Theoretical Analysis of Coil Finned Tube Type Heat Exchanger for Helium Liquefaction Plant

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Abstract— The cryogenic heat exchanger governs the performance of cryogenic system. The present work reports the theoretical analysis of heat transfer process of coil finned tube heat exchanger used in Collins cycle based medium capacity helium liquefier. The aim of present study is to design and optimize different geometrical and operating parameters for coiled finned tube exchangers. To improve the effectiveness of heat exchanger the theoretical analysis has been carried out by theoretical modelling. The efforts have been made to study the effect of different geometrical parameters like coil diameter, tube diameter by in depth study of DIN number, fin height and fin spacing etc. and operating parameters like pressure drop. The design and optimization of geometrical and operating parameters are done to achieve the desired temperature drop of cold fluid. The variation in properties of helium for specified temperature range are studied and taken into consideration.

Key words: Cryogenic Heat Exchanger, Steady State Analysis

I. INTRODUCTION

Helium is widely used in space research, superconducting magnets and medical fields. Helium is very rare and expensive gas, so to conserve it, every research institute using helium on large scale should have a helium liquefier. It has a consumption of about 100 million cubic meters per annum and it is increasing by 4 to 5 % every year [1]. The cryogenic system like liquefiers, heat exchanger is one of the most important components, and play significant role. In fact, a cryogenic liquefier will produce no liquid if the heat exchanger effectiveness is less than approximately 85% [2]. If the effectiveness of a heat exchanger is reduced from 97% to 95% the liquid yield is reduced by 12% [3]. These facts suggest the need of high-effectiveness heat exchangers, of the order of more than 90%. So a heat exchanger should be designed in a manner to have optimum effectiveness with lower pressure drop. As heat exchanger is the most critical component of liquefier system, this recuperative heat exchanger has been studied extensively by many researchers. Xue et al.[4] and Ng et al[5] have carried out steady state analysis of a miniature Hampson type heat exchanger for argon as a working fluid. An accurate geometrical model for the helical finned tube is included in the steady state thermodynamic model of the miniature heat exchanger by Chua et al. [6] and Hong et al. [7]. They had used an effectiveness-NTU approach to predict the performance of the heat exchanger for argon and nitrogen as working fluids. Ardhapukar and Atrey [8] presented a steady state analysis for the performance optimization of a miniature J–T cryocooler in which they have used this type of heat exchanger.

There are many different configurations for cryogenic heat exchangers, which generally can be classified as tubular exchangers, plate-fin exchangers and perforated plate exchangers. Every kind of exchanger has their own importance and limitations, like plate-fin heat exchangers are very compact but at the same time very costly to fabricate. In the present work, designing of a coiled finned tube type heat exchanger for medium capacity helium liquefaction plant is discussed. This type of heat exchanger was used for the first time in Helium Liquefier by Collins [9].

In the present work, one dimensional transient model is developed for coil finned tube heat exchanger used for medium capacity liquefier. Time dependent terms are taken into consideration for continuity, momentum and energy equations. Temperature profiles of fluid streams over heat exchanger length are compared with results published in literature [10].

II. COIL FINNED TUBE HEAT EXCHANGER

The special features of cryogenic heat exchanger, results in a particular design for the specific application. The designing of a heat exchanger involves consideration of many parameters that affect the sizing and performance of the exchanger. These parameters are basically grouped as physical parameters and operating parameters.

The schematic diagram of cross counter flow coil finned tube heat exchanger is shown in figure 1.The main parts are, finned tube with hot high pressure gas, a mandrel over which finned tube is wound and covering cylinder which forms external annular space for returning low pressure gas. The physical parameters like tube diameter, shell diameter, fin height, fin density, diametrical clearance etc. have significant effect on heat exchanger sizing and performance. The operating parameters like working pressure of cold and hot fluid, their mass flow rates, and four end temperatures have impact on the final sizing of heat exchanger. Thermodynamic considerations make cryogenic processes very sensitive to the heat exchanger performance

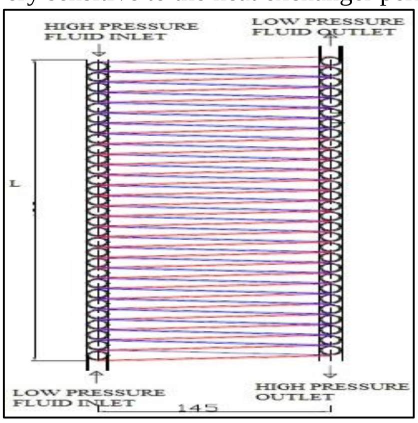

Fig. 1: Schematic presentation of coil finned tube heat exchanger

Normally, the high pressure gas enters the finned tube at a pressure range of 10-12 bar. The temperature at inlet is ambient temperature i.e. 300 K. The return gas in external annular space enters at low pressure around 2 bar and at inlet temperature of about 90-92 K. To initiate the design few assumptions are made like; pressure drop due to other effects are negligible in comparison to the core frictional pressure drop. The mass flow rate for cold side is assumed to be 4 g/s and 5 g/s. The schematic diagram of coil finned tube heat exchanger is shown in figure 1.The Thermal and pressure drop performance of heat exchanger is influenced by clearance which is provided for ease of assembly. A part of cold gas passes through clearance without taking into part of heat exchange process, making the heat exchanger ineffective. The dimensions of heat exchanger for numerical modeling is taken from literature [11], and mentioned in Table 1.

Geometrical parameters		Operating parameters	
Inner tube diameter (d_i)	8.2 mm	Working fluid	Helium
Finned tube diameter (d_f)	13.5 mm	Temperature range	300-90 K
No. of fins per meter(n)	1024	Mass flow rate	3.0g /s
Axial length(L)	1000.00 mm	High pressure	15 bar
Mean diameter (D_e)	145 mm	Low pressure	1.0bar

Table 1: Geometrical and Operating parameters

III. NUMERICAL MODELING

In the present work, one dimensional numerical model is developed for fluid streams and the solid elements. The governing equations for mass, momentum and energy are solved using fourth order Ranga-Kutta method. For numerical solution of governing equation, heat exchanger is divided in small segments along the length. For the finned tube nodes are placed at center of a control volume and for fluid stream nodes are placed at faces of control volume. For each segment, length of finned tube is calculated considering diameter and pitch. Similarly for fluid stream in annular space is also divided into small segments.

For numerical solution of equation following assumptions are made [12]

1) Heat transfer and fluid flow is one dimensional along the length of solid and fluid elements of the heat exchanger
2) Axial conduction in the fluid is neglected
3) Body forces and axial stresses are negligible;
4) The helical tube is assumed to be perfectly circular and closely spaced
5) Fin efficiency is assumed to be 100 %
6) Diametrical clearance between fins and outer vessel is considered

The conservation of mass, momentum and energy equation for fluid and energy equation for solid can be written as

Conservation of mass over a fluid CV

$$A\frac{\partial \bar{\rho}}{\partial t}+\frac{\partial \dot{m}}{\partial x}=0 \quad (1)$$

Conservation of momentum

$$A\frac{\partial(\bar{\rho}\bar{V})}{\partial t}+\frac{\partial(\dot{m}V)}{\partial x}=-\frac{\partial P}{\partial x}A-\tau_w l_p \quad (2)$$

Conservation of energy

Hot fluid :

$$m_h C_{ph}\frac{dT_h}{dx}= h_h P_{ci}(T_w-T_h) \quad (3)$$

Cold fluid:

$$m_c C_{pc}\frac{dT_c}{dx}= h_c[P_{co}(T_c-T_w)+P_{si}(T_c-T_s)+P_{mo}(T_c-T_m)] \quad (4)$$

The energy equations for the solid elements

Finned tube

$$K_w A_w\frac{d^2T_w}{dx^2}=h_h P_{ci}(T_w-T_h)+h_h P_{ci}(T_w-T_c) \quad (5)$$

Mandrel

$$K_m A_m\frac{d^2T_m}{dx^2}=h_c P_{mo}(T_m-T_c) \quad (6)$$

Shield

$$K_s A_s\frac{d^2T_s}{dx^2}=h_c P_{si}(T_s-T_c)+h_r P_{so}({T_s}^4-{T_a}^4) \quad (7)$$

Considering the effect of diametrical clearance, heat transfer coefficient and pressure drop coefficient are calculated [11]. If the mass flow rate of the cold stream flowing in the shell side is given by m_c, then the actual mass flow rate passing through fins is

$$m_f=\frac{m_c}{K+1} \quad (8)$$

Where , $K = A_{cc}/A_{fc}$

The Reynolds number will be calculated based on actual mass flow rate passing through fins and can be given by

$$Re_f=\frac{Re_{woc}}{K+1} \quad (9)$$

Where Re_{woc} is Reynolds number when c = 0.

$$Re_{woc}=\frac{m_c D_h}{A_{fc}\mu} \quad (10)$$

Where hydraulic diameter D_h, can be

$$D_h=\frac{4A_{sc}}{\frac{A_s}{L}} \quad (11)$$

$$G=\frac{m_c}{A_{sc}} \quad (12)$$

The total heat duty (Q) of the hot fluid stream which has to be removed by exchanging the energy with cold fluid streams is given by

$$Q= C_h(T_{h,in}-T_{h,out})=UL\Delta T_{LMTD} \quad (13)$$

Where ΔT_{LMTD} is log mean temperature difference, given by

$$\Delta T_{LMTD}=\frac{\Delta T_{hot\ end}-\Delta T_{cold\ end}}{\ln\left(\frac{\Delta T_{hot\ end}}{\Delta T_{cold\ end}}\right)} \quad (14)$$

The overall heat transfer coefficient U, based on per unit axial length of heat exchanger can be given by

$$U=[\frac{1}{h_i S_i}+\frac{1}{h_o S_o}]^{-1} \quad (15)$$

Where h_i and h_o are heat transfer coefficients of tube side and shell side respectively. Here the thermal resistance offered by tube wall is neglected. Expressions for determining h_i and h_o are discussed on later stage.

Pressure drop design is equally important as thermal design of heat exchanger for cryogenic systems. The amplitude of pressure drop of tube side or shell side per unit working length through heat exchanger is given by

$$\Delta P=\frac{fG^2}{2\rho D_h} \quad (16)$$

For the tube side:

For the turbulent flow inside the smooth tube of any cross section, the friction factor was calculated by the empirical equation suggested by Timmerhaus and Flynn[13]

$$f=0.184Re^{-0.2}(1+3.5\frac{d_i}{D_e}) \quad (17)$$

For shell side flow

The shell side flow is generally laminar in the coiled finned tube heat exchanger given by

$$f = 1.904Re^{-0.2} \qquad \text{for } 400 < Re < 10^4 \qquad (18)$$

A. Boundary Conditions

The inlet temperature, pressure mass flow rate are known for hot, high pressure gas in finned tube and cold return gas in annular space. Finned tube, Mandrel and outer vessel are assumed adiabatic at ends. The initial pressure and temperature conditions for solid and fluid stream are

At $X = 0$, $T_{h0} = T_{amb}$ $p = p_{hin}$, and

$X = L$, $T_c = Tc_{in}$, $p_{c0} = p_{cin}$

IV. VALIDATION OF MODEL

The numerical model developed is validated against the experimental results available in literature [10].Figure 2 shows temperature profile obtained for given parameters. It is observed from figure that temperature profile for hot fluid is in good agreement with the experimental results published in literature [10].

V. RESULTS AND DISCUSSION

Performance optimization is done for heat exchanger considering different parameters. The dimension of heat exchanger is shown in table 1.The programming is done in this work is for theoretical analysis of heat exchanger parameters at steady state.

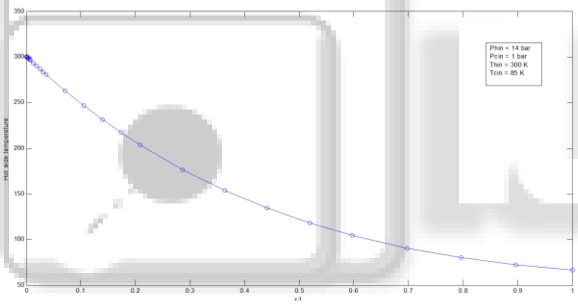

Fig. 2: Temperature Profile Along The Length Of Heat Exchanger

Figure 2 shows the temperature profile along the length of heat exchanger. It can be observed from the figure that temperature drop from 300 K to around 90 K is obtained for given range of parameters.

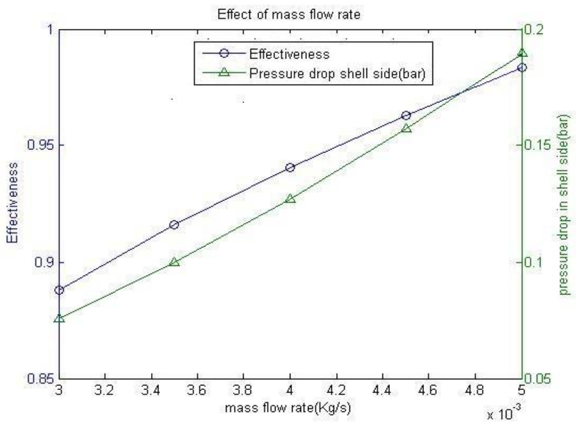

Fig. 3: Effect of Mass Flow Rate On Effectiveness And Pressure Drop

Results are plotted to study the effect of operating parameters and to decide the optimum operating range for getting maximum effectiveness of heat exchanger. The effect of mass flow rate on cooling effect and pressure drop is plotted in figure 3.

It is observed from the figure that Effectiveness increases with mass flow rate and subsequently shell side pressure drop also increases, and after certain range of mass flow rate effectiveness becomes constant. Figure 4 shows effect of mass flow rate on effectiveness for different coil diameter. It can be observed from the figure that with increase in mass flow rate effectiveness also increases for a given coil diameter. With increase in coil diameter, also effectiveness increases, but after certain range of coil diameter amount of increase in cooling capacity decreases.

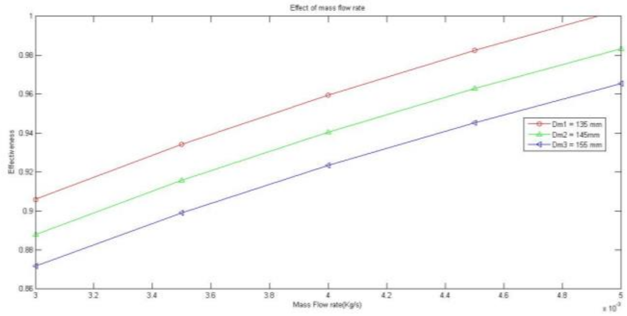

Fig. 4: Effect Of Mass Flow Rate And Coil Diameter On Effectiveness

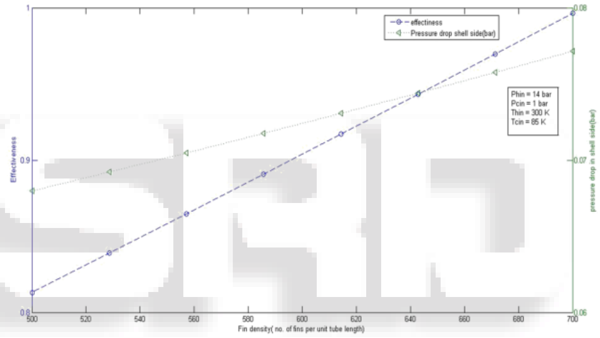

Fig. 5: Effect Of Fin Density On Effectiveness And Pressure Drop

Results are plotted for fin density verses effectiveness and pressure drop in figure 5. It can be observed from the figure that for given range of operating parameters fin density can be optimized for maximum effectiveness and minimum pressure drop. Results are plotted for DIN number in figure 6. It can be observed from the figure that tube diameter and mean coil diameter can be optimized in given range of operating parameters for thermal and pressure drop performance.

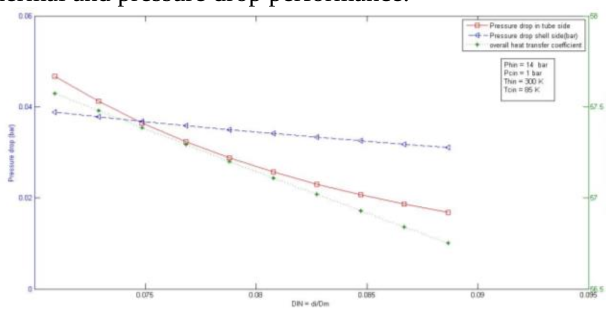

Fig. 6: Effect of DIN number

VI. CONCLUSION

A numerical model for theoretical analysis of different operating and geometrical parameters of cross-counter flow coil finned tube heat exchanger has been developed. For solution of mass, momentum and energy equations of fluid streams, algorithms are developed. The numerical values of outlet temperature of gas in tube are in good agreement with experimental results published in literature [10]. With the model developed in this work heat transfer characteristics can be very well explained. Theoretical analysed is done to determine optimum design and operating parameters in the given range of parameters in present work. Effect of different parameters such as fin density, coil diameter, fin height and cooling capacity, shell side pressure drop and mass flow rate on performance of heat exchanger is studied. Effectiveness increases with mass flow rate and subsequently shell side pressure drop also increases, and after certain range of mass flow rate effectiveness become constant. Effectiveness also increases with increase in coil diameter, but after certain range amount of increase in effectiveness decreases. Number of fins per meter length i.e. fins density, tube diameter and coil diameter can be determined for maximum effectiveness and minimum pressure drop.

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