Study on heat transfer and pressure drop characteristics in marine S-CO₂ power cycle hybrid heat exchangers

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Abstract. The S-CO₂ power cycle has the advantages of compact structure and high energy density, which can be used to recover the waste heat of ship exhaust, thus improving the energy efficiency of ships and reducing emissions. The hybrid heat exchangers with etched plates and fins can be used as the heat transfer device of S-CO₂ and exhaust, its heat transfer and pressure drop characteristics have a great influence on S-CO₂ power cycle performance. In this study, a CFD model of the hybrid heat exchangers was established. The effects of different exhaust inlet temperatures, inlet mass flow rates and inlet pressures on the heat transfer and the pressure drop characteristics were analyzed by Fluent. The results show that the inlet temperatures and inlet mass flow rates of exhaust have a great influence on the heat transfer characteristics of the hybrid heat exchanger. The inlet mass flow rates and inlet pressures of exhaust have a great influence on the pressure drop characteristics of the hybrid heat exchangers. In the design of the hybrid heat exchangers, the status of the exhaust need to be considered to ensure efficient operation of the heat exchangers. The study can provide guidance for the design of the hybrid heat exchangers.

1 Introduction

The application of S-CO₂ power cycle in ship waste heat recovery can reduce fuel consumption and protect the environment. The S-CO₂ power cycle uses CO₂ in the supercritical state as the working medium to convert the thermal energy of the heat source into mechanical energy. S-CO₂ is suitable for thermodynamics cycles due to its good fluidity, high heat transfer efficiency, low compressibility and chemical stability [1]. Due to the limited space inside the ship, the requirements for the volume of equipments are strict. Compared with Rankine cycle, S-CO₂ power cycle has the advantages of small size and high energy conversion efficiency, so it has advantages in application on ships. Combs et al. [2] of Massachusetts Institute of Technology have done research on the use of S-CO₂ power cycle in the recovery of exhaust heat from naval ships in the 1970s. Echogen Power Systems [3] designed the commercial S-CO₂ generator set EPS100, confirming the feasibility of a megawatt S-CO₂ generator set.

In the S-CO₂ power cycle where nuclear energy and solar energy are heat sources, the heat source fluid is relatively clean, so the heat exchangers are mainly printed circuit heat exchangers (PCHEs) [4]. The ship exhaust is complex, and the tar and particulate matter are likely to cause blockage of the PCHEs channel, making

it unable to work properly. Conventional plate-fin heat exchangers (PFHEs) and shell-and-tube heat exchangers are difficult to meet the compactness requirements and withstand the high pressure of S-CO₂. The hybrid heat exchangers with etched plates and fins through diffusion welding are an effective solution for marine S-CO₂ power cycle heat exchangers. The fluid in the etched channels is S-CO₂, and the fluid in the fin channels is the exhaust.

At present, there are few studies on the heat transfer and pressure drop characteristics of marine S-CO₂ power cycle hybrid heat exchangers, but many studies have been carried out on PCHEs and PFHEs. The research on PCHEs and PFHEs mainly 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 [5-6]; optimize the design of the local structure and overall size to obtain a balance between greater heat exchange and smaller pressure drop [7-8].

The exhaust characteristics of marine low-speed two-stroke diesel engines are mainly reflected in temperatures, pressures and mass flow rates changing with the loads of the diesel engines. In this study, a CFD model of the hybrid heat exchanger was established, and then the effects of the exhaust inlet temperatures, the mass flow rates, and the pressures on the heat transfer and pressure drop characteristics of the hybrid heat exchangers were

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analyzed. Finally, some conclusions have been drawn regarding the influence of diesel engine exhaust characteristics on the heat transfer and pressure drop characteristics of hybrid heat exchangers.

2 Model and numerical simulation

The core of the hybrid heat exchanger is mainly diffusion welded by fins, etched plates and baffles. In this study, a hybrid heat exchanger is designed, and the periodic unit is shown in Figure 1. The thickness of the fin is 0.6 mm,

the height of the fin channel is 3.4 mm, and the width of the channel is 2.4 mm. 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, where the length divided by the hydraulic diameter is greater than 65, and the influence of the inlet section can be ignored.

Fig 1. CFD model and meshing

Due to the complex composition of diesel exhaust, it is not easy to calibrate with accurate physical parameters, and the air thermal physical properties is very close to the diesel exhaust, so air is used to represent diesel exhaust. The material of the fluid in the fin channels is air, the fluid in the etched channels is S-CO₂, and the solid material is steel. 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 calculation satisfies conservation of mass, momentum, and energy and the residuals of K and omega are set to the 10⁻⁸. 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 Figure 1. Then, it was found that Type A and Type B are basically the same in calculating the heat transfer and pressure drop of the hybrid heat exchanger, and can be replaced with each other. In this study, Type B fins are selected for calculation.

3 Results and discussion

The exhaust characteristics of marine low-speed two-stroke diesel engines change with diesel engine loads, and the changes in exhaust characteristics are reflected in

temperatures, mass flow rates and pressures. The effects of temperatures, mass flow rates and pressures on the heat transfer and pressure drop characteristics of hybrid heat exchangers were studied separately.

3.1 Effect of different air inlet temperatures

Set the S-CO₂ inlet temperature to 600 K, change the air inlet temperature from 620 K to 700 K, and the step size is 20 K. The pressure of the air is 0.4 MPa, and the pressure of S-CO₂ is 15 MPa. The mass flow rate of air is 0.0006 kg/s, and the mass flow rate of S-CO₂ is 0.0006 kg/s. As shown in Fig 2 and Fig 3, the heat transfer and pressure drop characteristics were obtained. As the air inlet temperature increases linearly, the total heat transfer rate also increases linearly. However, the convection heat transfer coefficients of air and S-CO₂ remain basically unchanged. For every 20 K increase in air inlet temperature, the total heat transfer rate increases by 7.32 W. The convection heat transfer coefficient of air is about 485 W/m²-K, and the convection heat transfer coefficient of S-CO₂ is about 2355 W/m²-K. With the increase of the air inlet temperature, the pressure drop between the fin channel and the etched channel slightly increases, but f basically remains unchanged. The f of the air in the fin channel is about 0.35, which is higher than 0.28 of the S-CO₂ in the etched channel.

Fig 2. Effect of different air inlet temperatures on heat transfer characteristics

Fig 3. Effect of different air inlet temperatures on pressure drop characteristics

3.2 Effect of different air inlet mass flow rates

Set the S-CO₂ mass flow rate to 0.0006 kg/s. Set the air mass flow rate from 0.0004 kg/s to 0.0008 kg/s, and the step size is 0.0001 kg/s. The air inlet temperature is 700 K and the S-CO₂ inlet temperature is 600 K. The air pressure is 0.4 MPa and the S-CO₂ pressure is 15 MPa. 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. As the air inlet mass flow rate increases linearly, the total heat transfer rate and the convection heat transfer coefficient of air increases

linearly. For every 0.0001 kg/s increase in the inlet mass flow rate, the total heat transfer rate increases by 3.19 W, and the convection heat transfer coefficient of air increases by 53.77 W/m²·K. The convection heat transfer coefficient of S-CO₂ in the etched channel remains basically unchanged at 2366 W/m²·K. As the air inlet mass flow rate increases linearly, the pressure drop of air decreases. However, the f of air in the fin channel decreases. For every increase of 0.0001 kg/s of air inlet mass flow, the air pressure drop will increase by about 1377 Pa, while F decreases by about 0.002. The pressure drop and f of S-CO₂ in the etched channel remain basically unchanged at 4029 Pa and 0.029 respectively.

Fig 4. Effect of different air inlet mass flow rates on heat transfer characteristics

Fig 5. Effect of different air inlet mass flow rates on pressure drop characteristics

3.3 Effect of different air inlet pressures

Set the S-CO₂ inlet mass flow rate to 0.0006 kg/s and the air inlet mass flow rate to 0.0006 kg/s. Set the S-CO₂ inlet temperature to 600K and the air inlet temperature to 700 K. The air pressure is set from 0.1 MPa to 0.5 MPa, the step size is 0.1 MPa. The S-CO₂ pressure is 15 MPa. As shown in Fig 6 and Fig 7, the heat transfer and pressure drop characteristics of the fin channel and the etched channel were obtained. As the air inlet pressure increases linearly, the total heat transfer rate and the

convection heat transfer coefficient of air and S-CO₂ remain basically unchanged. The total heat transfer rate is about 36.58 W. The convection heat transfer coefficient of air is about 494 W/m²-K, and the convection heat transfer coefficient of S-CO₂ is about 2364 W/m²-K. As the air inlet pressure increases linearly, the pressure drop of air decreases. At the same time, the pressure drop of S-CO₂ remains basically unchanged at 4029Pa. The f of air in the fin channel and S-CO₂ in the etched channel remain basically unchanged, at 0.035 and 0.029 respectively.

Fig 6. Effect of different air inlet pressures on heat transfer characteristics

Fig 7. Effect of different air inlet pressures on pressure drop characteristics

4 Conclusion

In this study, a CFD model of the hybrid heat exchanger was established. The effects of different exhaust inlet temperatures, mass flow rates, and pressures on the heat transfer and pressure drop characteristics were analyzed. The main conclusions are as follows:

1) The temperature change of the exhaust will significantly affect the total heat transfer rate, and has little effect on the convection heat transfer coefficient and pressure drop characteristics.

2) The increase in exhaust mass flow rates can enhance the heat transfer characteristics on the fin channel, but the pressure drop also increases significantly.

3) When the exhaust temperature and mass flow rate are constant, the pressure has little effect on the heat transfer characteristics. The pressure drop of the fin channel decreases with the increase of the exhaust inlet pressure, and the pressure drop on the etched channel is basically unchanged.

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