

Study on Flow and Heat Transfer in Supercritical CO₂ in Micro-channel Heat Exchanger

Zhenwen Wei^{1, a}, Yanchao Jin^{1, b}, Jianbo Cui^{1, c}, Yazhou Han^{1, d}, Liangzhao Sun^{2, e}, Yan He^{2, f} and Gongpeng Wu^{1,2, g}

¹Doright Co., Ltd, Qingdao, China

²Qingdao University of Science and Technology, Qingdao, China

^az3692581471214@163.com, ^blynpersonal@163.com, ^c1921728390@qq.com,
^dusthanyazhou@163.com, ^esunliangzhao2023@163.com, ^fheyanqustjd@163.com,
^g15866117958@163.com

Abstract. In order to investigate the flow and heat transfer performances of supercritical CO₂ in the PCHE, a two-dimensional micro-channel heat transfer model was established. The impacts of the airfoil fin arrangement on flow and heat transfer of supercritical CO₂ in a PCHE were studied using Computational Fluid Dynamics software. The results show that the transfer efficiency of PCHE can be effectively improved by reducing the abeam and vertical distances between airfoil fins. However, the pressure drop of supercritical CO₂ flow in the microchannel reduces with an increase in abeam and vertical spacing distances.

Keywords: Supercritical; Numerical simulation; Flow and heat transfer; Microchannels.

1. Introduction

Printed Circuit Heat Exchanger (PCHE) is a compact plate heat exchanger designed for heat transfer in the microchannels. It has been widely used in various fields including renewable energy and marine fields because of its excellent heat transfer and high compactness [1, 2]. To enhance the flow and heat transfer performance of the PCHE, researchers recently used supercritical CO₂ as a new working fluid and modified the shape and arrangements of fins in the channel.

Yan et al. [3] proposed a non-continuous staggered airfoil heat transfer fin with a sinusoidal arrangement. They analyzed the effects of structural features of the fins and channels on the heat transfer efficiency of supercritical CO₂ under different channels and compared with the conventional folded fins. The simulation results show that under the same working condition, flow and heat transfer performances of the proposed heat transfer channel is better and pressure drop increases by about 31.14%. Liu et al. [4] conducted a theoretical and numerical study on the effectiveness and efficiency of a straight-channel PCHE fin. They obtained the vertical distribution of fins by means of deriving the heat conduction equation on it. The results show that the effectiveness of the PCHE fins can be improved by choosing a fin with high thermal conductivity, reducing the ratio of fin thickness to channel radius, or lowering convection coefficient. Chu et al. [5] numerically investigated geometrical parameters of the airfoil fin. The results show that heat transfer rate decreased due to significant changes of supercritical CO₂ properties, but pressure drop along the main flow direction remained nearly constant. Though the heat transfer performance of the PCHE under supercritical fluid conditions has been studied, the heat transfer mechanism and structural optimization of supercritical PCHE still remain challengeable and need to be further explored because of complex physical properties of supercritical fluids and unique microchannel characteristics.

In this work, flow and heat transfer performances of supercritical CO₂ fluid in the PCHE with airfoil fin were studied through numerical simulation method. The influences of airfoil fin arrangement on flow and heat transfer performances of supercritical CO₂ were analyzed. The deep heat transfer mechanisms of supercritical CO₂ fluid in the PCHE were revealed.

2. Method

2.1. Physical Model and Mesh Generation

In this paper, a two-dimensional physical model was established. The computational domain includes the CO₂ fluid domain and the solid airfoil fins domain. Fig.1 illustrates the fin arrangement. The physical model has a width of 1.1mm, a channel length of 10mm. The dimensions of fins are 1mm in length and a maximum of 0.2mm in width. The abeam and vertical distances between two fins were used as variables.

A quadrilateral mesh with a grid size of 0.02mm was used. To meet the computation accuracy, it was necessary to separately set up boundary layer meshes. The mesh size is a quarter of the fluid domain mesh and the boundary layers' width is 0.1mm. The physical model mesh is shown in Fig 2.

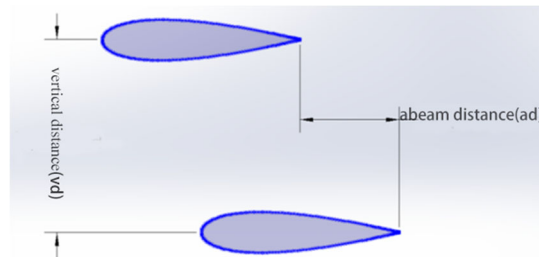


Fig. 1 The arrangement of airfoil fins

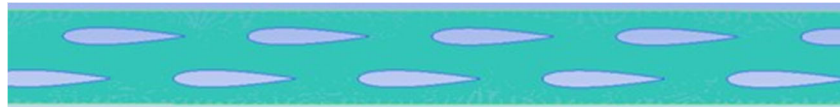


Fig. 2 Physical model mesh

2.2. Boundary Conditions and Solution Methods

The fin wall was set as stable thermal conditions with a wall temperature of 300K. The inlet mass flux was 300kg/m³ and the temperature was 411K. The outlet pressure is 6.5Mpa. The SST k-ε model was used as the turbulence model and the SIMPLEC algorithm was employed to solve the velocity and pressure coupling. The second order upwind scheme was used for discretization. The supercritical CO₂'s properties were accurately reflected by the fitting method. The residual for the mass and momentum transport equations were set at 10⁻⁴ and it was 10⁻⁶ for the energy transport equation.

A model validation was performed in this study according to the method proposed by Chu et al^[5]. Comparing the computational results with the experimental data, the average error for the outlet temperature and flow pressure drop in the PCHE was less than 10%.

2.3. Simulation data processing

The average convective heat transfer coefficient h can be calculated by:

$$h = \frac{q}{T_w - T_b} \quad (1)$$

Where q is the heat flux, T_w is the wall temperature of PCHE inner wing fins, T_b is the average temperature of supercritical CO₂ as flows through the PCHE channel, which can be derived directly from the FLUENT software.

3. Results and Discussion

3.1. Impacts of wing rib arrangement distribution on local flow and heat transfer

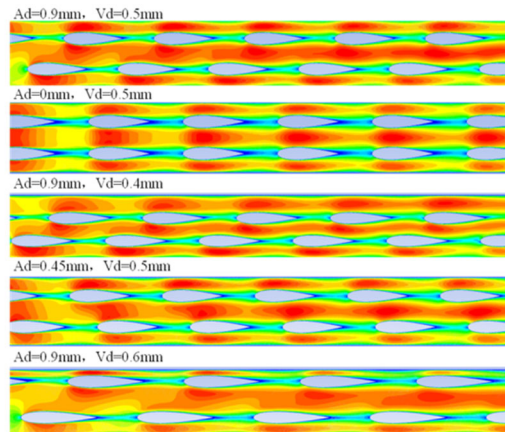


Fig. 3 The velocity distribution in different channels.

Fig.3 illustrates the velocity distribution in channels with different abeam and vertical distances between the airfoil fins. As the abeam distance increases from 0mm to 0.9mm, there is no significant difference in the velocity distribution, indicating minimal velocity variations. Furthermore, when $Ad=0$ mm, the velocity at the rear of the fins is high, suggesting that the flow uniformity of the fluid was improved with the increase in vertical distance. In addition, the difference between the maximum and minimum flow velocities is lower in the abeam direction than $Ad=0.9$ mm. Therefore, increasing the abeam distance of the fins promotes a more uniform fluid flow. Under identical conditions, small differences in fluid velocity can be observed when $Vd=0.4$ mm and 0.6 mm. At $Vd=0.5$ mm, the velocity in the channel is large and the distribution is more uniform. Since the fins are designed with a wide head and a narrow tail, the flow path is more likely to be streamlined when the fins are arranged at abeam spacing.

Fig.4 illustrates the temperature distribution when the fins are arranged at different abeam and vertical distances. At $Ad=0.9$ mm and $Vd=0.6$ mm, great color variations are observed in the temperature contour map. This means an increase in both abeam and vertical distance results in the non-uniform temperature distribution at the rear of fins. According to Fig.3, the velocity at the rear of the fins displays a greater variation compared to the mainstream, thus, significant temperature difference occurs between these two areas.

Fig.5 illustrates the pressure distribution when the fins are arranged at different abeam and vertical distances. The pressure of the supercritical CO_2 in the channel decreases along the flow direction. Additionally, the pressure decrement increases as approaching the outlet of the channel. The analysis shows that a decrease of the boundary layer's thickness during fluid flow leads to an increase in velocity within the channel. Consequently, the pressure loss increases sharply, and the pressure drop also enlarges. When the abeam distance between the fins increases, the magnitude of pressure loss decreases. Under the same condition of $Ad=0.9$ mm, the reduction of the vertical distance between the fins leads to an increase in pressure drop. The cross-section area of the channel is affected by the vertical distance between the fins, and a decrease in this distance results in a reduction in the channel's cross-section area, causing an increase of fluid velocity and pressure drop.

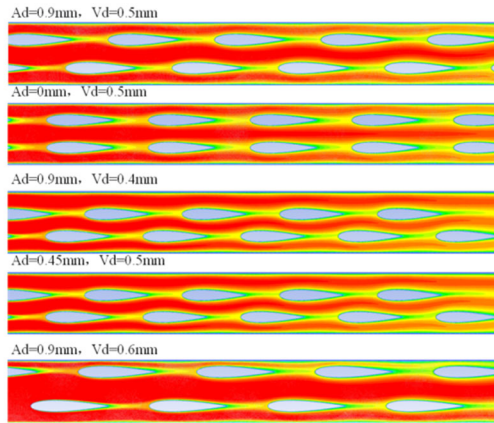


Fig. 4 The temperature distribution in different channels

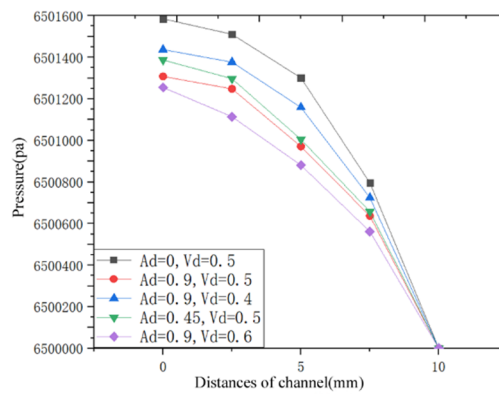


Fig. 5 Pressure distribution along the flow direction

3.2. Impacts of wing rib arrangement distribution on overall flow and heat transfer

Fig.6 illustrates the impacts of the abeam and vertical distance on the average convective heat transfer coefficient under different mass flow conditions. It was found that the convective heat transfer coefficient of supercritical CO₂ increases with reducing the abeam and vertical distance of the fins. Specifically, when Ad=0 mm and Vd=0.5 mm, the heat transfer coefficient reaches the maximum. As mentioned earlier, the non-uniformity and disturbance of the fluid flow raises because of the small fin spacing, promoting the heat transfer between supercritical CO₂ and the airfoil fins. Furthermore, at the Ad=0.9mm and Vd=0.6mm, the heat transfer coefficient decreases significantly compared to other fin arrangements. This may be due to the fact that fins are staggered at a large distance and the fluid flow is stable. Consequently, the fluid boundary layer is not easy to be destroyed and the convective heat transfer coefficient becomes small.

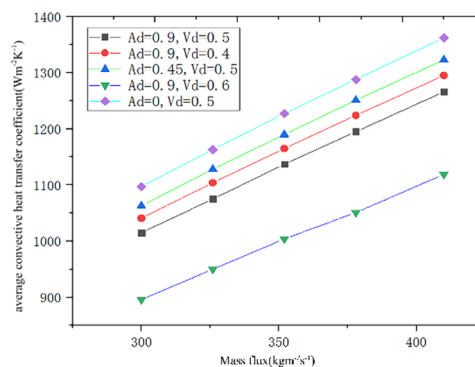


Fig. 6 The variations of convective heat transfer coefficient along the mass flow

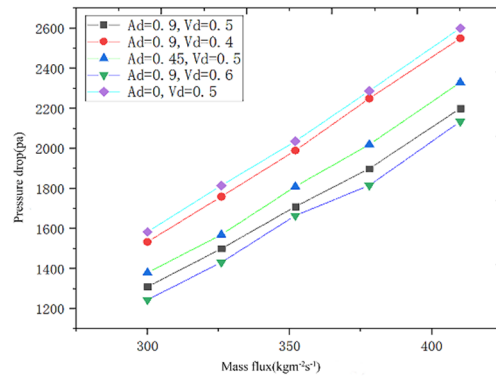


Fig. 7 The variations in pressure drop with mass flux in different flow channels

Fig.7 illustrates the variations in pressure drop with mass flux under different abeam and vertical distances in fins. It can be seen that pressure drop along the channel increases with the increasing of mass flux. Furthermore, pressure drop reduces with the increasing of the abeam and vertical distances between the fins. This is related to the fact that the increasing of the fin space reduces the disturbance between the fluid and the fins.

In summary, enhancing heat transfer performance in a flow channel was accomplished by adjusting the abeam distance or properly reducing the vertical distance.

4. Conclusion

Numerical simulation was employed to study the heat transfer characteristics and mechanisms of supercritical CO₂ fluid in the PCHE, in terms of airfoil fin arrangements. The main conclusions were summarized as follows:

- (1). When the abeam spacing between the fins increases, the variation of supercritical CO₂ flow velocity decreases along the channel. Moreover, the variation in pressure drop gradually increases with flow development of supercritical CO₂.
- (2). Compared to other channels, the heat transfer efficiency in the PCHE is the highest when Ad=0.45mm and Vd=0.5mm. Within the scope of this study, the convective heat transfer capability of the PCHE can be improved effectively via reducing the vertical and abeam distances between the airfoil fins.
- (3). Pressure drop in channels can be decreased by increasing the abeam and vertical spacing distances between the airfoil fins.

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