CFD study on heat transfer and pressure drop characteristics of an offset strip-fin heat exchanger in helium systems

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Abstract. The accuracy of correlations of colburn (j) and friction (f) factor has important effect on the accuracy of simulation results in the dynamic simulation of large scale cryogenic helium systems. However，air was used as heat transfer medium to derive most correlations available in the literatures and experimental results. In order to study the heat transfer and pressure drop characteristics of an offset strip-fin heat exchanger in helium systems, the steady-state three-dimensional numerical models were built. Orthogonal arrangement was adapted to reduce the numbers of simulation. Re, fin length, fin height, fin space, fin thickness were chosen as the parameters in the orthogonal simulation. Through numerical analysis, the j and f factor correlations were developed under different Reynolds (Re<800), which could predict 90% simulation data within ± 20% deviation. These results were compared with the existing results obtained by air to find the influence of different fluid medium. The general correlations of j and f presented here probably provide a selection in dynamic simulation of heat exchangers.

1. Introduction

Plate-fin heat exchanger is a kind of the compact heat exchangers, which has high coefficient of heat transfer and large specific surface. The main type of fins in plate-fin heat exchangers are straight fins, offset strip fins, wavy fins, and perforated fins etc. The offset strip fins are widely used in the large scale cryogenic helium plants to meet the demands for saving energy and sources. Considering the operating temperature and pressure in helium plants, aluminum is chosen commonly as the material of fins and sheets.

Due to the expensive price of helium, air is usually taken as the heat transfer medium in most experimental study. London and Shah [1] calculated the value of j and f under different geometries of fins by experiment study. Many numerical studies took their data as the evidence to prove the accuracy and reliability of CFD analysis. Wieting [2] put forward the correlations of laminar (Re<1000) and the turbulence region (Re>2000) through the data fit of 22 geometries of fins, and

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analyzed the limitation of the predicted models. The general correlations applied to the laminar, transition and turbulence region have been obtained by Manglik and Bergles [3]. Dong J and Chen J et al.[4] revealed the effects of different fins' sizes on the j, f factors, and received the general correlations for j and f factors which can predict 95% and 90% of the experimental data within ±10% derivation. With the development of computer technology, numerical calculation provided a new method of studying the features of heat transfer and fluid flow. Ismail and Velraj [5] analyzed the uncertainties in the estimation of j and f factors, compared the error between the different correlations of open literatures, the presented CFD results and the experimental data. The results [5] showed that Mason's correlations had the maximum deviation which over predicted the experimental results about 70-200% for f factor and 115-200% for j factor under the considered range of Reynolds number. Yang Y, Li Y [6] studied the 252 available fins through CFD approach, and the proposed correlations predicted the 92.5% of the j data and 90.3% of the f data within 20% derivation.

The above results were obtained on the occasion that air was taken as heat transfer medium. However, in large scale cryogenic systems, the general used gas is helium. Moreover, the available correlations in the open literatures are quite different even with same Re and geometries of fins. Therefore, it's hard to choose the suitable one to use in the design and simulation.

Developing the correlations for j and f factors of the plate fin heat exchangers using helium as working medium was the key issue in this paper. CFD simulation had been used because of the convenience. The j and f factor correlations had been attained by multiple regression, which could predict about 90% simulation data within ±20% derivation. Besides, the simulation results proved that the method of Orthogonal experimental design was suitable for solving the problems about the heat transfer and fluid flow.

2. Model

2.1. Physical model

The common expression of offset strip fins (OSF) is: h-J-s-t/l. J represents offset strip fins, l, s, t, h denote respectively the length, the space, the thickness and the height of the fins. The top view and axonometric drawing of the offset strip fins were shown in Figure 1. Usually, the fin-channel is assumed to be rectangular, and the fin offset is uniform and equal to half-fin spacing [6]. The hydraulic diameter for OSF fins is defined as follows:

$$D_h = \frac{4 \times (s-t)h}{4(lh+th+ls)/(2l)} = \frac{2 \times (s-t)h}{(lh+th+ls)/l} \tag{1}$$

The 3D computational domain of the OSF fins was shown in Figure 1 (b) with dotted lines. In order to neglect the effect of the entry, the model total length was chosen to guarantee that the ratio of flow length to the hydraulic diameter was more than 60.
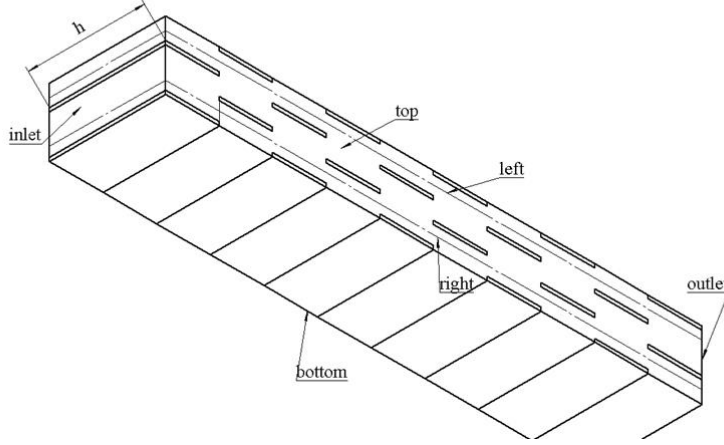

Figure 1(a) Top view of the OSF fins

Figure 1(b) Axonometric drawing of the OSF fins

2.2. Mathematical model

Table 1 The comparison of properties between helium and air

Name	density（kg/m³）	viscosity（kg/m-s）	Cp(j/kg-k)
helium	0.1625	1.99e-5	5193
air	1.225	1.7894e-5	1006.43

It's concluded from table1 that the density of helium is less than air. The Re of helium is about 6.5 times than that of air in the same inlet velocity and fin sizes. In our laboratory, the design flow state of plate-fin heat exchanger in small and medium-sized helium liquefiers is in laminar flow. Therefore, it's necessary to study the characteristics of strip fins in helium systems to obtain the more accurate correlations of j and f factors.

The numerical solution is the useful method in calculating the characteristics of OSF heat exchangers. In this paper, the commercial CFD code fluent 14.5 with finite volume method was used to solve the heat transfer and fluid flow equations. The hexahedral mesh was generated by Gambit 2.4.6. The general equation is as follows:

$$\frac{\partial(\rho \emptyset)}{\partial t} + \frac{\partial(\rho u_i \emptyset)}{\partial x_i} = \frac{\partial}{\partial x_i}\left(\Gamma_\emptyset \frac{\partial \emptyset}{\partial x_i}\right) + S_\emptyset \tag{2}$$

$\Gamma_\emptyset, S_\emptyset$ are decided by variable Φ. The boundary conditions were listed in table 2. The simulation

Table 2 Boundary conditions

Location	Condition
Inlet	Velocity-inlet
Outlet	outflow
Top	Constant wall temperature
bottom	Constant wall temperature
Left & right	periodic

[a]The locations were shown in Figure 1 (b)

was done as steady process and SIMPLE algorithm was implemented. The second order upwind scheme was used to discretize the above differential equations. In the present simulation, the convergence criterions for energy equation was less than 1×10^{-8} and others were less than 1×10^{-4}.

2.3. Model verification

2.3.1. Mesh independence verification

The fanning friction factor (f) is defined as follows:

$$\Delta p = 2f \frac{L}{D_h} \rho u^2 \tag{3}$$

Where, Δp is the pressure drop between inlet and outlet of the model. u is the inlet velocity of OSF fins. L is the length of the model.

The heat transfer coefficient is represented by the following equation:

$$j = \frac{Nu}{RePr^{1/3}} = St \times Pr^{2/3} \tag{4}$$

In this paper, the fin style- 6.3754-J-1.627-0.1016/3.175 was taken to carry out the grid independence test. The comparison between different grid numbers was shown in Figure 2. It is indicated that the pressure drop of model is tend to constant when the grid number is more than 753664. Hence, this grid number was chosen to calculate the j and f factors in the section 2.3.2 to compare the difference between CFD results and experimental data.
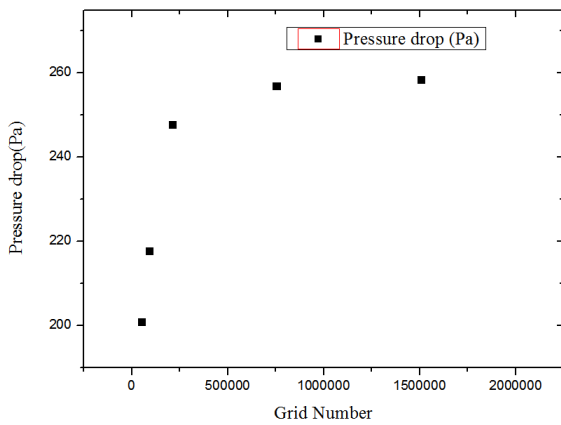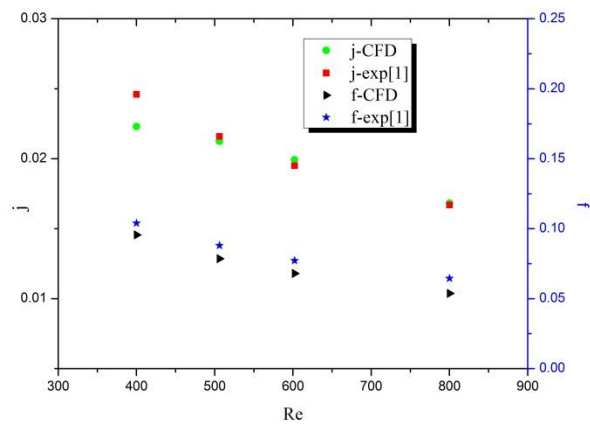

Figure 2 Grid independence test

Figure 3 Comparison of CFD results with the Shah and London[1]

2.3.2. The comparison between CFD and experimental results

The model verification used the air as the heat transfer medium was carried out and the comparison between simulation results and the experimental data [1] was shown in Figure 3. The maximum relative error of j and f factor was 9.1%, 17%, respectively. The agreement between CFD approach and experimental measurement satisfied the engineering application and verified that the numerical model was successful and reliable. This result provided the base on the calculation of the helium plate-fin heat exchangers.

2.4. Orthogonal design of simulation

The orthogonal experimental design is a kind of mathematical statistics method. It has been successfully used in many industrial and scientific experiments. For using orthogonal method to analyze the flow problems, the following step is necessary: 1) Choosing the main influence factors and deciding the suitable levels of the factors. 2) Choosing the suitable orthogonal table to arrange the simulations or experiments. 3) Using the multiple regression method to calculate the j and f factors.

It can be concluded from the analysis of the air plate-fin heat exchanger that the main influence factors of *j* and *f* are *Re, s, t, h, l*. The parameters used in orthogonal table are listed in table 3. The orthogonal table of 5 factors and 4 levels of factors is used to carry out the modeling experiment.

Table 3 Parameters of *Re, s, t, h, l*

factor	Levels of the factor
Re	400,500,600,700
s	1, 1.5, 2, 2.5
t	0.1, 0.15, 0.2, 0.3
h	3, 4, 5, 6
l	2, 3, 4, 5

3. Results and discussions
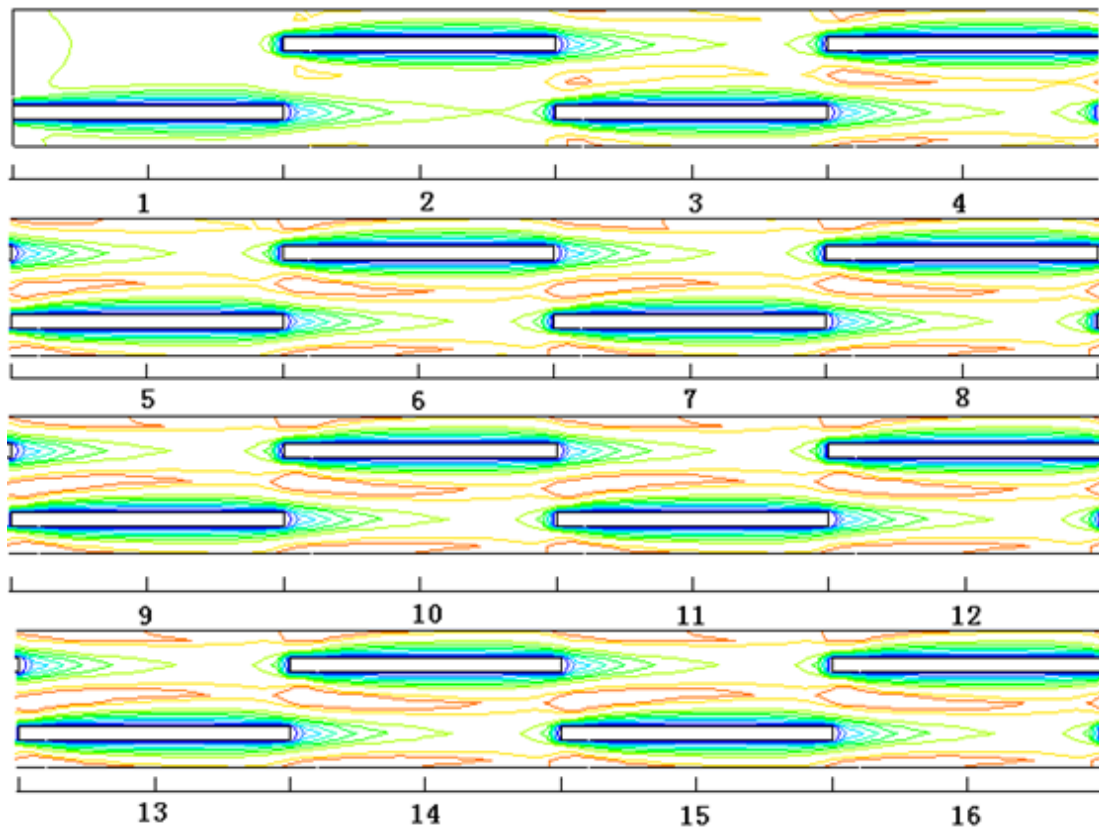
3.1. The inner flow analysis of the model

Figure 4 The variation of velocity along with the length of heat exchanger

One of the advantages of the numerical method is that it can be used to observe the flow pattern in every part of the model. The contour of velocity in one cross profile of the fins was showed in the Figure 4, and the number of the x-axis was on behalf of the fins number.

  With the development of the flow, the velocity of the inlet increased when it through the minimum cross-section. The contour of velocity didn't show the periodicity for the first nine fins because of the entrance effect. In the available literature [7], the length of entrance effect in laminar can be solved as follows:

$$\frac{l}{D_h} = 0.05 RePr \tag{5}$$

For this condition, $\frac{l}{D_h} = 9.1$. The simulation results got consistent conclusion with the empirical equation.

3.2. The correlations of the j and f factors

The correlations of j and f factors are obtained considering the parameters of *Re, s, h, l, t*. On the basis of Manglik and Bergles[3] correlations, the general equations to calculate the j and f factor in helium systems can be written as:

$$j = aR_e{}^b \left(\frac{s}{h}\right)^c \left(\frac{t}{l}\right)^d \left(\frac{t}{s}\right)^e \tag{6}$$

$$f = a'R_e{}^{b'} \left(\frac{s}{h}\right)^{c'} \left(\frac{t}{l}\right)^{d'} \left(\frac{t}{s}\right)^{e'} \tag{7}$$

Where a, b, c, d, e, a', b', c', d', e' are the constant coefficients.
Through linearization technique, the equations (6)-(7) can be written as:

$$\log j = \log(a) + b \times \log(Re) + c \times \log\left(\frac{s}{h}\right) + d \times \log\left(\frac{t}{l}\right) + e \times \log(\frac{t}{s}) \tag{8}$$

$$\log f = \log(a') + b' \times \log(Re) + c' \times \log\left(\frac{s}{h}\right) + d' \times \log\left(\frac{t}{l}\right) + e' \times \log(\frac{t}{s}) \tag{9}$$

Multiple regression method was used to fit the data in the orthogonal table, and the correlations of j and f factors were:

$$j = 0.377R_e{}^{-0.5485} \left(\frac{s}{h}\right)^{-0.4544} (\frac{t}{l})^{0.2074}(\frac{t}{s})^{-0.3448} \tag{10}$$

$$f = 10.63R_e{}^{-0.6959} \left(\frac{s}{h}\right)^{-0.3185} (\frac{t}{l})^{0.3219}(\frac{t}{s})^{-0.0295} \tag{11}$$
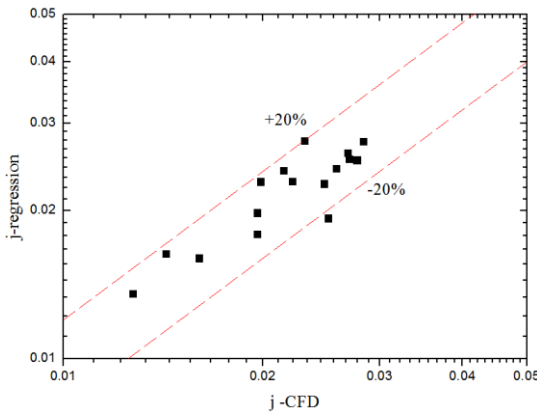

Figure 5 Comparison of predictions for j given by Equation (10) with CFD results.
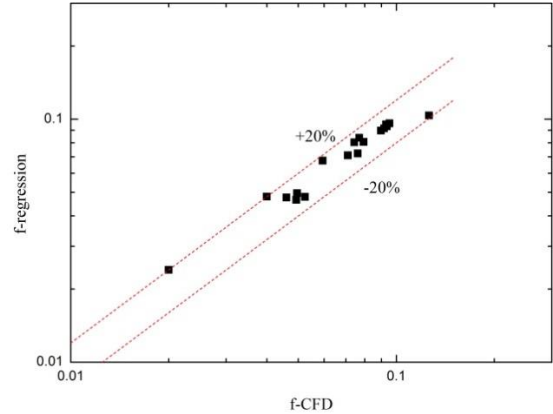
Figure 6 Comparison of predictions for f given by Equation (11) with CFD results.

Figure 5-6 showed the comparison of the simulation data and the present correlations of the j and f factors. The correlations and CFD results were in good agreement, and the 90% of the simulation data were correlated within ±20% derivation.

3.3. The comparison between present results and the available empirical correlations

The difference between the correlations using the air as heat transfer medium and the present results were shown in Figure 7-8. The *Pr* of the helium and air is close, so the trends between different correlations are same. The results can be proved that the orthogonal experimental method is the

effective way to solve the multifactor problems of the thermodynamic filed. Obviously, there exists difference in different correlations because the fin geometries and fluid medium used in the experiment are not same.
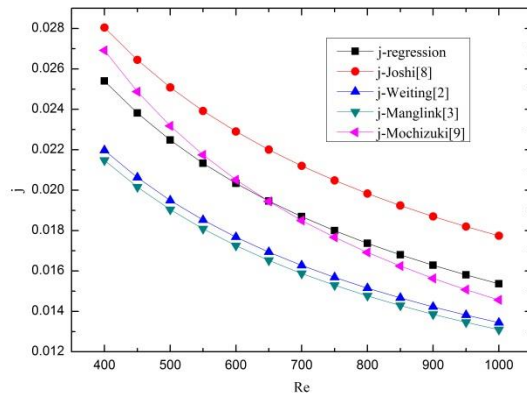

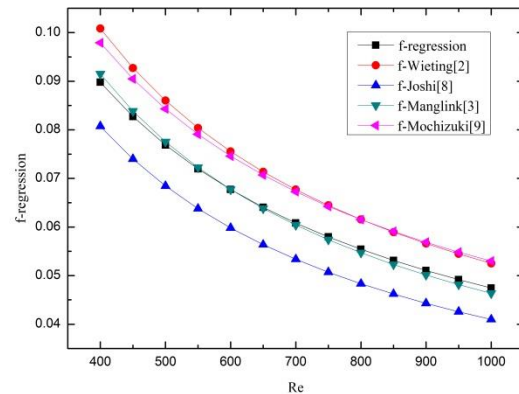Figure 7 Comparison of open literatures' correlations with present results of CFD versus Re

Figure 8 Comparison of open literatures' correlations with present results of CFD versus Re

4. Conclusion

The simulation results on the offset strip fin heat exchangers of helium systems denoted that orthogonal experimental method was applicable in solving the heat transfer and fluid flow problems. The correlations for j and f factors had been developed by the multiple regression analysis, which could predict 90% simulation data within $\pm 20\%$ derivation. The comparison between the present and the open literatures' correlations reveal that the fluid medium will affect the j and f factors. The simulation results will provide a selection in the design and dynamic simulation of the offset strip fin heat exchangers in helium systems.

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