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RESEARCH ON FLOW HEAT TRANSFER CHARACTERISTICS OF HEAT EXCHANGER BASED ON BIONIC FRACTAL STRUCTURE

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Abstract

Aiming at the requirements of aero-engine thermal management system, a bionic fractal structure heat exchanger is proposed, and the internal flow heat transfer problem is studied numerically and experimentally. Through research, it is found that the mimic alveolar pore structure can effectively improve the efficiency of the heat exchanger, which has obvious advantages such as large heat exchange area and small pressure drop, and has good flow heat transfer characteristics. At the same time, the numerical simulation results were verified experimentally based on 3D printing technology. The experimental values are in good agreement with the simulated values, which proves that the three-dimensional numerical model of flow heat transfer is correct and credible.

Keywords: Bionic Fractal; Mimic alveolar pore structure; 3D printing; Enhanced heat exchange.

1. Introduction

The aero-engine thermal management system is responsible for the design of the engine components, between the system and between the aircraft and the engine heat distribution, so as to improve the efficiency of energy use, achieve the purpose of system optimization design. As the core component of the engine thermal management system, the heat exchanger's compactness and flow heat transfer characteristics directly affect the distribution and utilization of heat. At present, the heat exchanger has been widely used in the cooling and cooling air system in the foreign aero-engine thermal management system, indirect cooling and heat recovery system, fulcrum booster system and air-to-air pre-cooling system, etc., as shown in Figure 1, the design technology of compact and efficient heat exchanger has become the key technology in the design of aero-engine thermal management system.

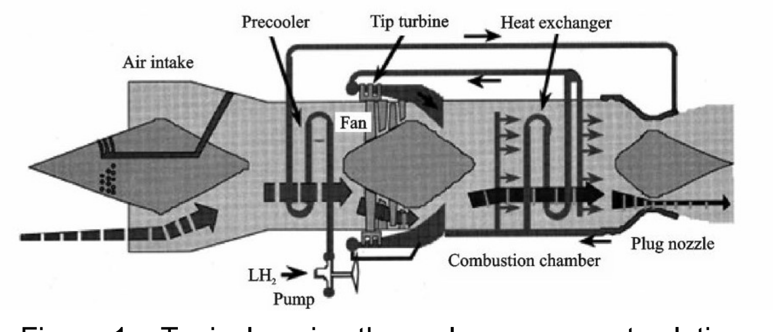

Figure 1 – Typical engine thermal management solutions

However, lightweight and compact and high efficiency, high reliability and high temperature resistance are contradictory to each other in heat exchanger design, and the aeroengine has the characteristics of compact structure, narrow space, high temperature and high pressure. These factors are huge challenges to the design, forming and reliable performance of heat exchange components. In this case, bionics can often provide useful inspiration for heat exchanger design. For example, the respiratory and circulatory system of the human body is a very efficient heat and mass transfer system. The blood vessels, trachea and lymphatic vessels in the human body are constantly bifurcated from the macroscopic scale to the cellular scale. In these bifurcations, high-level and low-level The bifurcation structures are similar, which is called fractal structure by B.B.Mandelbrot[1]. If this fractal structure is applied to the design and development of airborne heat exchange devices, its thermal effectiveness can be greatly improved, and because the channels are distributed in a tree network, the temperature distribution of the heat exchange surface can be more balanced. Fractal tree channel heat exchanger is a new type of high-efficiency cooling and heat-dissipating product developed under the inspiration of this idea.

In recent years, some progress has been made in the field of fractal structure flow heat transfer research. A. Bejan et al [2] drew on fractal theory and proposed a design scheme for a tree structure heat transfer system for electronic device cooling, and pointed out that the Compared with the traditional parallel channel heat exchanger structure, the pump power consumption and flow resistance of the structure are greatly reduced. D.V.Pence et al[3] designed a set of fractal heat exchangers on the circular heat dissipation surface, but most of the conventional electronic chips have a rectangular surface and the application range of such circular heat dissipation devices is relatively narrow. However, the structure is difficult to realize fluid circulation. In response to this problem, Y.P.Chen et al[4] designed a series of sandwich structure fractal tree heat exchangers suitable for rectangular surfaces, making the fractal structure more practical. The heat exchanger has greater heat dissipation capacity and thermal efficiency than traditional parallel channel heat exchangers. In terms of optimizing the heat transfer efficiency, Wechsatol W et al [6-13] found that the fractal structure has a strong promoting effect on improving the heat and mass transfer efficiency of the system. In order to guide the optimal design of the heat and mass transfer system, A. Bejan et al [14] proposed a set of self-construction theory for system optimization design based on the fractal theory.

In this paper, based on 3D printing technology, combined with the working characteristics of aero-engine thermal management system and the rigid requirements of heat exchanger, a bionic fractal structure heat exchanger was proposed. At the same time, numerical and experimental research on the flow heat transfer characteristics of bionic fractal structure heat exchanger under the working conditions of the engine was carried out.

2. Heat exchanger with imitated alveolar pore structure

Shell-and-tube type and plate-fin type are relatively mature heat exchanger structures in civil heat exchangers. Among them, the plate-fin type has relatively weak pressure resistance and is not suitable for occasions where the pressure difference between cold and hot fluids is large. Therefore, aiming at the performance requirements of aero-engines for heat exchangers that are lightweight, compact, efficient, and highly reliable, this paper proposes a heat exchanger structure based on bionic fractal structure. The structure of the imitation alveolar heat exchange core is shown in Figure 2. The structure has three flow cavities: the yellow tube is a connected flow cavity, the blue tube is a connected flow cavity, the gap between the yellow and blue tube is a third connected flow cavity. The two cavities are intended to be connected to form a set of channels. One fluid flows into the tube cavity from top to bottom, another fluid flows in the gap between the tubes from the side, and the two fluids participate in heat transfer near the core.

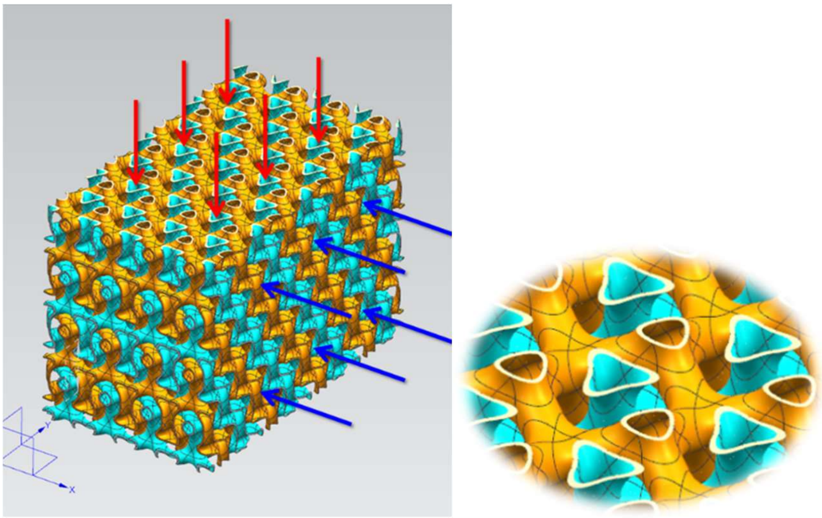

Figure 2 – Structural diagram of imitation alveolar heat exchange core

2.1 Bionic original surface heat exchange unit

The biomimetic original surface heat exchange unit or "cell" is the most basic structural unit in the simulated alveolar heat exchange core. The proposal of this concept makes the design of the simulated alveolar heat exchanger have a macro-scale and a micro-scale. According to the design requirements, this project completed the design of the alveolar-like heat exchange core structure based on the "cell", including the design of the external contour and shape of the structure, the internal circulation, and the optimization analysis of the overall heat exchange. This design process reflects the idea of local and global self-similarity in bionic fractals.

The biomimetic original surface heat exchange unit draws on the connection structure of biological blood vessels and alveolar. Based on its basic type, the unit bodies are combined in space, and then the connected pipeline model is spatially translated to obtain a model containing two connected pipelines as shown in Figure 4 (blue is a connected pipeline, yellow is another connected pipeline), that is, the heat exchange core used in this project. The structure of the bionic fractal heat exchange core is shown in Figure 2.

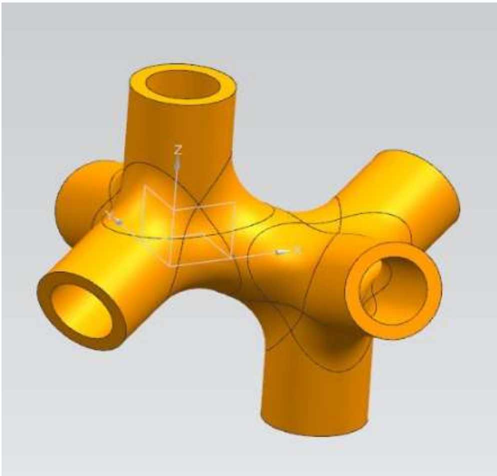

Figure 3 – Bionic original surface heat exchange unit structure diagram

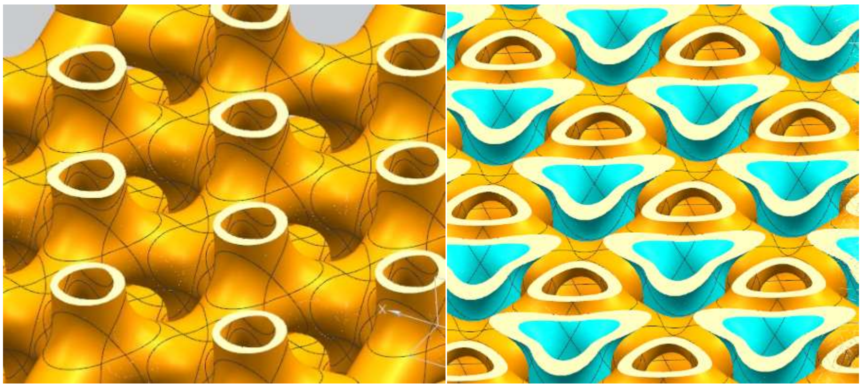

Figure 4 – Schematic diagram of the combination of bionic original surface heat exchange units

2.2 Heat exchange unit size optimization

In order to improve the flow heat transfer efficiency of the simulated alveolar heat exchanger, a total of 7 schemes were designed to optimize the heat exchanger, as shown in Table 1. By controlling the relationship between wall thickness δ, tube outer diameter d, tube center distance S and chamfer radius r, as shown in Figure 5. The flow heat transfer characteristics of each scheme are studied respectively, and the heat transfer area per unit mass and unit volume heat transfer area of each scheme are obtained, as shown in Figure 6.

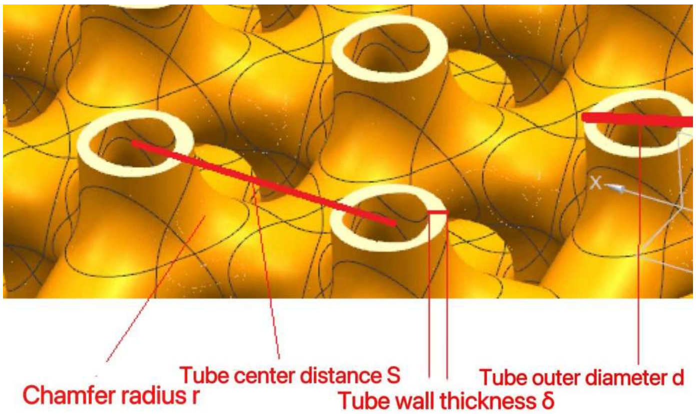

Figure 5 – Dimensions of heat exchange unit

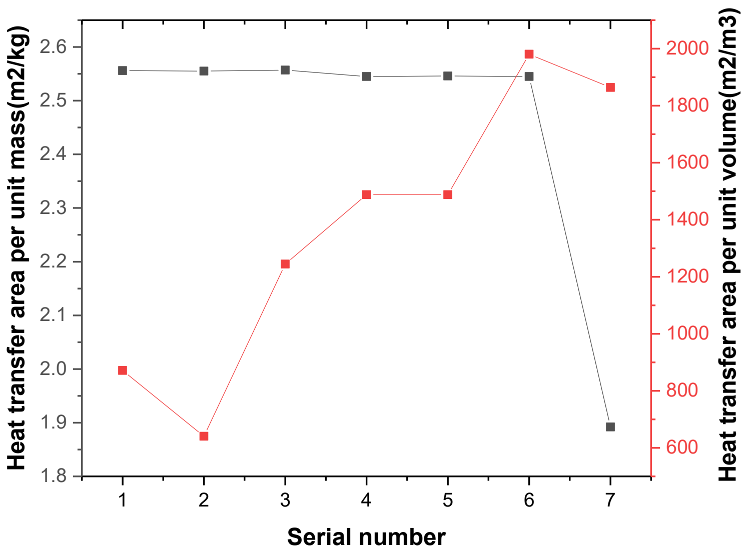

Figure 6 – Heat transfer area per unit mass/volume for each scheme

Table 1 – Data table of each program

Serial number	Tube outer diameter d(mm)	Tube wall thickness δ(mm)	Tube center distance S(mm)	Chamfer radius r(mm)
1	3	0.3	10	2.5
2	2	0.3	10	2.5
3	3	0.3	8	2.5
4	2	0.3	6	1.5
5	2	0.3	6	2.5
6	**2**	**0.3**	**5**	**1.5**
7	2	0.4	5	1.5

Through the comparison of 7 schemes, it is concluded that the influence of chamfering radius on heat transfer is not obvious; the heat transfer area per unit mass is only related to the wall thickness of the tube; the distance between the center of the tube affects the heat transfer area per unit volume; the outer diameter of the tube affects the inner cavity and between the tubes. The ratio of the flow area of the cavity should be selected considering the flow conditions. Option 6 was finally selected as the research model for this project.

3. Numerical simulation method

In this paper, the internal flow and heat transfer characteristics of the simulated alveolar heat exchanger are analyzed by the method of numerical simulation. The numerical simulation conditions are the same as the experimental conditions. First, the grid independence verification is carried out, the number of grids is more than 554,000, and the governing equations are assumed: steady state process, turbulent flow model, fluid is Newtonian incompressible fluid, thermal radiation and wall convection can be ignored. The final calculation results tend to be stable and more reasonable.

4. Results Analysis and Discussion

The factors affecting the flow heat transfer of the simulated alveolar heat exchanger include the influence of its geometric structure and the flow conditions of the inlet and outlet. Therefore, this project conducts flow heat transfer analysis for the two factors respectively.

4.1 Geometry structure

Figure 7 shows that the air and water side flow is constant at 90g/s, the air temperature is 120°C, the air and water outlet back pressure is 0.1MPa, and the heat exchanger efficiency ε (ε=actual heat exchange/theoretical maximum heat exchange It can be seen from the figure that with the increase of the distance between the centers of the tubes of the simulated alveolar heat exchange unit, the efficiency of the heat exchanger gradually increases, and the pressure drop of the heat exchanger increases continuously. This is because as the pipe center distance increases, the fluid flow path becomes longer and the heat transfer effect is enhanced. At the same time, the fluid consumes too much energy due to the resistance along the path and the local resistance, and the pressure drop continues to increase.

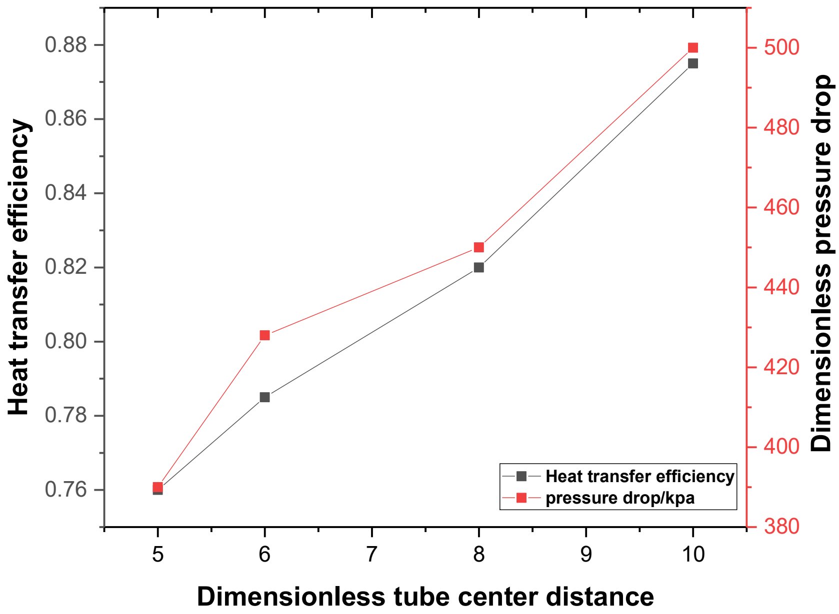

Figure 7 – Variation curve of heat exchanger efficiency and pressure drop with tube center distance

Figure 8 shows that the air and water side flow is constant at 90g/s, the air temperature is 120°C, the air and water outlet back pressure is 0.1MPa, and the heat exchanger efficiency ε (ε=actual heat exchange/theoretical maximum heat exchange It can be seen from the figure that with the increase of the wall thickness of the simulated alveolar heat exchange unit, the efficiency of the heat exchanger gradually decreases, and the pressure drop of the heat exchanger decreases continuously. This is because with the increase of wall thickness, thermal conductivity resistance becomes larger, heat transfer coefficient becomes smaller, so the efficiency of heat exchanger gradually becomes smaller. In addition, as the fluid flow path becomes shorter, the energy consumption generated by the fluid is too small due to the resistance along the path and local resistance, so the pressure drop keeps decreasing.

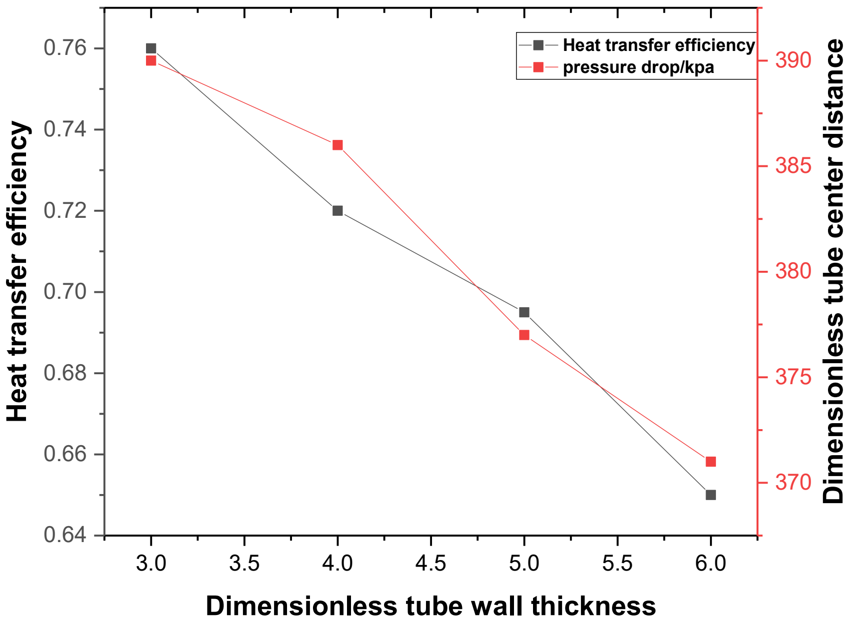

Figure 8 – Variation curve of heat exchanger efficiency and pressure drop with tube wall thickness

Figure 9 shows that the air and water side flow is constant at 90g/s, the air temperature is 120°C, the air and water outlet back pressure is 0.1MPa, and the heat exchanger efficiency ε (ε=actual heat exchange/theoretical maximum heat exchange It can be seen from the figure that with the increase of the chamfering radius of the simulated alveolar heat exchange unit, the efficiency of the heat exchanger and the pressure drop of the heat exchanger are almost unchanged. Because the chamfering radius has little effect on the flow characteristics of the fluid, the result is almost unchanged

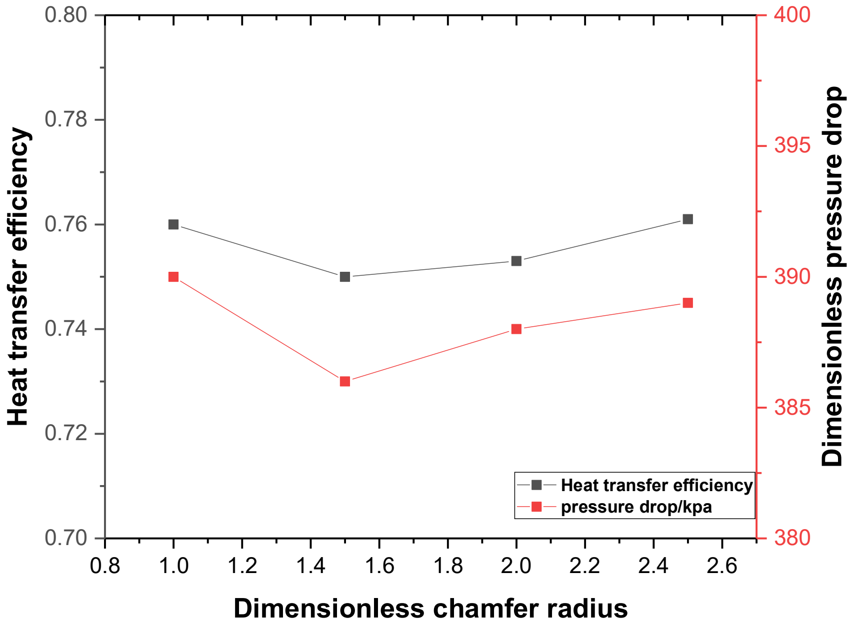

Figure 9 – Curves of heat exchanger efficiency and pressure drop as a function of chamfer radius

4.2 Flow factor

The water side flow is constant at 90g/s, the inlet temperature is normal temperature, and two independent variables are set: temperature and mass flow. The heat exchanger efficiency is calculated according to formula 1, and the effect of temperature and flow rate on the heat exchanger efficiency is shown in Figure 10. The heat exchanger efficiency of the alveolar heat exchanger decreases with the increase of the air inlet temperature; The flow rate increases and decreases, the heat exchanger efficiency can reach 0.77 at the highest, and the heat exchanger efficiency is at least 0.56. This is because when the flow rate is large, with the increase of the mass flow, the fluid disturbance in the heat exchanger is gradually enhanced, making the pressure drop become large, and the heat exchanger efficiency is reduced.

$$\varepsilon = \frac{t_1^{'} - t_1^{''}}{t_1^{'} - t_2^{'}} \tag{1}$$

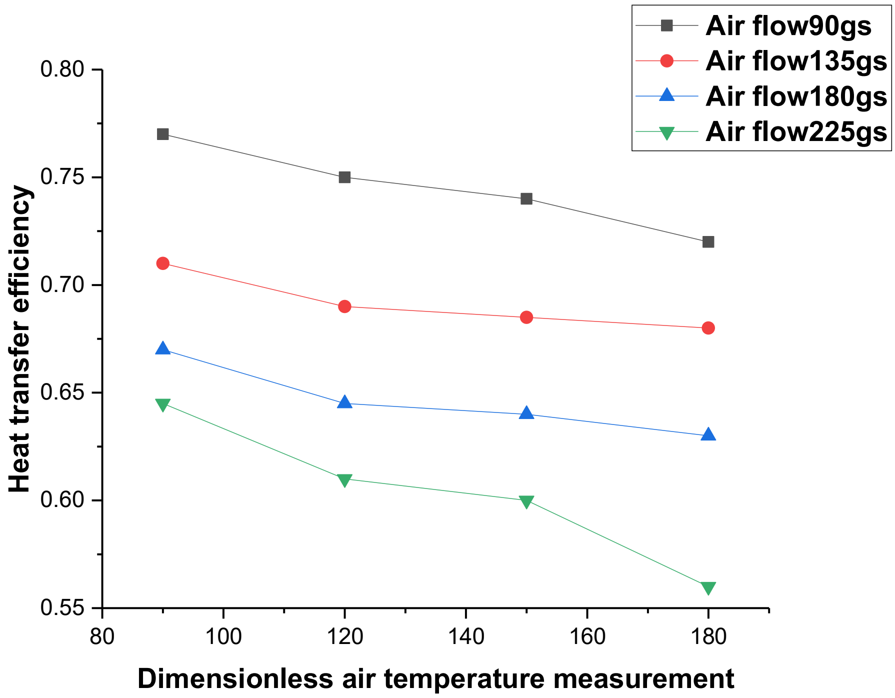

Figure 10 – Variation curve of heat exchanger efficiency with air-side temperature and air-side flow rate

The effect of temperature and flow rate on the heat exchange of the heat exchanger is shown in Figure 11. The heat exchange is obtained from the heat exchange of the water supply side heating. Increase; increase with the increase of air flow, with the change of air inlet temperature and flow, the heat exchange varies within 217W-1104W. This is because as the air inlet temperature increases, the temperature difference between the hot flow and the cold flow becomes larger, and according to the basic law of heat transfer, the heat transfer is also gradually increased. And with the increase of air flow, the fluid disturbance in the heat exchanger gradually increases, and the heat transfer gradually increases.

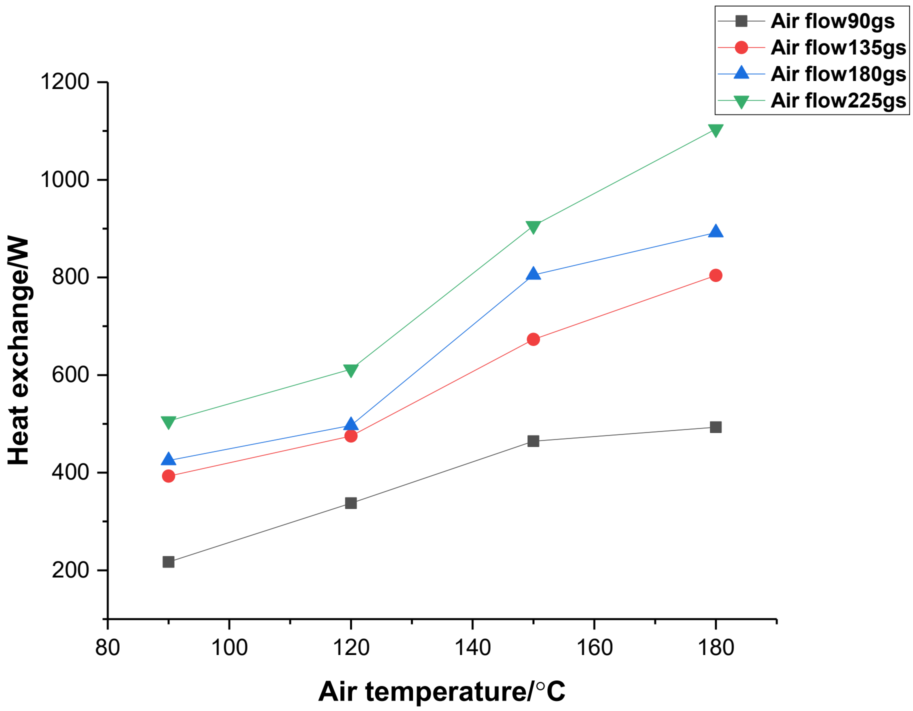

Figure 11 – Variation curve of heat exchange with air-side temperature and air-side flow rate

The effect of temperature and flow rate on air-side pressure drop is shown in Figure 12. The air-side pressure drop of alveolar heat exchanger increases with the increase of air inlet temperature; With the increase of air flow rate, the pressure drop varies from 147KPa to 730KPa with the change of air inlet temperature and flow rate. This is because in the process of heat transfer, with the increase of mass flow, the Reynolds number is increasing, and the fluid disturbance in the heat exchanger is gradually enhanced, making the pressure drop become larger.

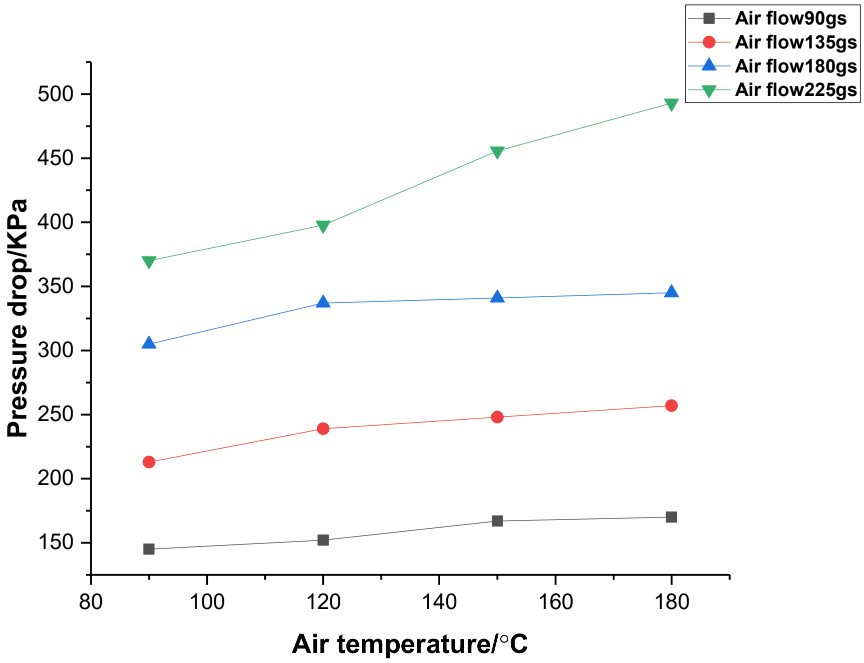

Figure 12 – Variation curve of air-side pressure drop with air-side temperature and air-side flow rate

The effect of temperature and flow rate on the temperature rise of the water side of the heat exchanger is shown in Figure 13. The temperature difference of the water side of the alveolar heat exchanger increases with the increase of the air inlet temperature; it increases with the increase of the air flow rate, the maximum temperature difference on the water side can reach 26°C, and the minimum temperature difference on the water side is 9.7°C. This is because according to the law of conservation of energy, the heat released by the heat flow is equal to the heat absorbed by the cold flow. With the continuous rise of the measured temperature of the air, the heat transfer is increasing, so the temperature difference between the water side is increasing.

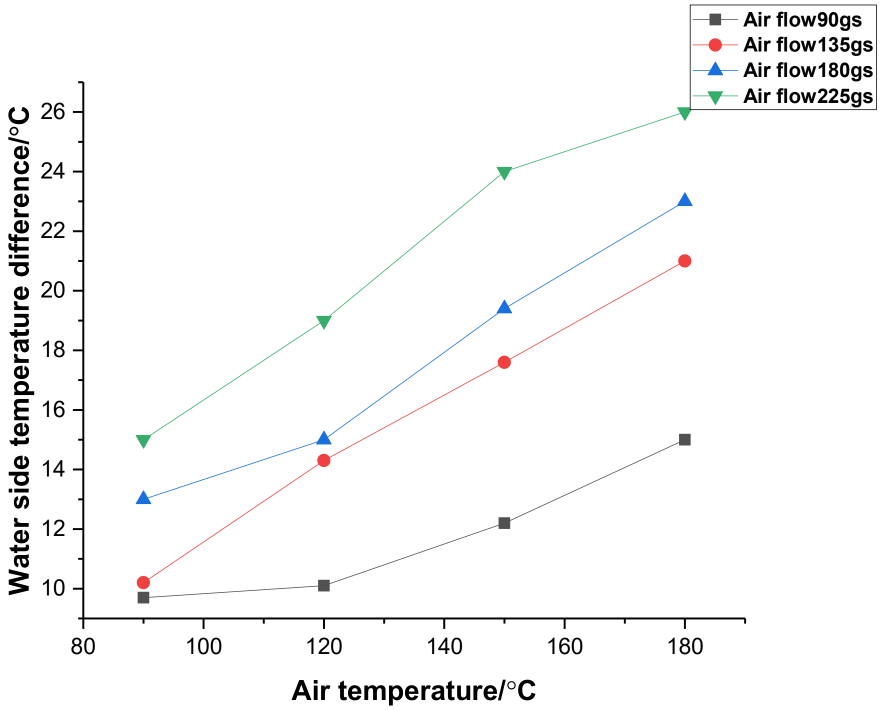

Figure 13 – Curve of water side temperature difference with air side temperature and air side flow rate

The flow characteristics of the alveolar-like heat exchange structure are shown in Figure 14. The fluid flows uniformly in the core. Compared with the ordinary heat exchanger structure, the fluid temperature distribution is more uniform after adding the alveolar-like structure, and the heat exchange Works well.

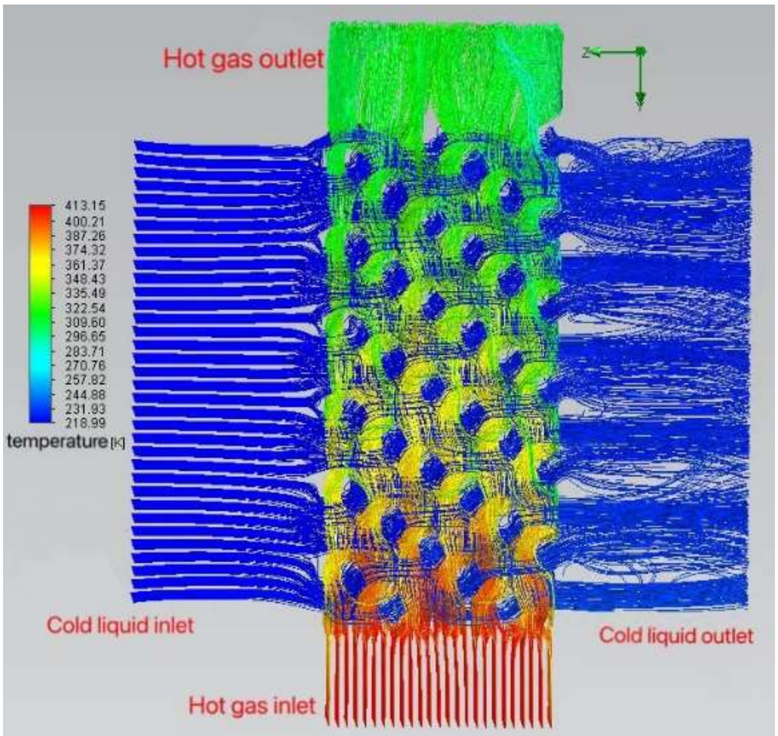

Figure 14 – Temperature distribution of flow field inside heat exchanger

5. Experimental verification

5.1 Test device

In order to verify the accuracy of the calculation, this experiment uses 3D printing technology to realize the complex model. The printed parts are imported into the machine to start printing through the pre-processing process to increase the support and other links. After printing, the post-processing process is carried out. Finally, through the analysis of the processing technology, the results show that there is no excess powder in the channel of the radiator, and there is no defect in the manufacture of the internal lattice. The internal porosity of the part is within an acceptable range, indicating that the model is machinable. The 3D printing test piece used in this experiment is shown in Figure 15.

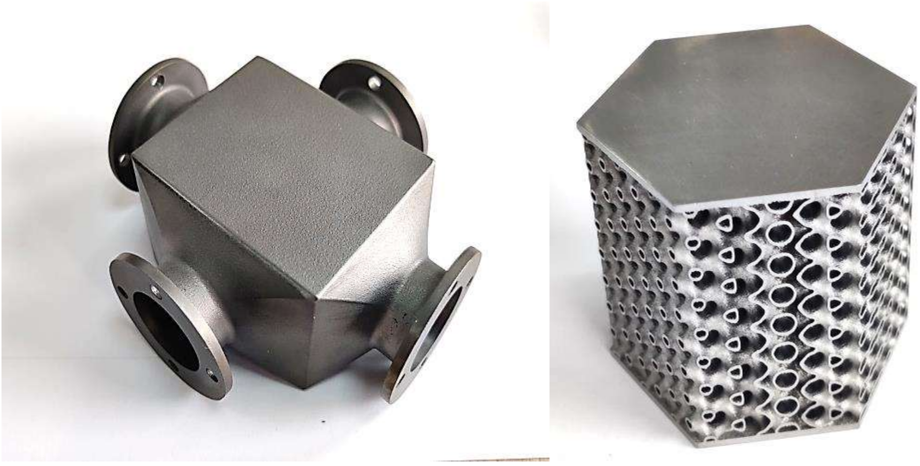

Figure 15 – Physical map of the 3D printing test piece

In this paper, an experimental study on the flow heat transfer characteristics of heat exchangers with different structures is carried out. Figure 16 is a schematic diagram of the test bench. The test system consists of four parts: heating air supply system, heating water supply system, measurement system and data acquisition system.

Figure 16 – Schematic diagram of the test bench

5.2 test results

In this test, the water side flow rate was constant at 90g/s, the inlet temperature was normal temperature, and the temperature and mass flow rate were changed. Control the relevant variable and vary the other variable in the same set of experiments. The heat exchanger efficiency is calculated according to formula 1. The effect of temperature and flow rate on the heat exchanger efficiency is shown in Figure 17. The heat exchanger efficiency of the alveolar heat exchanger decreases with the increase of the air inlet temperature; The flow rate increases and decreases, the maximum heat exchanger efficiency can reach 0.767, and the minimum heat exchanger efficiency is 0.558.

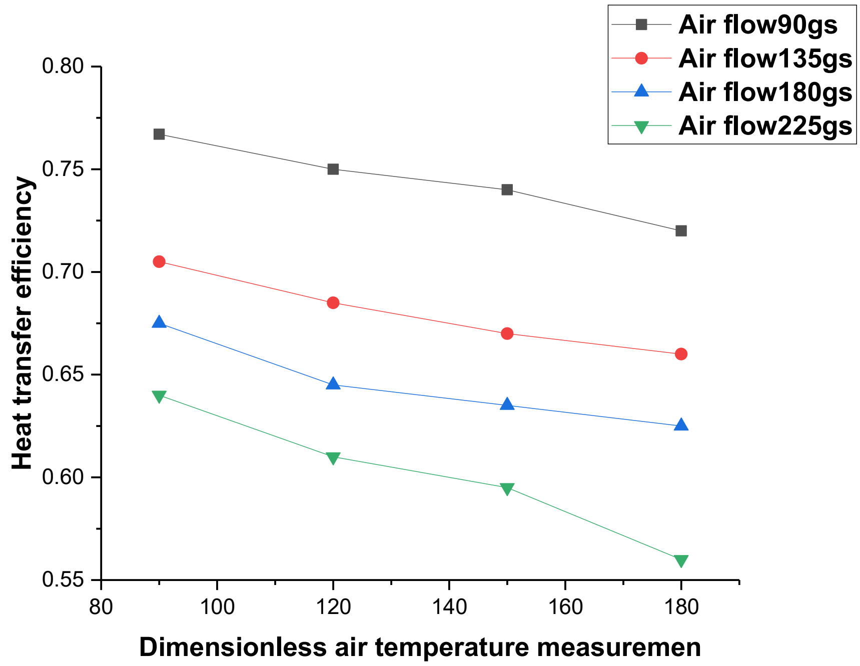

Figure 17 – Variation curve of heat exchanger efficiency with air-side temperature and air-side flow rate

The effect of temperature and flow rate on the heat exchange of the heat exchanger is shown in Figure 18. The heat exchange is obtained according to the heat exchange of the water supply side heating. The heat exchange of the alveolar heat exchanger increases with the increase of the air inlet temperature. Increase; with the increase of air flow, the maximum heat exchange can reach 12.31kW, and the minimum heat exchange is 0.837kW.

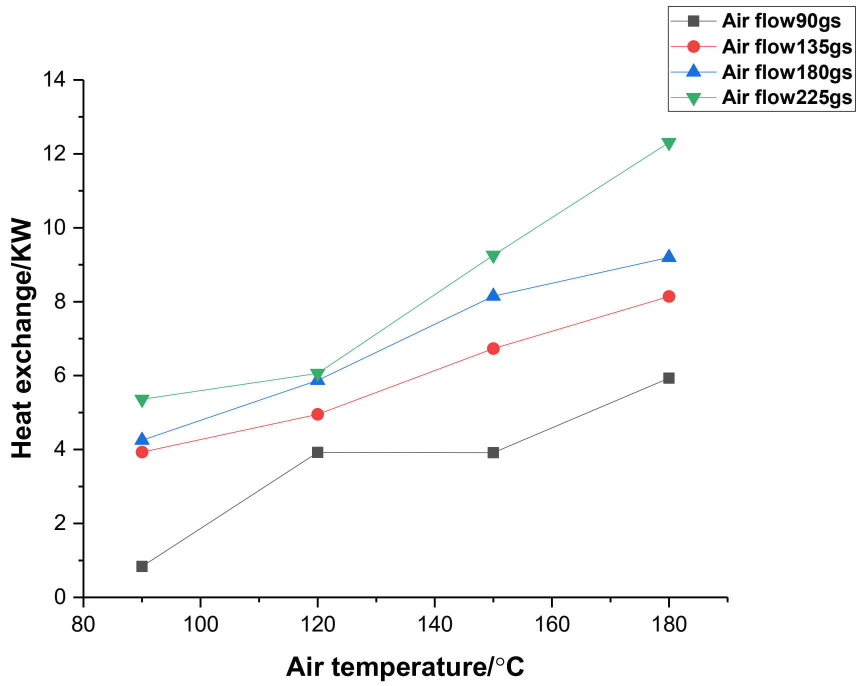

Figure 18 – Variation curve of heat exchange with air-side temperature and air-side flow rate

The effect of temperature and flow rate on the air side pressure drop is shown in Figure 4. The air side pressure drop of the alveolar heat exchanger increases with the increase of the air inlet temperature; it increases with the increase of the air flow rate. Under the working conditions of 180℃ -90g/s-225g/s, due to the high temperature of the water during the experiment, a gas-liquid two-phase flow is generated, and there may be problems in the last set of data due to multiple factors. The minimum pressure at the air side inlet is 234kPa, and the highest pressure drop on the air side can be as low as 135.206kPa. Under the working conditions of 150℃-90g/s-225g/s, there is currently a maximum air inlet pressure of 690.6kPa and a maximum pressure drop of 419.498kPa.

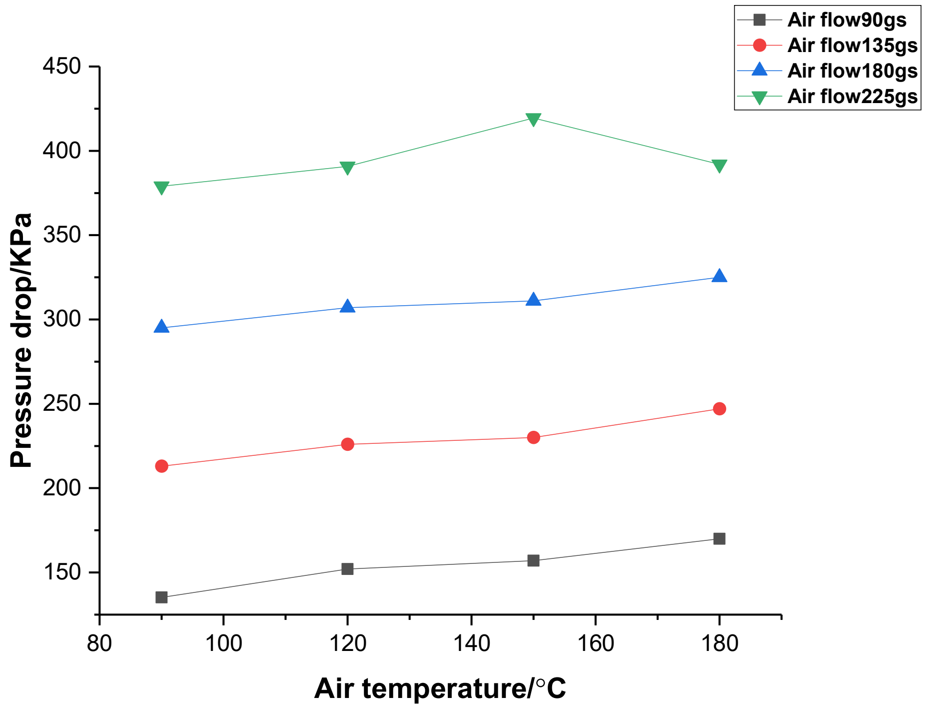

Figure 19 – Variation curve of air-side pressure drop with air-side temperature and air-side flow rate

The effect of temperature and flow rate on the temperature rise of the water side of the heat exchanger is shown in Figure 20. The temperature difference of the water side of the alveolar heat exchanger increases with the increase of the air inlet temperature; it increases with the increase of the air flow rate. , the maximum temperature difference on the water side can reach 32.049℃, and the minimum temperature difference on the water side is 7.505℃.

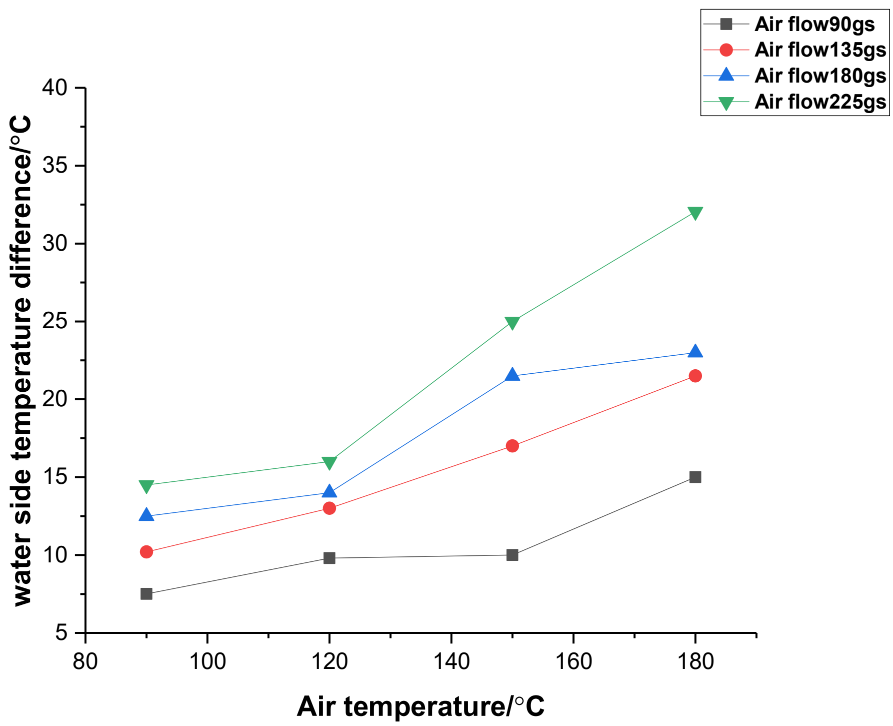

Figure 20 – The curve of the temperature difference on the water side with the temperature on the air side and the flow rate on the air side

The experimental data conclusions of temperature and flow on heat exchanger efficiency, heat exchange heat exchange, air side pressure drop heat exchanger, and water side temperature rise and pressure drop are basically consistent with the simulation values. This proves that the three-dimensional model of flow heat transfer established in this paper is accurate and reliable.

6. Conclusion

In this paper, a bionic fractal structure heat exchanger is proposed, the flow heat transfer characteristics of the fluid in the alveolar-like structure are studied, and the important geometric parameters of the structure are optimized. Combined with 3D printing technology for experimental verification, the conclusions are as follows.

(1) In the simulated alveolar heat exchange unit, its chamfer radius has no obvious effect on the heat transfer area per unit mass/volume; the heat transfer area per unit mass is only related to the wall thickness of the tube; the distance between the tube centers affects the heat transfer per unit volume Area; the outer diameter of the tube affects the ratio of the flow area between the inner lumen and the inter-tube lumen, and the flow situation needs to be considered.

(2) The Heat exchanger with imitated alveolar pore structure can effectively enhance the degree of heat exchange, and has the obvious advantages of good temperature uniformity and small pressure drop. It can significantly reduce the maximum temperature of the whole field, improve the uniformity of the temperature field, and effectively reduce the total pressure drop at the inlet and outlet, but with the increase of the air inlet temperature and flow rate, the flow resistance in the heat exchanger will continue to increase.

(3) Experiments were carried out based on 3D printing technology, and the numerical simulation results were experimentally verified. The experimental values were in good agreement with the simulated values, which proved that the three-dimensional numerical model of flow heat transfer was correct and credible.

In conclusion, the simulated alveolar heat exchanger has obvious advantages such as high heat exchange area and small pressure drop, and has good flow heat transfer characteristics. This project applies interdisciplinary technology to generate new design ideas and methods, and breaks through the limitations of conventional heat exchanger design and processing. The results of this study can provide technical support for active and efficient heat dissipation of future high-performance aero-engine hot-end components. At the same time, the existing methods also have areas that need to be improved, including that the existing structural design is not perfect, the summary of the heat transfer empirical relationship has not been completed, and the bionic fractal database needs to be established.

7. Copyright Statement

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