NUMERICAL SIMULATION AND EXPERIMENT OF LAMINAR HEAT TRANSFER CHARACTERISTICS IN MICRO-CHANNEL COLLECTOR

by

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In response to the problems of high mass and high thermal resistance in traditional cold plate collectors, the author proposes a shaped and efficient micro-channel collector structure design for non-normal temperature control scenarios such as high power, multiple heat sources, and highly non-uniform power density. The author conducted numerical and experimental studies on the laminar heat transfer in a highly efficient micro-channel shaped collector for non-normal temperature control scenarios such as high power, multiple heat sources, and highly non-uniform power density, the results show that: The relative deviation between the simulated and experimental values of the pressure drop of the micro-channel collector using perfluorotriethylamine as the working fluid is within –20%, and the relative deviation between the simulated and experimental values of the surface temperature is within +3 ° C, the predicted trend of the pressure drop and temperature field of the collector is in good agreement with the experimental values, indicating the feasibility of using numerical simulation methods for performance analysis and design optimization of 3-D printed micro-channel collectors. As the flow rate increases, the pressure drop of the collector increases approximately linearly, while the value increase of the total heat transfer coefficient gradually decreases, and increasing inlet temperature or heating power will reduce pressure drop of collector and increase total heat transfer coefficient. The influence of gravity on the pressure drop and total heat transfer coefficient of micro-channel collectors is less than 1. The straight through micro-channel collector has lower pressure drop and stronger heat transfer ability compared to the folded type collector.

Key words*: heat transfer characteristics, shaped micro-channel collector, laminar flow, numerical simulation, high power heat source*

Introduction

As a new type of microscale heat exchanger, micro-channel heat exchanger has been widely used in aerospace, electronic industry, nuclear reactor and other fields [1]. However, with the development of equipment integration and miniaturization, micro-channel heat exchangers that combine traditional working fluids with conventional flat structures can no longer meet the growing heat transfer needs, further research is needed on the flow and heat transfer characteristics of micro-channel heat exchangers from the perspectives of heat exchange working fluids, micro-channel structures, and external physical fields. Heat exchanger is a widely used heat exchange equipment in industry. In recent years, with the continuous growth of energy demand and material costs, the development of energy-saving energy supply chain has been promoted. Among

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various types of heat exchangers, shell and pipe-line heat exchangers are still the most widely used types. The main factors affecting the size and cost of the furnace are the heat transfer rate of the pipe-line and the pressure drop in the tube. While enhancing heat transfer inside the tube, it is often accompanied by a decrease in pressure drop loss, resulting in a decrease in energy utilization efficiency. Therefore, developing theories and technologies to enhance heat transfer and reduce drag in pipes is the key to improving energy utilization efficiency [2].

In order to enhance convective heat transfer within the tube without increasing the flow resistance, inserting objects inside the tube is often a simple and economical choice. Common insertions in pipes include vortex generators, spiral coils, conical rings, conical plates, spiral rotors, and spiral twisted belts. The principle of a vortex generator is to use its certain angle of attack to generate a certain strength of longitudinal vortices in the fluid, and under a certain pressure pushing effect, its wake can stably extend to a place far downstream, driving the downstream fluid to rotate, scouring the wall, disturbing the boundary-layer and strengthening heat transfer [3]. The spiral coil mainly makes the fluid near the pipe wall generate swirling flow, which periodically disturbs the boundary-layer and stops its development. The conical ring/plate utilizes its rapidly shrinking and expanding flow area to make turbulence more severe. Spiral twisted tape is the most widely used insert in pipes, and the longitudinal vortex formed by it can significantly enhance heat transfer inside the pipe, but at the same time, the presence of twisted tape brings about significant pressure drop. Figure 1 shows the heat exchange system [4].

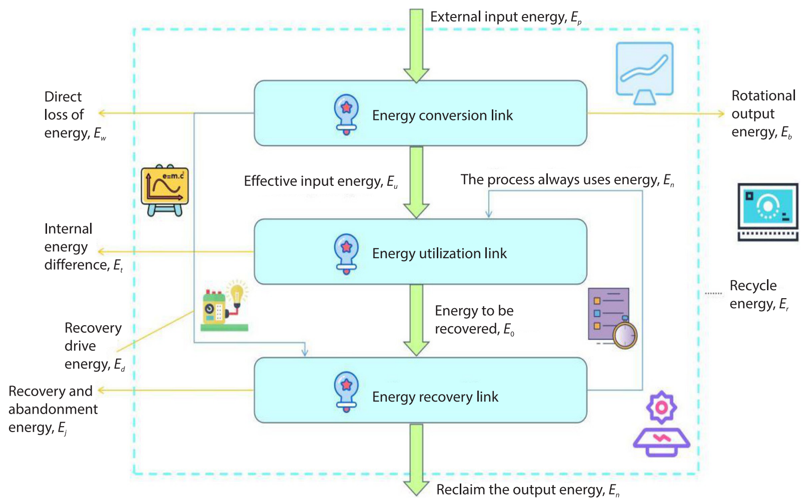

Figure 1. Heat exchange system

The author first proposes a design of a shaped and efficient micro-channel collector structure for non-normal temperature control scenarios such as high power, multiple heat sources, and highly non-uniform power density, in response to the problems of high mass and high thermal resistance in traditional cold plate collectors. Then, combining numerical simulation and experimental results, the effects of flow rate, inlet temperature, heating power, and gravity on the heat transfer characteristics of the author are analyzed, and the relationship between the variation of collector coefficient and Nusselt number is obtained. This provides guidance for the design of the collector's working conditions and the optimization process, in order to improve the collector's heat collection capacity [5].

Physical and numerical models

Physical model

The structure of the micro-channel collector studied by the author: the collector collects heat from six different heat sources (regions), with a power density ratio of 3:12:12:3:2:8 for regions 1-6. The heat exchange working fluid is perfluorotriethylamine, which flows in from the inlet and carries out the heat generated by the heat source through a zigzag flow channel, the flow channel has a total of four cavity structure flow zones, which can change the direction of fluid transport. From the cross-section of the collector channel, it can be seen that the collector channel has a total of five channel units, each consisting of five rectangular micro-channels [6, 7].

Numerical methods

The finite volume method is used to solve the governing equations, and the simplified Method 5 is used to solve the coupling problems of velocity and pressure fields. In energy equation, the convection time is discretized using the second upwind theory, the diffusion time is average difference, and the pressure time is discretized using the pressure theory. The discretization of the convection and diffusion terms in the energy equation adopts a second-order upwind scheme and a central difference scheme, respectively. The residual control of the energy equation is 10^{-8}, while the residual control of other equations is 10^{-5} [8].

Parameter definition

In order to more accurately simulate the impact of temperature changes on fluid-flow and heat transfer characteristics, fit the physical parameters of perfluorotriethylamine as a polynomial with respect to temperature and add them through a user-defined function [9].

Grid division

The computational model of the micro-channel collector studied by the author adopts a mixed grid, where the solid region is a tetrahedral grid and the fluid region is a hexahedral grid. This cannot only improve the computational accuracy and convergence of the fluid region, but also reduce the consumption of computational resources, saving grid division and computational time. The computational model adopted by the author has passed the grid independence assessment.

Experimental methods and numerical model validation

The flow and heat transfer characteristics of a 3-D printed micro-channel collector were tested using a single-phase fluid loop heat transfer test platform [10, 11]. The heat exchange working fluid is perfluorotriethylamine, and a micro flowmeter (suitable for medium temperature: –40~100 °C, range: 0.55~5.5 Lpm, accuracy better than ±0.5% R. S.) is used to measure the loop flow rate, the inlet/outlet of the collector is equipped with an absolute pressure sensor (suitable for medium temperature: –40~85 °C, range: 0~500 kPa, accuracy better than +0.25% F. S.) and a Pt100 temperature sensor (range: –40~85 °C, accuracy Level B), in order to obtain pressure and temperature data at the inlet/outlet of the collector. Several *T*-type thermocouples (range: –40~85 °C, tolerance: ±0.5 °C) are pasted with silicone rubber on the surface of the collector to obtain its surface temperature distribution. The entire circuit is wrapped with rubber plastic insulation cotton for insulation treatment, and the heat collected by the circuit is taken away by the chiller through a plate heat exchanger [12]. A cylindrical aluminum alloy block with a central opening is installed in the circular arc area of the collector, and an electrically heated ceramic rod is inserted at the opening to simulate the heat generated by the heat source, the total heating power under typical working conditions is 600 W.

Result analysis

Analyze the simulation results of the aforementioned micro-channel collector

From figs. 2 and 3, it can be seen that with the increase of flow rate, the pressure drop of collector increases approximately linearly, but the growth of total heat transfer coefficient gradually decreases with the increase of flow rate. Correspondingly, the maximum, T_{max}, the minimum temperature, T_{min}, and the temperature difference, $T_{max} - T_{min}$, on the surface of the collector gradually decrease with the increase of the flow rate, but the decreasing trend. Therefore, keeping the total flow rate constant, transforming the tortuous flow to the straight from the mode, reducing the flow rate for a single channel and the distance from the way, can reduce the total pressure drop of the author [13, 14]. In addition, the flow rate when the total heat transfer coefficient changes slowly can be set as a typical working condition, which cannot only ensure the heat exchange capacity of the collector, but also avoid excessive pressure loss in the collector.

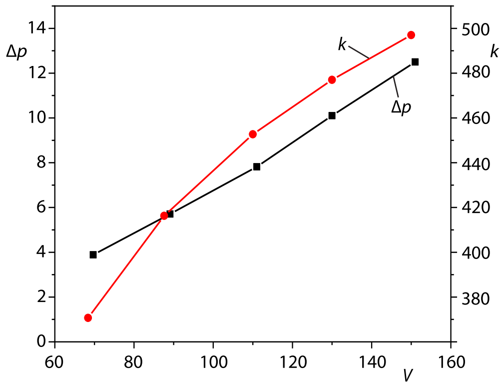

Figure 2. Effect of flow rate on pressure drop and total heat transfer coefficient of collector

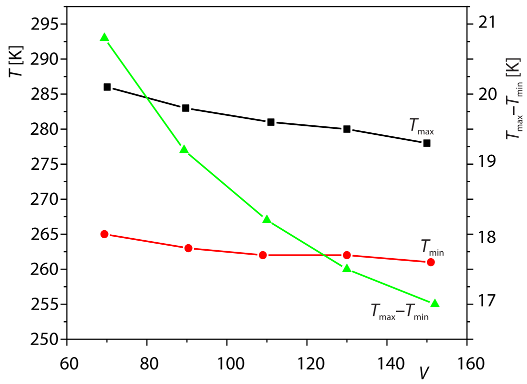

Figure 3. Effect of flow rate on the surface temperature of a collector

Effect of inlet temperature on heat transfer characteristics of collectors

It can be seen from figs. 4 and 5 that with the increase of inlet temperature, the pressure drop of the collector gradually decreases, and the total heat transfer coefficient gradually increases, this is because an increase in inlet temperature will cause a decrease in viscosity and an increase in thermal conductivity of perfluorotriethylamine, the former reduces the resistance of fluid-flow, while the latter enhances the ability of fluid heat transfer [15]. Although the heat transfer capacity of the collector increases with the increase of fluid inlet temperature, the surface temperature level of the collector is still determined by the inlet temperature, and the temperature uniformity improves with the increase of fluid thermal diffusion ability. In addition, reducing the inlet temperature can more effectively reduce the surface temperature level of the collector with less head loss compared to increasing the flow rate.

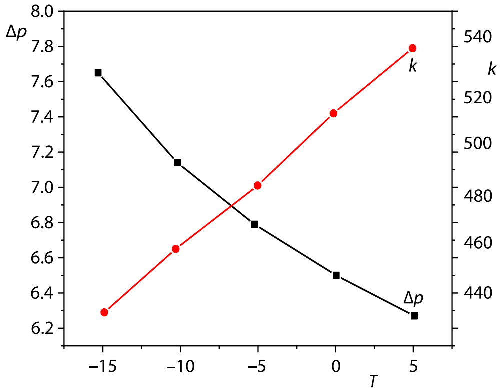

Figure 4. Influence of inlet temperature on pressure drop and total heat transfer coefficient of collector

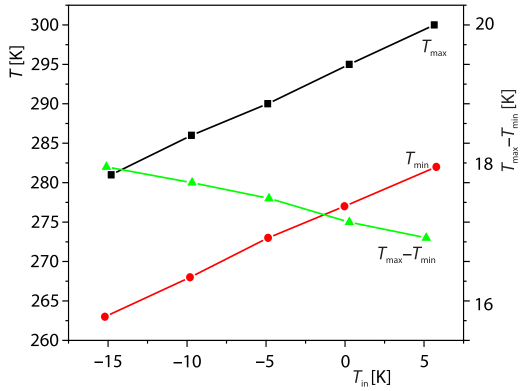

Figure 5. Effect of inlet temperature on the surface temperature of a collector

The influence of gravity on the heat transfer characteristics of collectors

The calculation results show that the difference between pressure drop and total heat transfer coefficient in microgravity and oxygen absorption is less than 1%, and the flow rate and heat transfer performance of the micro-channel collector in microgravity can be evaluated by ground experiment [16, 17].

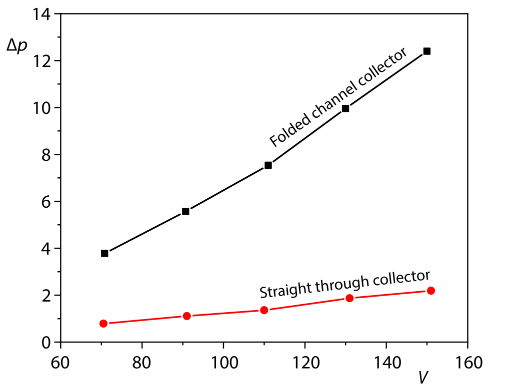

Figure 6. Comparison of pressure drop of collectors with different structural forms

Structural optimization

In order to further reduce the flow pressure drop and surface temperature level inside the collector, the author optimized the structure of the collector and changed the flow channel from a broken line type to a straight through type [18-20]. Simulate and calculate the heat transfer characteristics of the collector, and the results are shown in fig. 6. It can be seen that under the condition of constant total flow rate, the flow rate and distance within a single channel of a straight through micro-channel collector are significantly reduced, its pressure drop is reduced by about 79-82% compared to the curved micro-channel collector.

Conclusion

In response to the heat transfer and dissipation needs of high power, multiple heat sources, and highly non-uniform power density in satellite loads, the author has developed a 3-D printed shaped micro-channel collector. Based on the tests, the feasibility of numerical simulation is used to predict the complex flow and heat transfer characteristics of the micro-channel collector. Numerical simulation and numerical simulation have studied the effects of flow rate, inlet temperature, thermal energy, and gravity on laminar heat transfer characteristics in the authors, an empirical correlation between the collector resistance coefficient and Nusselt number was obtained, and optimized the configuration of the micro-channel collector. The results show that with the increase of flow rate, the pressure drop of the collector increases approximately linearly, while the increase rate of the total heat transfer coefficient decreases gradually. Increasing the inlet temperature or thermal power will reduce the pressure drop of the collector and increase the total heat transfer coefficient. In the future, the simulation model of the micro-channel collector will be further optimized to improve its prediction accuracy of pressure drop and design accuracy.

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