Flow mal-distribution study in cryogenic counter-flow plate fin heat exchangers

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Abstract. Plate Fin Heat Exchangers are one of the main components in modern large capacity helium liquefiers/refrigerators. These heat exchangers should have more than 95% effectiveness in order to liquefy helium gas. Design of these heat exchangers are complex one and govern by many parameters such as flow mal-distribution, variable fluid properties, heat-in-leak from ambient and longitudinal heat conduction through wall. Among these design parameters, flow mal-distribution within heat exchanger layers is one of the important design parameters for achieving higher effectiveness. Flow mal-distribution reduces the effectiveness significantly and may bring down it to a much lower value than design value. In the present study, a numerical model has been developed which is capable to evaluate layer by layer temperature distribution in presence of flow mal-distribution. Two major mal-distribution conditions, linear weighted and center weighted, might occur when flow leads from nozzle to different layers in plate fin heat exchangers. Present work studied the effect of these two conditions on performance of plate fin heat exchanger in the temperature range of 300-90 K as a case study.

1. Introduction

Helium liquefiers/refrigerators are the energy intensive systems and require very highly effective (> 95 %) and compact heat exchangers. Brazed aluminum plate fin heat exchangers are the most suitable heat exchangers used in medium to very large capacity modern helium liquefiers/refrigerators. The stringent requirement of high effectiveness, low pressure drops and high degree of compactness posed by the cryogenics systems led to the development of these plate-fin heat exchangers. With the help of modern manufacturing technologies, these heat exchangers can be made without any mechanical joints. Plate fin heat exchangers can be built by stacking the layers of corrugated fins separated by parting sheets and side bars are used for sealing the all around edges as shown in Figure 1. The constructional feature of this kind of heat exchanger allows to operate these heat exchangers with large number of streams at different or same pressures in a single body. One of the major technical challenges to achieve the required higher effectiveness of plate fin heat exchangers for these systems is to minimize the flow mal-distribution problem among different stacking layers. Therefore careful evaluation of header design is required for successful development of these heat exchangers.

Figure 1. Different components of heat exchanger core
Flow distribution among different layers of plate fin heat exchangers is usually achieved by means of nozzle, header and distribution fins systems. Header and nozzle combinations attached to heat exchanger core at both the ends are responsible to distribute the fluid flow in different stacking layers and regrouping the whole fluid flow at the exit of heat exchanger core. Therefore fluid flow leads from nozzle/ header combination to the heat exchanger core layers through distributor fins. In general, heat exchanger performs better when mass flow rate is uniformly distributed among the different stacking layers of heat exchanger core. However flow mal-distribution among different layers of heat exchanger can deteriorate the thermal and hydraulic performance of heat exchanger. Some of the general reasons of flow mal-distribution in plate-fin heat exchangers are

- Uneven local pressure distribution in nozzle/header combinations at the entry and exit core of heat exchanger
- Uneven flow resistance in different layers caused by difference in channel dimensions or due to manufacturing defects, different flow length and fluid parameters like density and viscosity variations

Flow distribution problem in heat exchangers has been treated by many investigators. Mueller and Chio [1] have listed different factors responsible for mal-distribution in shell and tube heat exchangers. Flemming [2] investigated the effect of flow mal-distribution in parallel channels of counter flow heat exchangers. Other different works [3-9] also studied the flow mal-distribution problem in different heat exchangers. Jiao et al. [10] and Zhe et al. [11] also carried out experimental research on the effect of flow mal-distribution in plate fin heat exchangers. Actual flow distribution among different stacking layers of plate fin heat exchangers is hard to measure experimentally. But understanding the effect of flow mal-distribution on the performance of plate fin heat exchangers is crucial for designing these heat exchangers. Therefore, it is important to develop different simplified model to understand the effect of flow mal-distribution on the thermal performance of plate fin heat exchangers. Present study is aimed for broadening the understanding regarding the effect of flow mal-distribution on thermal performance of plate fin heat exchangers. In the present study it is assumed that when flow leads from the nozzle/header combination to different layers of heat exchanger, there might be flow mal-distribution among different layers of plate fin heat exchangers. In header/nozzle combination, the nozzle could be placed at two locations either center of header or top of the header as shown in Figure 2a and Figure 2b. When nozzle is located at top of the header, layers near the nozzle locations would be subjected to maximum mass flow rate and then it is assumed that mass flow rate would be in decreasing trend. This flow mal-distribution condition is termed as linear weighted condition. On the other hand when nozzle is located at the center of header, the center layers would be subjected to maximum mass flow rate and then it is assumed that the mass flow rate would be in decreasing trend outwards. This flow mal-distribution condition is termed as center weighted condition. In the present work the thermal model has been developed to simulate these two conditions.

Figure 2. (a) Linear weighted distribution (b) Center weighted distribution
2. Mathematical Modeling and Solution Procedure

To simulate flow mal-distribution conditions mentioned in the preceding section, a mathematical model has been developed. In the present work, a simple method to model flow mal-distribution effect on heat exchanger performance is developed. It is assumed that one side either hot or cold flow side of heat exchanger is having homogeneous flow and on the other side fluid flow is mal-distributed in different layers of heat exchanger.

In the present study, mass flow rate distributions among different layers have been calculated for linear weighted and center weighted conditions. The total mass flow rate available for distribution among different layers is conserved and causes of mal-distribution are not studied in the present work.

When flow is distributed uniformly among different layers, the average mass flow rate $m_{avg}$ can be calculated by following expression:

$$m_{avg} = \frac{m}{N}$$  \hspace{1cm} (1)

where $m$ is the total mass flow rate either hot side or cold side of heat exchanger and $N$ is the total number of layers either side.

When flow is not distributed uniformly among the different layers, the flow deviation parameter must be established mathematically and this parameter is simply the maximum relative deviation from the average mass flow rate. In the mathematical form this flow deviation parameter for hot fluid $\Phi_h$ could be expressed as follows:

$$\Phi_h = \frac{m_{h,max} - m_{h,avg}}{m_{h,avg}}$$  \hspace{1cm} (2)

Similarly flow deviation parameter for cold fluid $\Phi_c$ can also be defined.

2.1. Linear weighted flow distribution among different layers

In this flow distribution condition, nozzle is fitted to the top of header as shown in Figure 2a. The distributed mass flow rate could be calculated by assuming following two assumptions:

- Consider the linear drop of mass flow rate from the closest layer to the farthest one and the center layer is subjected to the average mass flow rate.
- The maximum of the total mass flow rate goes to the layer which is very close to the nozzle.

Mass flow rate among the different layers, $j=1,2,3,\ldots,N$, is linearly distributed and can be expressed as

$$m(j) = \Phi j + c$$  \hspace{1cm} (3)

where $m(j)$ is mass flow rate corresponding to layer $j$.

By applying the relevant boundary conditions, the flow distribution among different layers could be deduced as follows:

$$m(j) = m_{avg} \left[ \Phi \left( 1 - \frac{2j - 1}{N} \right) + 1 \right]$$  \hspace{1cm} (4)

2.2. Center weighted flow distribution among different layers

In this flow distribution condition, nozzle is fitted to the center of header as shown in Figure 2b. The distributed mass flow rate could be calculated by assuming following two assumptions:

- Consider that maximum mass flow rate should enter near the middle layers and then linearly drops to the farthest layer of both sides.
- The maximum of total mass flow rate goes to the layer which is very close to the nozzle.

The flow rate among different layers can be calculated by the following two expressions.
For the layers \( j = 1 \) to \( \frac{N+1}{2} \)

\[
m(j) = m_{avg} \left[ \Phi \left( \frac{2j-1}{N} - 1 \right) + 1 \right]
\]

Similarly for the layers \( j = \frac{N+1}{2} \) to \( N \)

\[
m(j) = m_{avg} \left[ \Phi \left( 1 - \frac{2j-(N+1)}{N} \right) + 1 \right]
\]

The Eqs. 4 to 6 described above will calculate the mass flow rates in different layers of heat exchanger for different flow mal-distribution conditions. The calculated mass flow rate would be the input to obtain the hot fluid and cold fluid temperature profiles for individual layers of plate fin heat exchanger.

The governing energy equations for the temperature profiles of hot and cold streams with no axial conduction through wall, with no heat generation in the fluids and with no external heat-in-leaks have been formulated. These governing partial differential equations coupled with heat transfer process for the counter-flow heat exchangers can be written in the following form:

\[
\text{Hot fluid} : \quad \dot{m}_h c_{ph} \frac{dT_h}{dx_h} + U A_h (T_h - T_c) = 0 \tag{7}
\]

\[
\text{Cold fluid} : \quad \dot{m}_c c_{pc} \frac{dT_c}{dx_c} + U A_c (T_h - T_c) = 0 \tag{8}
\]

Where \( \dot{m}_h \) and \( \dot{m}_c \) are the mass flow rate of hot and cold streams. \( c_h \) and \( c_c \) are the specific heat of the respective fluids. \( U \) is the overall heat transfer coefficient between the two fluid streams. \( A_h \) and \( A_c \) are the heat transfer area for hot side and cold side. \( L \) is the axial length of heat exchanger. Layer by layer temperature profiles have been determined using these energy equations. These energy equations (Eqs.7 and 8) of heat exchanger have been divided into number of elements using the finite difference method and converted into linear algebraic equations and are then solved by an appropriate solver. The heat transfer coefficients for offset strip fins (OSF) for each layer is calculated by an appropriate formulae and methods described elsewhere [12]. Then these heat transfer coefficients have been used for calculating the value of \( U \). Table 1 shows the different operating process parameters of the plate-fin heat exchanger considered in this study.

| Table 1: Process data and some geometric data for case study |
|---------------------------------------------------------------|
| **Operating parameters** | **Values** |
| Hot and cold fluid mass flow rates (g/s) | 50 |
| Hot fluid inlet temperature (K) | 300 |
| Cold fluid inlet temperature (K) | 90 |
| Process Fluid | Helium |
| No. of hot fluid layer | 11 |
| No. of cold fluid layer | 11 |

Flow mal-distribution in different layers will result in different outlet temperatures at different layers and therefore mean outlet temperatures are defined as follows:
The effectiveness, $\varepsilon$, of heat exchanger is calculated using following equation:

$$
\varepsilon = \frac{q}{q_{\text{max}}}
$$

where $q$ is the heat transfer rate and $q_{\text{max}}$ is the maximum heat that can be transferred by the heat exchanger.

3. Simulation Results and Discussion

Flow mal-distribution effect in plate fin heat exchangers has been evaluated by solving the above described energy equations for each layer. The mass flow rate distributions on either side of heat exchanger have been calculated among different layers according to linear distribution profile. Figure 3 shows flow rate distribution for linear weighted conditions among the different layers for different flow mal-distribution parameters. Figure 3 shows that top layers where nozzle is located is subjected to higher mass flow rate than average flow rate.

![Figure 3](image-url)

Figure 3. Mass flow rate distribution for linear weighted conditions among the different layers

Mass flow rate distributions are important input parameter for calculating the temperature profiles of different layers. When flow is uniformly distributed among different layers, the outlet temperature coming out from different layers would be same and therefore average outlet temperature of individual stream would also be same as shown in Figure 4.

Flow mal-distribution among different layers degraded the performance of heat exchanger due to poor heat exchange. Figure 5 shows the effect of flow mal-distribution on temperature profiles of different layers in linear weighted condition. The effect of flow mal-distribution could be clearly visualized from this figure. The outlet temperature of each layer is different as each layer of heat exchanger is subjected to different mass flow rate. This figure shows that temperature profiles of layer 6 are linear as in this layer average mass flow rate entered. The temperature drop or rise of each stream depends on the heat capacity of individual layer.
Figure 4. Temperature profiles of heat exchanger when flow is uniformly distributed

Figure 5. Effect of flow mal-distribution on temperature profiles of different layers in linear weighted condition

The heat capacity rate of each layer changed due to different flow distribution in each layer. In linear weighted condition, the mass flow rate is more concentrated to the initial layers of heat exchanger and therefore performance of hot stream is degraded significantly in these layers. On the other hand outermost layers subjected to the low mass flow rate and therefore heat capacity rate get reduced in these layers. The outlet temperature of hot fluid stream in these layers may be as close as to the inlet temperature of the cold fluid stream depending on the mal-distribution parameter. Figure 6 shows the outlet temperature of hot fluid as a function of different flow mal-distribution parameters for different layers of heat exchanger. This figure shows that the outlet hot fluid temperature of each layer significantly varies with mal-distribution parameter. The outlet hot fluid temperature in the first layer
could be as high as 155.71 K and it is nearly 90 K in the last layer for $\phi_h = 0.5$ as shown in Figure 6. Constructural feature of plate fin heat exchanger allows the collection of different mass flow rates coming out from the different layers in outlet header. These different temperature streams get mixed in outlet header and come out at an average temperature for other process use. The global performance of heat exchanger could be expressed in terms of effectiveness of heat exchanger for different mal-distribution parameters. Figure 7 shows the % effectiveness of hot fluid of heat exchanger vs. mal-distribution deviation parameter.

![Figure 6](image.png)

**Figure 6.** Outlet temperatures of hot fluid as a function of different flow mal-distribution parameters for different layers of heat exchanger

![Figure 7](image.png)

**Figure 7.** % effectiveness of heat exchanger vs mal-distribution deviation parameter

This figure shows effectiveness decreases significantly for both flow distribution conditions as deviation parameter increases. The effect of flow mal-distribution is more pronounced in linear
weighted than the center weighted condition. This might be because of less flow mal-distribution among the central layers of heat exchanger in center weighted condition.

4. Conclusions
The effect of flow mal-distribution on heat exchanger thermal performance has been studied for different flow distribution conditions. Model developed in present study is able to evaluate the temperature profiles of different layers of plate fin heat exchanger in presence of flow mal-distribution. Present model evaluates the performance with respect to homogeneous flow condition and shows that the effectiveness of heat exchanger drops in presence of flow mal-distribution and varied significantly with this parameter. Effect of linear weighted mal-distribution condition is more severe than the center weighted mal-distribution condition. Therefore, findings of the present study are similar in line that most of the industrially manufactured plate fin heat exchanger fitted with nozzle at the center of header.

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