal matrix, transverse heat conduction, parasitic heat in-leak from surroundings, variation in fluid/ metal properties and flow mal-distribution.

Effects of various secondary parameters on heat exchanger performance have been studied by many authors. A review on these articles is presented by Pacio et. al. [2]. Available thermal design methodologies for multistream heat exchangers have been reviewed in detail by Das et. al. [3].

A numerical model of PFHE is presented by Goyal et. al. [4]. This model explicitly accounts for the effects of various secondary parameters like AHC, property variation and parasitic heat in-leak from surroundings. The authors then followed up this work by developing a model based on finite volume analysis for multistream plate fin heat exchangers for cryogenic applications [5].

In the present paper, sizing calculations are performed, using in-house developed numerical model/ codes based on Goyal et al [4-5], for a set of high effectiveness PFHE to be used in a modified Claude cycle based helium liquefier/ refrigerator operating in the refrigeration mode without liquid nitrogen (LN_2) pre-cooling. The combined effects of secondary parameters like axial heat conduction through the heat exchanger metal matrix, parasitic heat in-leak from surroundings and variation in the fluid/ metal properties are taken care of in the sizing calculations. Numerical studies are carried out to predict the off-design performance of the PFHEs in the refrigeration mode with LN_2 pre-cooling. Iterative process cycle calculations are also carried out to obtain the inlet/ exit state points of the heat exchangers.

2. Sizing of PFHE for Refrigeration Mode Without LN_2 Pre-cooling

2.1 Process Schematic and Cycle Calculations

Figure 1 shows the process schematic of the modified Claude cycle based helium refrigeration/ liquefaction system considered for the study. Process cycle calculation are carried out with the in-house developed simulation code based on solution of mass and energy balance equations coupled with efficiency definitions for all process equipment such as heat exchangers and turboexpanders. Process flow rates, effectiveness of the heat exchangers, efficiency of the turboexpanders, pressure drops across various equipment and heat in-leak to various equipment are the inputs to the process simulation code. Details of the process flow rates are provided in Table 1. Table 2 exhibits the details of the effectiveness/ efficiency/ pressure drops associated with different process equipment. The TS diagram generated through the simulation code is shown in Figure 2, the calculated refrigeration capacity of the system is 376W @ 4.5K. Calculated process parameters of PFHE and turboexpanders are provided in Table 3 and 4 respectively.

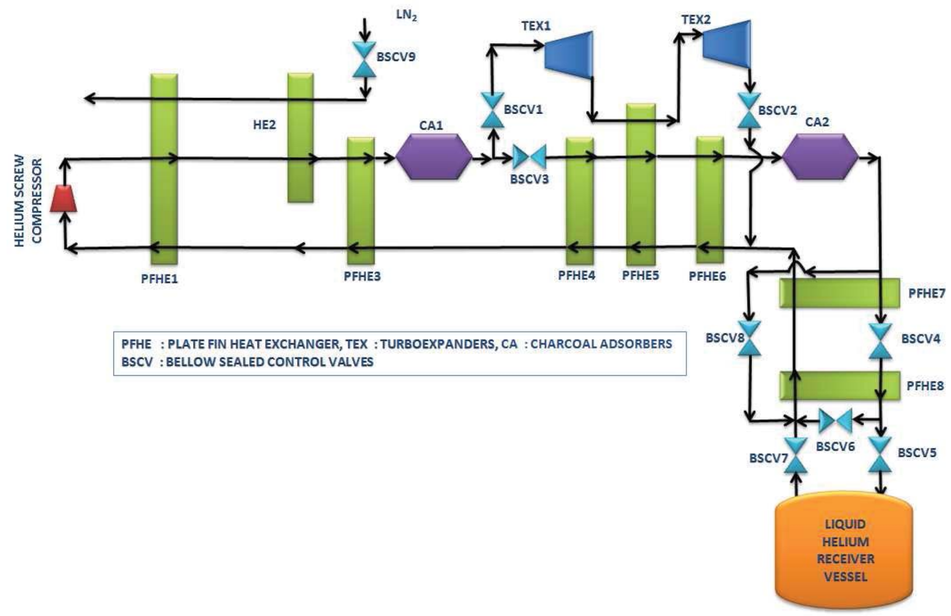

Figure 1. Process Schematic of the Modified Claude Cycle Based Helium Refrigeration/ Liquefaction System.

2.2 Sizing of PFHE

Aluminium plate fin heat exchangers are designed for the process parameters presented in Table 3. Serrated type fins are used in the PFHE core. Manglik and Bergles correlations [6] are used for the j and f characteristics of the fins. Two stream PFHE rating calculations as well as rating calculations for multistream PFHE are done as per the reported model/ code by Goyal et. al. [4, 5]. For ease of cold box piping, all PFHE have the same width. From the consideration of the available brazing furnace to develop the heat exchangers, maximum core length of the PFHE is limited to 1500 mm for design calculations. Similarly, the highest available fin density of 18.14 fpi serrated fins, presently available from local fabricator, are considered for the design. Common construction features of the PFHE are provided in Table 5. Different number of layers and fin heights are used in various PFHE to take care of heat transfer and maximum allowable pressure drop requirements. Calculated number of layers, fin heights, and core length for different PFHE to be used in the refrigerator/ liquefier process are presented in Table 6. Core lengths are selected such that physical number of heat exchangers can be reduced by combining heat exchangers using intermediate entry/ exit options.

Table 1. Process Flow Rates for Refrigeration Mode Without LN_2 Pre-cooling.

Sr. No.	Item	Value	Unit
1	Total Mass Flow Rate	62	g/s
2	Mass Flow Rate Through Turboexpanders	38	g/s
3	Process Compressor Inlet Pressure	0.105	MPa
4	Process Compressor Exit Pressure	1.3	MPa
5	Process Compressor Exit Temperature	310	K
6	LHe Dewar Pressure	0.13	MPa

Table 2. Effectiveness/ Efficiency/ Pressure Drops of Various Equipment for Refrigeration Mode Without LN_2 Pre-cooling.

Sr. No.	Equipment	Effectiveness/ Efficiency	Heat In-leak (W)	Pressure Drop HP Stream (MPa)	Pressure Drop LP Stream (MPa)
1	LP Pipe Line			0	0.005
2	PFHE-1	0.96	10	0.005	0.006
3	PFHE-2	0	5	0.002	0
4	PFHE-3	0.95	5	0.002	0.004
5	PFHE-4	0.95	5	0.002	0.002
6	PFHE-5 IP	0.96	10	0.002	0.002
7	PFHE-5 HP	0.96	0	0.002	
8	PFHE-6	0.97	10	0.002	0.002
9	PFHE-7	0.97	5	0.002	0.002
10	PFHE-8	0.950	5	0.002	0.002
11	He Receiver Dewar		10		
12	TEX 1	0.68		0.7	
13	TEX 2	0.68		0.372	
14	CA 1		5	0.005	
15	CA 2		5	0.005	
16	BSCV-1		2	0.086	
17	BSCV-2		2	0	
18	BSCV-3		2	0	
19	BSCV-4		2	0.776	
20	BSCV-5		2	0.365	
21	BSCV-6		2	0	
22	BSCV-7		2		0
23	BSCV-8		2	0	

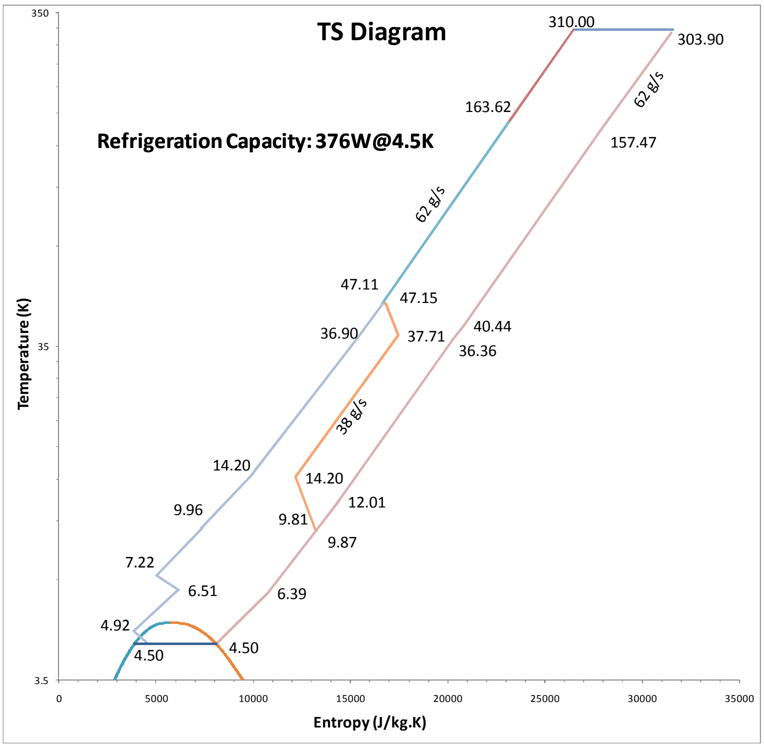

Figure 2. TS Diagram for Refrigeration Mode Without LN2 Precooling.

Table 3. Process Parameters of PFHE for Refrigeration Mode Without LN_2 Pre-cooling.

Sr. No.	Equipment	$T_{in, HP}$ (K)	$T_{out, HP}$ (K)	$T_{in, LP}$ (K)	$T_{out, LP}$ (K)	$P_{in, HP}$ (MPa)	$P_{in, LP}$ (MPa)	$\dot{m}_{HP}$ (g/s)	$\dot{m}_{LP}$ (g/s)
1	PFHE-1	310.00	163.62	157.47	303.90	1.300	0.116	62	62
2	HE-2	163.62	163.64	-	-	1.295	-	62	0
3	PFHE-3	163.64	47.11	40.44	157.47	1.293	0.120	62	62
4	PFHE-4	47.14	36.90	36.36	40.44	1.286	0.122	24	62
5	PFHE-5 IP	37.71	14.20	12.01	36.36	0.5	0.124	38	62
6	PFHE-5 HP	36.90	14.20			1.284		24	
7	PFHE-6	14.20	9.96	9.84	12.01	1.282	0.126	24	62
8	PFHE-7	9.98	7.22	6.39	9.87	1.275	0.128	24	24
9	PFHE-8	6.51	4.92	4.52	6.39	0.497	0.130	24	24

Figure 3 shows the temperature of the fluids along the length of PFHE for different heat exchangers. For PFHE 1 & 3 large temperature gradients are obtained along the length of PFHE which would give rise to large AHC and hence should be properly taken care of during sizing/ rating. NTU required for PFHE-1 without considering AHC is 24 while the actual NTU required to take care of AHC is 44. For heat exchangers placed at low temperature ends of the process, large variations in the fluid properties along the length of PFHE is exhibited and hence consideration of variable fluid property is vital for proper design. In such cases, LMTD method with averaged properties might give results with unacceptable errors. Length required for PFHE-6, considering helium property variation, is 600 mm against required length of 527 mm with averaged properties. Length required for PFHE-8, taking into account property variation, is 480 mm against required length of 1115 mm with averaged properties.

Table 4. Process Parameters of Turboexpanders for Refrigeration Mode Without LN_2 Pre-cooling.

Sr. No.	Equipment	T_{in} (K)	T_{out} (K)	P_{in} (MPa)	P_{out} (MPa)	$\dot{m}$ (g/s)
1	TEX-1	47.15	37.71	1.2	0.5	38
2	TEX-2	14.20	9.81	0.498	0.126	38

Table 5. Common Construction Details of PFHE.

Description	Value
Core Width	350mm
Side Bar Width	10mm
Total Width	370mm
Separating Plate Thickness	0.8mm
End Plate Thickness	5.8mm
Fin Type	Serrated
Fin Metal Thickness	0.2mm
Serration Length	3mm
Fin Pitch	1.41 mm

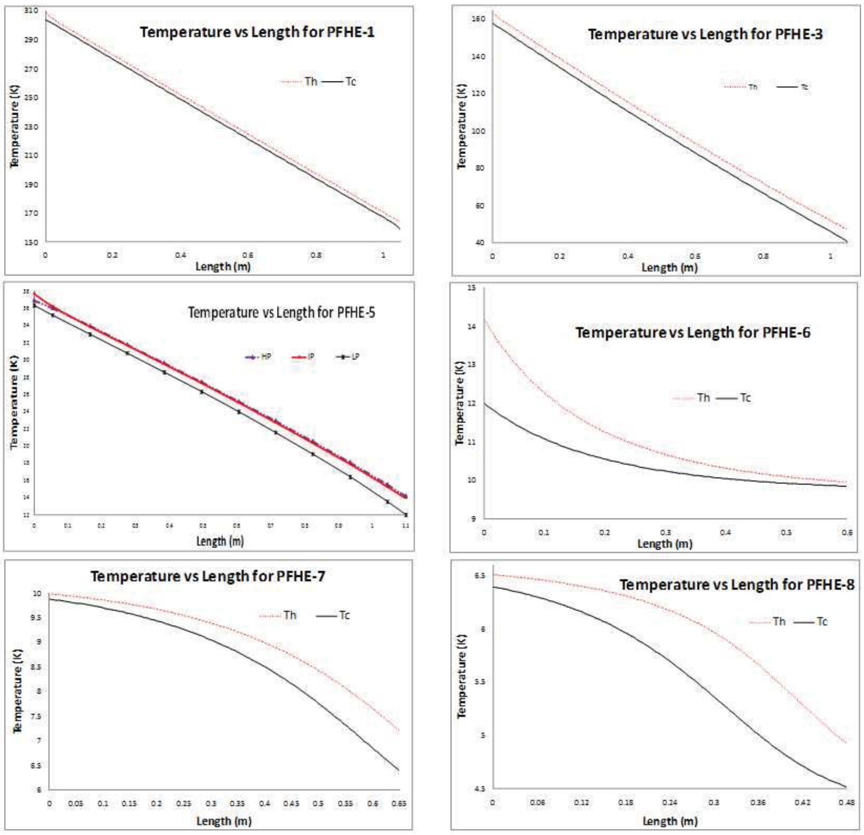

Figure 3. Fluid Temperature Profile Along the Length of PFHE for Refrigeration Mode Without LN_2 Precooling.

Table 6. Selected Fins and Core Lengths of PFHE for Refrigeration Mode Without LN_2 Pre-cooling.

Sr. No.	Equipment	Plate Spacing, b_{HP} (mm)	Plate Spacing, b_{LP} (mm)	No. of Layers, n_{HP}	No. of Layers, n_{LP}	Core Length, L (mm)
1	PFHE-1	6.5	6.5	14	26	1050
2	PFHE-3	6.5	6.5	7	14	1050
3	PFHE-4	6.5	6.5	7	14	160
4	PFHE-5 IP	3.8	3.8	13	20	1100
5	PFHE-5 HP	3.8	3.8	8		
6	PFHE-6	3	6.5	4	5	600
7	PFHE-7	3	3	6	7	650
8	PFHE-8	3	3	6	7	480

3. Rating of PFHE for Refrigeration Mode With LN_2 Pre-cooling

3.1 Cycle Calculations

In the refrigeration mode with LN_2 pre-cooling, temperatures at turboexpanders will be lower compared to that without LN_2 pre-cooling. Therefore, mass flow rates through the turboexpanders and JT valves can be increased. Total helium flow rate in the refrigeration mode with LN2 pre-cooling is 90 g/s and flow through the turboexpanders is taken as 46 g/s (constrained by maximum allowable turbine speed of 4500 Hz). For the cycle simulation, heat in-leaks, pressures and pressure drops at various equipment are considered to be similar to the mode without LN_2 pre-cooling. To match with the available turboexpander characteristics, exit pressure of TEX-1 in this mode is changed to 6 bar (a) compared to that of 5 bar (a) in the mode without pre-cooling. LN_2 mass flow rate is adjusted to achieve 80K temperature at the HP exit of PFHE-2. LN_2 consumption is dependent on off-design performance of PFHE-1, while the refrigeration capacity is more dependent on performance of other heat exchangers and turboexpanders. During process simulations, effectiveness of the heat exchangers are iteratively adjusted based on the rating calculations. The TS diagram generated through the simulation code is shown in Figure 4, the calculated refrigeration capacity of the system is 697W @ 4.5K. Calculated process parameters of PFHE and turboexpanders are provided in Tables 7 and 8 respectively.

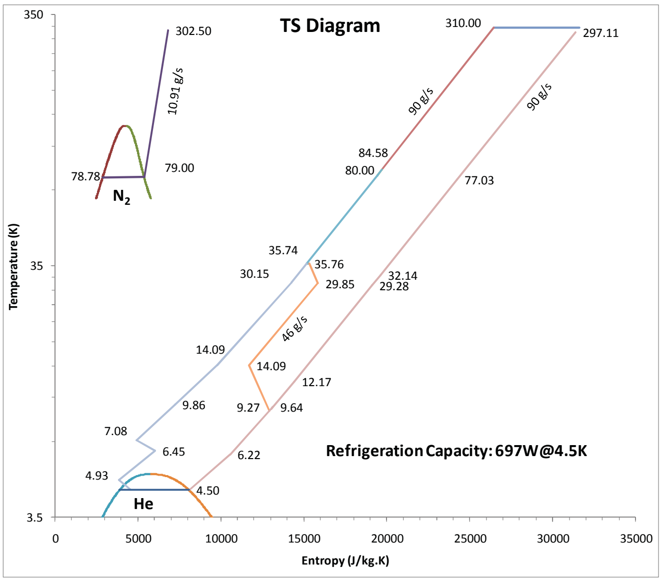

Figure 4. TS Diagram for Refrigeration Mode With LN_2 Precooling.

3.2 Rating of PFHE

PFHE-1 in the case of refrigeration mode with LN_2 pre-cooling is a three stream heat exchanger, HP and LP helium being two streams and nitrogen vapour being the third stream. Therefore, PFHE 1 is rated as per the multistream code [5]. There are 14 layers for HP helium and 26 layers for LP helium as described in Table 6. The two outermost layers are meant for N_2 vapour flow during LN_2 pre-cooling mode, and hence would see no flow during the non-pre-cooling mode. Distance between separating plates for these two layers is 6.5 mm. PFHE-5 is also a three stream heat exchanger. HP, IP streams are high temperature streams which are cooled by return LP cold stream. This heat exchanger is also rated as per the multistream code [5]. All other heat exchangers are two stream heat exchangers and hence are rated as per two stream code [4]. Table 7 details the effectiveness of heat exchangers and inlet exit process conditions as per rating calculations. Figure 5 shows the temperature of the fluids along the length of PFHE for different heat exchangers.

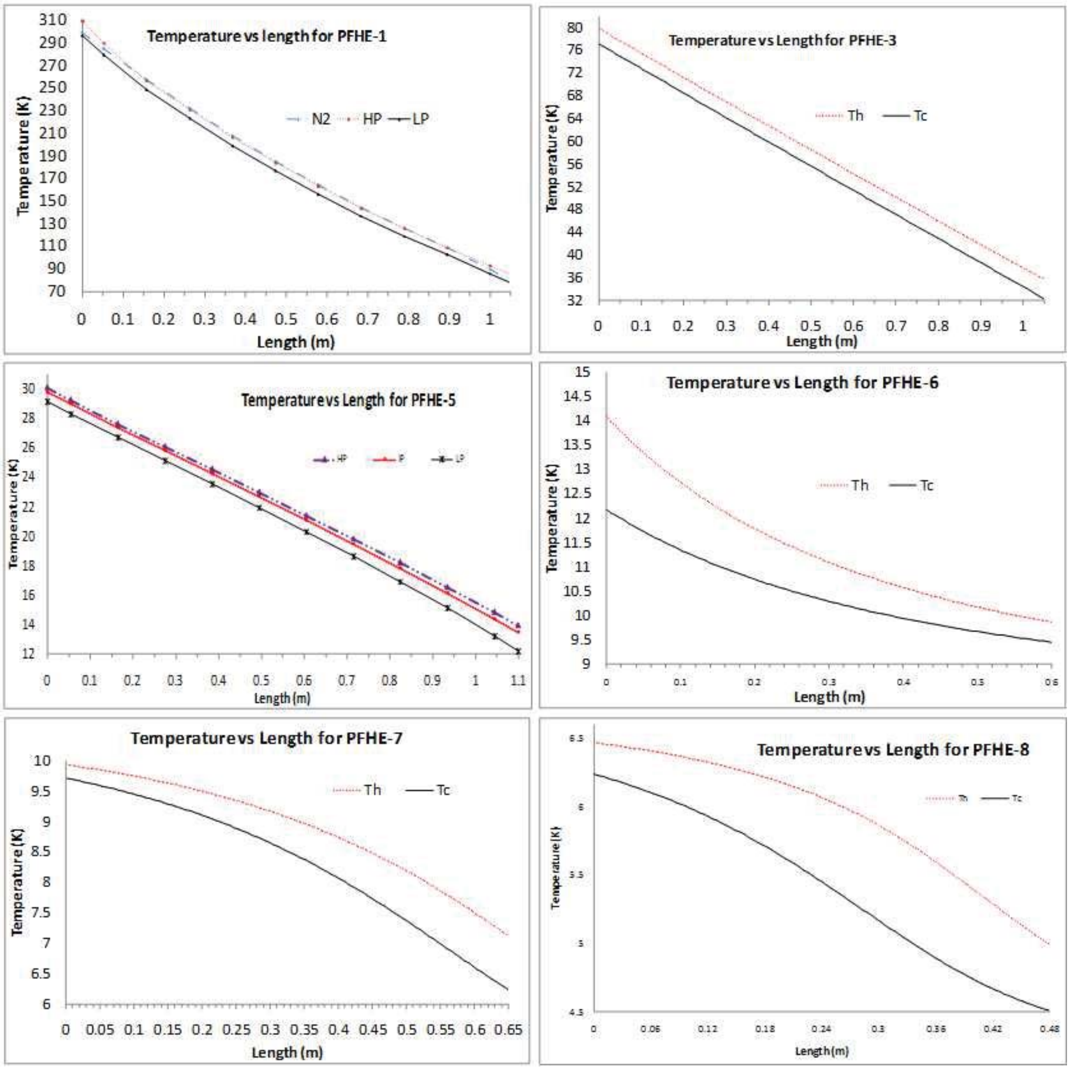

Figure 5. Fluid Temperature Profile Along the Length of PFHE for Refrigeration Mode With LN_2 Precooling

Table 7. Process Parameters of PFHE for Refrigeration Mode With LN_2 Pre-cooling.

Sr. No.	Equipment	$T_{in, HP}$ (K)	$T_{out, HP}$ (K)	$T_{in, LP}$ (K)	$T_{out, LP}$ (K)	$P_{in, HP}$ (MPa)	$P_{in, LP}$ (MPa)	$\dot{m}_{HP}$ (g/s)	$\dot{m}_{LP}$ (g/s)	Eff.
1	PFHE-1	310.0	84.58	77.03	297.11	1.300	0.116	90	90	0.968
2	HE-2	84.58	80.0	78.78	79.0	1.295	0.12	90	10.9*	0.79
3	PFHE-3	80.0	35.74	32.14	77.03	1.293	0.120	90	90	0.938
4	PFHE-4	35.76	30.15	29.28	32.14	1.286	0.122	44	90	0.865
5	PFHE-5 IP	29.85	14.09	12.17	29.28	0.6	0.124	46	90	0.96
6	PFHE-5 HP	30.15	14.09			1.284		44		0.96
7	PFHE-6	14.09	9.86	9.45	12.17	1.282	0.126	44	90	0.905
8	PFHE-7	9.87	7.08	6.22	9.64	1.275	0.128	44	44	0.94
9	PFHE-8	6.45	4.93	4.51	6.22	0.497	0.130	44	44	0.90

* Flow rate of N_2

Table 8. Process Parameters of Turboexpanders for Refrigeration Mode With LN_2 Pre-cooling.

Sr. No.	Equipment	T_{in} (K)	T_{out} (K)	P_{in} (MPa)	P_{out} (MPa)	$\dot{m}$ (g/s)
1	TEX-1	35.76	29.85	1.2	0.6	46
2	TEX-2	14.09	9.26	0.598	0.126	46

4 Conclusion

Process simulation is carried out for a modified Claude cycle based helium liquefier/ refrigerator working in the refrigeration mode without LN_2 pre-cooling. Sizing of the PFHE for this mode is discussed and results are presented. Off-design performance of the PFHE is predicted for the refrigeration mode with LN_2 pre-cooling. Process parameters are updated for this mode, while taking into account the off-design performance of PFHE and turboexpanders. Heat exchanger sizing will depend on most preferred mode of operation and off-design performance in other modes. The work presented in this paper can be augmented in future through the inclusion of studies on off-design performance of PFHEs and turboexpanders in helium liquefaction mode with/without LN_2 pre-cooling.

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References

[1] Atrey MD Thermodynamic analysis of Collins helium liquefaction cycle. *Cryogenics* 1998 **38(12**) 1199-1206.
[2] Pacio JC and Dorao CA A review on heat exchanger thermal hydraulic models for cryogenic applications. *Cryogenics* 2011 **51(7)** 366-79.
[3] Das PK and Ghosh I Thermal design of multistream plate fin heat exchanger-a state of the art review *Heat Transfer Engineering* 2012 **33(4-5)** 284–300.
[4] Goyal M, Chakravarty A and Atrey MD. Effects of axial conduction, property variation, and parasitic heat in-leak on performance of compact plate fin heat exchangers *Indian journal of cryogenics* 2014 **39** 58-63.
[5] Goyal M, Chakravarty A and Atrey MD Two dimensional model for multistream plate fin heat exchangers *Cryogenics* 2014 **61** 70-78.
[6] Manglik RM and Bergles AE Heat transfer and pressure drop correlations for the rectangular offset_strip fin compact heat exchanger *Experimental Thermal and Fluid Science* 1995 **10(2)** 171-80.