Study on Heat Transfer Performance of Pulsating Flow in Convergent-Divergent Tube

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Abstract. The heat transfer performance of the pulsating flow in the convergent-divergent tube is analyzed. The influence of pulsation amplitude, pulsation frequency and divergent segment-convergent segment ratio on heat transfer and resistance of the tube was simulated by numerical simulation. The results show that the heat transfer performance of the pulsating flow in the convergent-divergent tube is better than the fluid steady flow in the tube. The heat transfer is enhanced by about 11.4% compared with the fluid flow in the tube was steady. The pulsating flow in the tube strengthens the heat transfer, but also increases the resistance. Through the analysis of enhanced heat transfer comprehensive index, the heat transfer performance of the tube under pulsating flow conditions is significantly enhanced.

1. Introduction
Convergent-divergent tube is a typical reinforced tube, has been widely used in electric power, chemical, petroleum and refrigeration industries. It has the advantages of smooth surface transition, smaller flow resistance and less scaling with simple processing technology and low manufacturing cost. Domestic and foreign scholars have done a lot of research on the heat transfer performance of the convergent-divergent tube \cite{1-4}, but there are few researches on the tube under fluid pulsation condition. This paper established a reasonable mathematical model. Fluent software was used to study the influence of pulsation amplitude, pulsation frequency and different divergent segment-convergent segment ratio on the heat transfer performance and resistance of the tube.

2. Model

2.1. Physical model
According to the structural parameters of a convergent-divergent tube in a practical engineering application, set the total length of the tube \( L = 1000 \text{ mm} \), pitch \( P = 12 \text{ mm} \). In order to make the fluid fully flow at the inlet and outlet, a 50mm long straight tube section is set at the inlet and outlet of the tube. The divergent segment-convergent segment ratio defined as \( \gamma = \frac{L_1}{L_2} \).
2.2. Mathematical model

Fluid flow in the convergent-divergent tube follows the fundamental conservation law. And based on the structural symmetry of the tube, the hypothetical model can be simplified to a two-dimensional computational domain so that the system of equations can be expressed as follow\textsuperscript{[5-7]}.

2.2.1. Mass conservation equation

\[
\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0
\]  

(1)

2.2.2. Momentum conservation equation

\[
\left\{ \begin{array}{c}
\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} = -\frac{\partial p}{\partial x} + \frac{1}{\rho} \left( \frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} \right) \\
\frac{\partial v}{\partial t} + u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} = -\frac{\partial p}{\partial y} + \frac{1}{\rho} \left( \frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} \right)
\end{array} \right.
\]

(2)

2.2.3. Energy conservation equation

\[
\frac{\partial T}{\partial t} + u \frac{\partial T}{\partial x} + v \frac{\partial T}{\partial y} = \frac{k}{\rho c_p} \left( \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} \right)
\]

(3)

Where, \( p \) is the density of the fluid, \( t \) is the time, \( \vec{u} \) is the velocity vector, \( u, v \) are the components of the velocity vector in x, y directions, respectively. \( c_p \) is the specific heat capacity, \( T \) is the temperature, \( k \) is the heat transfer coefficient of fluid.

3. Numerical simulation

3.1. Meshing

The local lattice structure of the physical model is shown in ‘figure 2’. Considering that the boundary has a great influence on the heat transfer, it is necessary to encrypt the mesh near the wall.

3.2. Boundary conditions

According to the characteristics of flow in the convergent-divergent tube, set the boundary conditions.

3.2.1. Boundary condition of velocity inlet
\[ u = u_s [1 + A \sin(2\pi ft)] \quad (4) \]

where, \( u \) is the instantaneous velocity of the fluid inlet, \( u_s \) is the velocity of steady state flow, \( A \) is the dimensionless pulsation amplitude and \( f \) is the pulsation frequency. The medium inside the tube is water. The fluid inlet temperature is 333K.

3.2.2. Boundary condition of pressure outlet.
With atmospheric pressure as the reference pressure, the outlet pressure is zero.

3.2.3. Boundary condition of the wall. The wall is set as a non-slip rigid wall, so the condition is:
\[ u = v = 0, T = 293K \quad (5) \]

3.2.4. Boundary condition of axial symmetry.
According to the characteristics of the heat transfer in the tube and the axisymmetric distribution of the flow, the axis of the tube is set as follow:
\[ y = 0, \frac{\partial u}{\partial y} = 0, \frac{\partial T}{\partial y} = 0, \frac{\partial p}{\partial y} = 0, u = 0 \quad (6) \]

3.3. Parameter setting

3.3.1. Enhanced heat transfer coefficient
\[ E(K) = (k_m - k_o) \times 100\% \quad (7) \]

Where, \( k_m \) and \( k_o \) are the heat transfer coefficients under pulsating and without pulsation (steady-state).

3.3.2. Resistance coefficient
\[ E(\lambda) = (\frac{h_m}{h_o} - 1) \times 100\% = (\frac{\Delta p_m}{\Delta p_o} - 1) \times 100\% \quad (8) \]

Where, \( h_m \) and \( h_o \), respectively, is the average resistance loss period in pulsation and the resistance loss without pulsation. \( \Delta p_m \) and \( \Delta p_o \) are the average pressure drop period between inlet and outlet of the tube under pulsating conditions, and the pressure drop without pulsation.

3.3.3. Enhanced heat transfer comprehensive index.
The enhanced heat transfer comprehensive index used in this paper is based on the judgment criteria [8].
\[ E = \left( \frac{k_m}{k_o} \right)^{3.5} - \left( \frac{h_m}{h_o} \right) = \left( \frac{k_m}{k_o} \right)^{3.5} - \frac{\Delta p_m}{\Delta p_o} \quad (9) \]

If the comprehensive index is positive, it shows that the overall performance of the fluid pulsation is better than the steady state. Oppositely, the overall performance is worse due to fluid pulsating.

4. Simulation results analysis

4.1. Effect of pulsation amplitude on heat transfer and resistance
According to the setting of structural parameters in a practical engineering application, the range of pulsation amplitude is 0.2 ~ 1, which is divided into five groups for testing. The other four parameters are set to a fixed value. That is, \( u_s = 1 \text{ m/s}, f = 4 \text{Hz}, \gamma = 0.5 \) and \( e = 1 \text{mm} \).

In ‘figure 3’ and ‘figure 4’, it can be seen that both the enhanced heat transfer coefficient and the resistance coefficient increase obviously with the increase of pulsation amplitude. Considering the combined effect of heat transfer and resistance, further research and analysis are needed.

4.2. Effect of pulsation frequency on heat transfer and resistance
The range of pulsation frequency is selected to be 2Hz~10Hz and equally divided into five groups. And the other four parameters are fixed value, \( u_s = 1 \text{m/s}, A = 0.8, \gamma = 0.5, e = 1 \text{mm} \).

As can be seen from ‘figure 5’, the enhanced heat transfer coefficient increases significantly with increasing pulsation frequency firstly and then slow down. ‘figure 6’ shows that the resistance coefficient decreases and increases suddenly after the frequency \( f = 8 \text{Hz} \).

4.3. Effect of divergent segment-convergent segment ratio on heat transfer and resistance
The research scope of divergent segment-convergent segment ratio is 0.5 to 2, divided into four groups. The other parameters are set to a fixed value. Respectively, \( u_s = 1 \text{m/s}, A = 0.8, f = 4 \text{Hz}, e = 1 \text{mm} \).
The average velocity of fluid inlet takes 1m/s. The divergent segment-convergent segment ratio takes 0.5. The rib height takes 1mm, and the pulsation amplitude respectively takes 0.2, 0.4, 0.6, 0.8. The pulsation frequency respectively takes 2Hz, 4Hz, 6Hz, 8Hz.

In figure 7, the enhanced heat transfer coefficient increases and then decreases. As shown in figure 8, the divergent segment-convergent segment ratio is 1, the resistance coefficient increases obviously.

4.4. Effect of pulsation amplitude, pulsation frequency and divergent segment-convergent segment ratio on the enhanced heat transfer comprehensive index

The parameters are set as follows. The average velocity of fluid inlet takes 1m/s. The divergent segment-convergent segment ratio takes 0.5. The rib height takes 1mm, and the pulsation amplitude respectively takes 0.2, 0.4, 0.6, 0.8. The pulsation frequency respectively takes 2Hz, 4Hz, 6Hz, 8Hz.

From figure 9, it can be seen that the overall performance continuously increase. From figure 10, the comprehensive index first increase then tends to be gentle. In figure 11, the comprehensive index first increases and then decreases gradually. From figure 12, it shows that the enhanced heat transfer coefficient increases steadily. The maximum heat transfer coefficient can reach about 11.4%. And the enhanced heat transfer coefficient in all figures are positive to achieve enhanced heat transfer.
5. Conclusion

- The results of all simulation experiments can be seen that show that fluid pulsating in the tube significantly enhances the heat transfer performance of the tube;
- the pulsation of the fluid also directly causes the resistance of the tube to increase obviously;
- through the numerical simulation of the influence of various parameters on the heat transfer performance, the comprehensive heat transfer performance of the tube is enhanced.

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