Study on thermal-hydraulic characteristics of hybrid heat exchangers with interpolated etched plates

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Abstract—The Supercritical carbon dioxide (S-CO₂) Brayton cycle can be used to recover the exhaust heat energy of marine diesel engines. The hybrid heat exchanger is one of the potential solutions for heat exchange between flue gas and S-CO₂, but there is no good design theory and design method at present. The traditional hybrid heat exchanger has an one-to-one correspondence between the fin and the etched plate. However, under special requirements, it is necessary to insert etched plates in the hybrid heat exchanger to improve the thermal-hydraulic characteristics. In this study, four CFD models of the hybrid heat exchangers with interpolated etched plates were established. When the total mass flow rate and the total mass velocity are constant, the thermal-hydraulic characteristics of the hybrid heat exchanger are analyzed by Fluent. The results show that regardless of the constant mass flow rate or the constant mass velocity, inserting etched channels into the hybrid heat exchanger will increase the total heat transfer coefficient. When the total mass flow rate of the cold and hot fluids is unchanged, the heat transfer coefficient and pressure drop of the etched channel decrease with the increase of the inserted etched channel. When the total mass velocity of the hybrid heat exchanger is unchanged, the insertion of the etched channel causes the pressure drop and the convective heat transfer coefficient of the fin channel to increase. Meanwhile, the pressure drop and convective heat transfer coefficient of the etched channels are reduced, but the total heat transfer coefficient is increased. The study can provide guidance for the design of the hybrid heat exchangers.

1. Introduction

With its good characteristics, S-CO₂ Brayton cycle can be used in the field of ship engine exhaust heat recovery [1]. The equipment for heat exchange between flue gas and S-CO₂ is one of the core components for S-CO₂ Brayton cycle, which needs to withstand high temperature and high pressure. The hybrid heat exchanger made by diffusion bonding of fins and etched plates is one of the most potential solutions [2]. However, there is currently no effective solution for the design of the hybrid heat exchanger.

The composition of the flue gas is very complicated [3]. It contains not only nitrogen, carbon dioxide, water vapor, oxygen, but also nitrogen oxides, sulfur oxides and other gases. In particular, the
particulate matter of the flue gas is also very obvious, and its size and composition are also very complicated [4]. The acid gas in the exhaust gas may corrode the heat transfer surface and form oxides. In addition, its particulate matter is also very easy to adhere to the heat exchange surface, which is very easy to cause blockage of the heat exchanger, making the heat exchanger unable to work normally, and then affecting the performance of the S-CO₂ power generation system. Therefore, the circulation area of the fin channel is often much larger than that of the etched channel. The solution of one layer of fin channels corresponding to one layer of etched channels may not meet the requirements. Therefore, sometimes it is necessary to interpolate the etched channel to meet the design requirements.

For the design of the hybrid heat exchanger, the heat transfer, pressure drop, and strength of the hybrid heat exchanger need to be able to meet the requirements [5]. Current research focuses on the thermal-hydraulic characteristics of fin channels and etched channels. The researchers focuses on two aspects: to research the variation of convection heat transfer coefficient and fanning drag coefficient with operating conditions and geometry parameters of channels [6-7]; optimize the design of the local structure and overall size to obtain a balance between greater heat exchange and smaller pressure drop [8-9].

There are no related reports on the insertion of etched channels in conventional hybrid heat exchangers in the published literature. But in the design of hybrid heat exchangers, this is also an important issue that needs to be considered and solved. In this study, four corresponding situations are considered, which are 3 fin channels corresponding to 3 etched channels (3F&3E), 4 etched channels (3F&4E), 5 etched channels (3F&5E), and 6 etched channels (3F&6E). First, the computational fluid dynamics models under four conditions are established, and then considering the constant mass flow rate and equal mass velocity, the thermal-hydraulic characteristics of the hybrid heat exchanger are studied respectively. Finally, some useful conclusions are obtained about the interpolated etched channel of the hybrid heat exchanger.

2. Model and Numerical Simulation

The core of the hybrid heat exchanger is mainly diffusion bonding by fins, etched plates and baffles. In this study, four different cores were established (Fig. 1). Each model has 3 fin channels, but the number of etched channels are 3, 4, 5, and 6, respectively. The thickness of the fin channel is 0.6mm, the height is 4mm and the pitch is 3mm. The etched plate has a thickness of 2 mm and the semicircle channel has a diameter of 2 mm, a pitch of 3 mm. The thickness of the baffle is 1 mm. The length of the numerical model is 300mm.
3F&3E
3F&4E
3F&5E
3F&6E

Fig.1 CFD models and meshing

The material of the fluid in the fin channels is air, the fluid in the etched channels is S-CO$_2$, and the solid material is steel. The thermal properties of S-CO$_2$ and air are estimated based on the well-known software REFPROP. We correlated the properties of S-CO$_2$ and air with temperature and selected multiple typical points. The turbulence model used is SST K-omega turbulence models. The top and bottom of the model are translational boundary conditions, and the left and right are adiabatic boundary conditions. The convergence criteria for all residuals are set to be below $10^{-8}$ and with no observable change in the surface temperatures (in the final iterations). The independence of grid division is demonstrated first, and a grid that can meet the calculation accuracy and economic efficiency is obtained, as shown in Fig.1.

3. Results and Discussion

Two practical situations need to be considered when inserting etched channels in a hybrid heat exchanger. One is that the total mass flow rate of the hot and cold fluids of the hybrid heat exchanger is unchanged, and the height of heat exchanger core will change. The second is that the total size of the hybrid heat exchanger core remains unchanged, and increasing the etched channel will inevitably lead to a reduction in the number of fin channels. This study separately explores the thermal-hydraulic characteristics of the two practical situations.

3.1. Thermal-hydraulic characteristics under constant mass flow rate

Set the S-CO$_2$ inlet temperature to 600 K, the air inlet temperature to 720 K. The pressure of the air is 0.4 MPa, and the pressure of S-CO$_2$ is 15 MPa. The total mass flow rate of air and S-CO$_2$ channel is equal, respectively 0.018kg/s, 0.0027kg/s, 0.0036kg/s. The total mass flow rate is evenly distributed to each channel. As shown in Fig 2 and Fig 3, the heat transfer and pressure drop characteristics were
obtained. As the number of inserted etched channels increases, the mass flow rate of each fin channel does not change, while the mass flow rate of each etched channel decreases. With the increase in the number of inserted etched channels, the convective heat transfer coefficient on the side of the fin is basically unchanged, while the convective heat transfer coefficient on the side of the etched plate gradually decreases, but the total heat transfer coefficient is increasing. Each additional layer of etched channel will increase the total heat transfer coefficient by about 10W/(m²ꞏ℃). Because the convective heat transfer coefficient of S-CO₂ is much higher than that of air, increasing the etched channels objectively increases the heat transfer area of the etched channels, resulting in an increase in the total heat transfer coefficient. As the number of inserted etched channels increases, the pressure drop on the fin channel is basically unchanged, while the pressure drop on the side of the etched plate gradually decreases. The decrease in pressure drop of the etched channel is due to the decrease in the S-CO₂ mass flow rate.

Fig.2 The heat transfer characteristics under constant mass flow rate

Fig.3 The pressure drop characteristics under constant mass flow rate
3.2. Thermal-hydraulic characteristics under constant mass velocity corresponding core section

Set the S-CO$_2$ inlet temperature to 600 K, the air inlet temperature to 720 K. The pressure of the air is 0.4 MPa, and the pressure of S-CO$_2$ is 15 MPa. The total mass flow rate of 3F&3E is equal, respectively 0.018kg/s, 0.0027kg/s, 0.0036kg/s. Taking the mass velocity of 3F&3E as the benchmark, the mass flow rates of the remaining models were calculated under different total mass flow rates. As the inserted etched channel increases, the mass flow rate of the fin channel and the etched channel is changed to keep the mass velocity consistent. For example, in model 3F&4E, the mass flow of each fin channel is 0.0006571kg/s, 0.0009857kg/s, 0.001314kg/s, corresponding to the etched channel 0.0004929kg/s, 0.0007393kg/s, 0.0009857kg/ s. The heat transfer and pressure drop characteristics of the fin channel and the etched channel were obtained, as shown in Fig 4 and Fig 5. When the total mass velocity of the hybrid heat exchanger is unchanged, the insertion of the etched channel causes the pressure drop and the convective heat transfer coefficient of the fin channel to increase. At the same time, the pressure drop and convective heat transfer coefficient of the etched channels are reduced, but the total heat transfer coefficient is increased. Each additional layer of etched channel will increase the total heat transfer coefficient by about 35W/(m$^2$·K). When the pressure drop limit of the fin channel is not high, inserting the etching channel increases the total convective heat transfer coefficient.

![Fig.4 The heat transfer characteristics under constant mass velocity](image-url)
4. Conclusion
In this study, the thermal-hydraulic characteristics of the hybrid heat exchangers with interpolated etched channels were studied at constant mass flow rate and constant mass velocity. The models of the hybrid heat exchanger are 3 fin channels corresponding to 3 etched channels, 4 etched channels, 5 etched channels and 6 etched channels. The main conclusions are as follows:

(1) When the total mass flow rate of the cold and hot fluids of the hybrid heat exchanger is unchanged, inserting the etched channel causes the volume of the heat exchanger to increase. The heat transfer coefficient and pressure drop of the etched channel decrease with the increase of the inserted etched channel. However, the total convective heat transfer coefficient of the heat exchanger increases.

(2) When the total mass velocity of the hybrid heat exchanger is unchanged, the insertion of the etched channel causes the pressure drop and the convective heat transfer coefficient of the fin channel to increase. Meanwhile, the pressure drop and convective heat transfer coefficient of the etched channels are reduced, but the total heat transfer coefficient is increased.

(3) Regardless of the constant mass flow rate or the constant mass velocity, inserting etched channels into the hybrid heat exchanger will increase the total heat transfer coefficient. In future research, the flow channel design and the number of layers can be used as research points to improve the thermal-hydraulic characteristics of the heat exchanger.

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