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Study on Oil-Gas Two-Phase Flow Characteristics in Air-Oil Heat Exchanger

PANG Xiaodong[1], *SUI* Hongren[1], *JIANG Xinwei*[1], *LIU Guochao*[1]

[1]AECC Shenyang Engine Research Institute,110015 Shenyang， China

Abstract

For aeroengine lubricating oil heat exchanger oil mixed with air condition, the numerical simulation research is carried out. The flow characteristics of the two media under different mass mass flux combinations are obtained.The full-factor experimental design of 3 input variables is planned, and the numerical simulation study of 9 groups of working conditions is carried out. The simulation results of pressure drop and friction factor are obtained.The correlation between friction factors and input variables was obtained by regression analysis. Through the CFD simulation results, it can be seen that when the mass flux of the oil is large, it is easy to form a single bubble. And the bubble flows in the middle of the channel. When the mass flux of the oil is small, it is easy to form a stratified flow. With the increase of oil mass flux and decrease of air mass flux, the friction factor decreases continuously. The study of two-phase flow characteristics in heat exchanger flat tube provides a basis for engineering design of air-oil heat exchanger.

Keywords: aeroengine; air-oil heat exchanger; oil-gas two-phase flow; design of experiment

1. Introduction

As advanced aircraft and engine performance has increased, because of increased aerodynamic heat load and cooling system needs a substantial increase in[1-2], the engine or aircraft need internal high temperature lubricating oil with low temperature culvert air for cooling.The air-oil heat exchanger as key components of the cooling air, its structure is usually tube fin type or fin type[3]. In the structural design of the air-oil heat exchanger, it is generally considered that the oil side of the heat exchanger does not contain other impurities. But in actual operation, the air inside the oil tank will be mixed with the air under the action of the pump drive, and become the mixture of oil and air. So that the flow characteristics of the radiator is not easy to determine.

Scholars have carried out relevant research on the flow characteristics of air oil heat exchanger.Zhong Bingbing[4] investigated the intermittent failure of heat dissipation performance of an air-oil heat exchanger and determined that the reason for the APU oil overtemperature fault was the foreign body stuck in the bypass valve of the air-oil heat exchanger. Liao[5] design a kind of lubricating air-oil heat exchanger, effectively improve the cooling capacity of aeroengine lubricating oil system, solve the plane in close to the ground, low-speed taxiing generates huge heat engine trouble. And the numerical simulation method is analyzed in the presence of air flow by the heat exchanger pressure drop and flow under the condition of air velocity variation. Sun Huguo[6] analyzed the explosion phenomenon of air-oil heat exchanger used in helicopters, conducted blasting test and pressure test to verify the structural strength of the heat exchanger, and confirmed that the weld joint at the cover plate was the origin of failure. Zhang Qin[7] established the mathematical model of air-oil heat sink, designed a three-flow heat exchanger, used fuel oil, lubricating oil and air for heat exchange. The dynamic response of heat exchanger is analyzed and the effect of multi-flow heat exchanger performance is studied deeply.Li Bo[8] used numerical simulation to study the heat transfer characteristics and flow characteristics of the fuel oil heat exchanger used in aero-engines, and planned the experiment of the flow heat transfer component, and obtained the test data. Ren Guozhe[9] conducted a simulation study on the complex oil-gas two-phase flow in the bearing chamber of an aeroengine.

An air-oil two-phase flow model was established in euler system using level set and VOF method to track the interface between air and oil. Yang Peijie[10] conducted transient simulation of two-phase flow in the bearing cavity based on the VOF multiphase flow model to obtain pressure fluctuation signals in the cavity under specific working conditions, and analyzed its spectral characteristics using the Method of Hilbert-Huang transform to establish the association between energy characteristic values and flow patterns. Wang Youyong[11] used the Mixture multiphase flow model to numerically simulate the flow characteristics of oil-gas two-phase flow in the bearing chamber under selected test conditions, and obtained the distribution characteristics of velocity field, pressure field and temperature field of oil-gas two-phase flow. Guo Yuxiang[12] used the VOF method to establish the calculation model of large liquid droplets impacting the wall, and analyzed the liquid-gas two-phase flow. Liu Gang[13] used finite element software to simulate gas-oil two-phase flow in the process of aviation lubricating oil injection, and summarized the influence of physical parameters of lubricating oil on the ejection state of oil droplets.

The function of air-oil heat exchanger determines its wide application prospect in aero-engine. The existing studies mainly focus on the single-phase flow heat transfer and two-phase flow in the oil cavity of the air-oil heat exchanger, but there are few studies on the oil-gas two-phase flow in the channel of the air-oil heat exchanger. In order to study the characteristics of oil-gas two-phase flow in the air-oil heat exchanger, the flow characteristics of medium in different mass flux combinations in the tube are analyzed by taking the flat tube finned air-oil heat exchanger as an example. It provides the basis for the optimization design of air oil radiator.

2. Calculation Model

2.1 Governing Equation

The aero-engine air-oil heat exchanger contains air and oil, and the influence of viscosity needs to be considered when flowing. Therefore, the internal flow heat transfer control equation adopts three-dimensional steady-state viscous compressible N-S equation, and its continuity, momentum and energy conservation equations are as follows:

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$$\nabla\cdot(\rho V)=0 \tag{1}$$

$$\nabla\cdot(\rho u V)=-\frac{\partial p}{\partial x}+\frac{\partial \tau_{xx}}{\partial x}+\frac{\partial \tau_{yx}}{\partial y}+\frac{\partial \tau_{zx}}{\partial z} \tag{2}$$

$$\nabla\cdot(\rho v V)=-\frac{\partial p}{\partial y}+\frac{\partial \tau_{xy}}{\partial x}+\frac{\partial \tau_{yy}}{\partial y}+\frac{\partial \tau_{zy}}{\partial z} \tag{3}$$

$$\nabla\cdot(\rho w V)=-\frac{\partial p}{\partial z}+\frac{\partial \tau_{xz}}{\partial x}+\frac{\partial \tau_{yz}}{\partial y}+\frac{\partial \tau_{zz}}{\partial z} \tag{4}$$

$$\begin{aligned}\nabla\cdot\left(\rho\left(e+\frac{V^2}{2}\right)V\right)=&\frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(k\frac{\partial T}{\partial y}\right)+\frac{\partial}{\partial z}\left(k\frac{\partial T}{\partial z}\right)\\&-\frac{\partial(up)}{\partial x}-\frac{\partial(vp)}{\partial y}-\frac{\partial(wp)}{\partial z}+\frac{\partial(u\tau_{xx})}{\partial x}+\frac{\partial(u\tau_{yx})}{\partial y}+\frac{\partial(u\tau_{zx})}{\partial z}\\&+\frac{\partial(v\tau_{xy})}{\partial x}+\frac{\partial(v\tau_{yy})}{\partial y}+\frac{\partial(v\tau_{zy})}{\partial z}+\frac{\partial(w\tau_{xz})}{\partial x}+\frac{\partial(w\tau_{yz})}{\partial y}+\frac{\partial(w\tau_{zz})}{\partial z}\end{aligned} \tag{5}$$

Where e is the internal energy, k is the thermal conductivity, P is the pressure, T is the temperature, V is the combined velocity, u, v and w are the velocity components in x, y and z directions respectively, ρ is the gas density, τ is the normal stress and shear stress of the controlling surface.

Coupled algorithm of second order upwind format is used for steady-state numerical simulation. In the two-phase flow analysis, the VOF method is adopted. In the calculation, the fluid volume fraction α is introduced to mark the fluid of different phases, the region of different phases is

dynamically tracked, and the interface reconstruction technique is used to determine the phase interface. Assuming that there are n-phase fluids in the computational domain, the volume fraction of k-phase fluids in any computational grid may exist in the following three situations, namely, α_k=0, 1 or 0 ~ 1. If the volume fraction is 0, there is no k-phase fluid in the grid. If the volume fraction is 1, only k-phase fluid exists in the grid. If the volume fraction is between 0 and 1, it indicates that multiphase fluid exists in the grid, and the sum of the volume fraction of each phase is 1.
VOF method uses volume average in each grid to calculate flow equation and capture phase interface through fluid volume fraction. Figure 1 is a schematic diagram of VOF interface tracking.

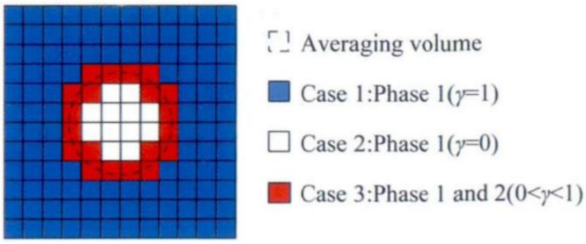


Figure 1 – Interface diagram of VOF method

The fluid calculated in this paper includes two phases of air and lubricating oil. Air and lubricating oil are considered to have the same velocity at the same position, and the momentum equation is:

$$\frac{\partial}{\partial t}(\rho v)+\nabla\cdot(\rho vv) = -\mathrm{gradP}+\mu\nabla^2 v+\rho g+F_{SF} \quad (6)$$

Where, P is pressure, and F_{SF} is momentum source term caused by surface tension.

2.2 Geometric Model

The flat tube in the core of the flat tube finned heat exchanger is used in the numerical simulation. In order to improve the pressure resistance and heat transfer capacity of the flat tube, the flat tube contains several rectangular oil channels. The geometric parameters of the flat tube are shown in Table 1, and the contour model is shown in Figure 2.

Table 1 – geometric parameters

Geometric parameters	Numerical value
Flat pipe length /mm	110
Flat tube width /mm	10
Flat pipe height /mm	2
Flat tube thickness /mm	0.2
Number of contained channels	5

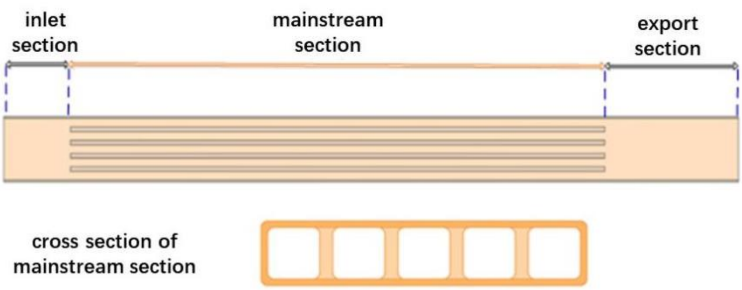


Figure 2 – Contour model

2.3 Grid and Boundary Conditions

The air-oil heat exchanger contains a plurality of flat tubes, which are arranged in parallel. In order to simplify the calculation, a single flat tube is selected as the calculation model. Workbench software was used for fluid meshing. The number of meshes was 1.61 million, and the average mesh quality was 0.84. See FIG. 3 for grid schematic diagram and FIG. 4 for grid quality. In the calculation, mass flow inlet boundary condition was adopted at the inlet, pressure outlet boundary condition was set at the outlet. High speed external culvert flow is applied outside the flat pipe, and temperature boundary condition is simplified at the outer surface.

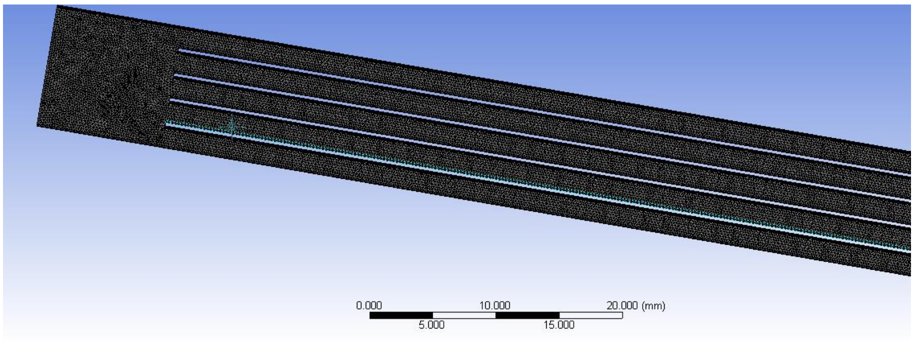


Figure 3 – Schematic diagram of grid

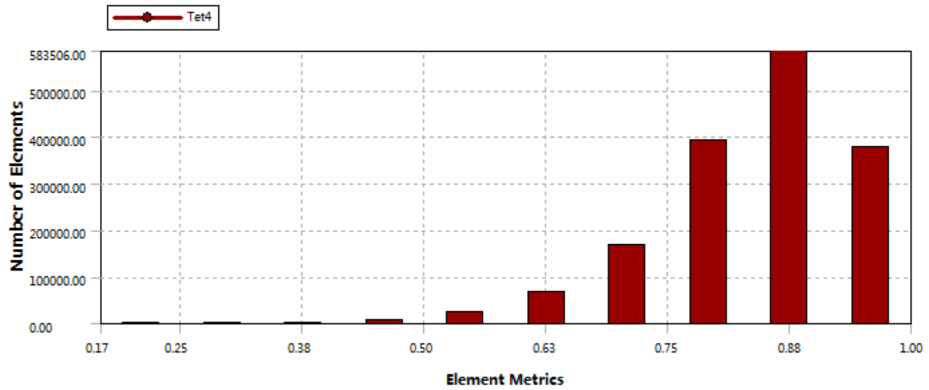


Figure 4 – Mesh quality

2.4 Test Planning

According to the engineering design experience of air-oil heat exchanger, the main input influencing variables are oil mass flux, air mass flux and heat exchange temperature difference. With the help of Minitab tool, the DOE all-factor test design is planned. Oil mass flux varies from 30 to 600kg/(m^2 • s), air mass flux varies from 0 to 3kg/(m^2 • s), and heat transfer temperature difference varies from 50 to 100K.

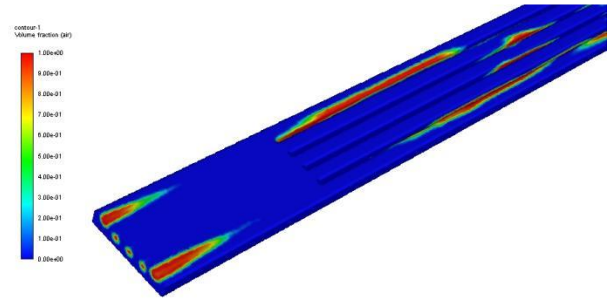
Table 2 – Full factor test planning table

Working condition number	Oil mass flux (kg/(m^2·s))	Air mass flux (kg/(m^2·s))	Heat transfer temperature difference（K）
1	600	3.0	50
2	30	0.0	50
3	30	0.0	100
4	30	3.0	100
5	600	0.0	50
6	600	3.0	100
7	30	3.0	50
8	315	1.5	75
9	600	0.0	100

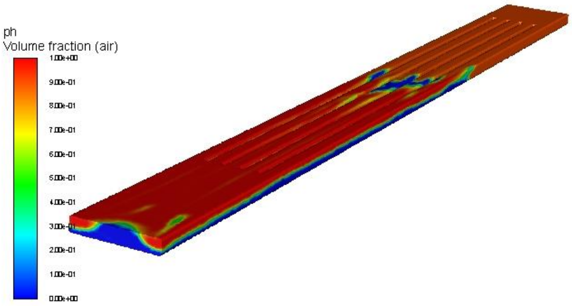
3. Numerical Simulation Results

Three kinds of gas phase under the condition of distribution as shown in figure 5. By comparing the working condition of 6 and 7, wnen oil mass flux is big,it is easy to form a separate bubble. Bubbles in the middle of the flow channel, the gas flow between different channels mainstream area does not occur after mixing. When oil mass flux is small,it is easy to form the stratified flow. Air and oil have a clear interface. Air is located in the upper layer. By comparing working conditions 6 and 8, it can be seen that air distribution will change when mass flux of lubricating oil and air is reduced at the same time. After the total flow is reduced, bubbles move from the center area of the channel to the upper layer of the channel, and mixing will occur when bubbles flow out of the mainstream area.

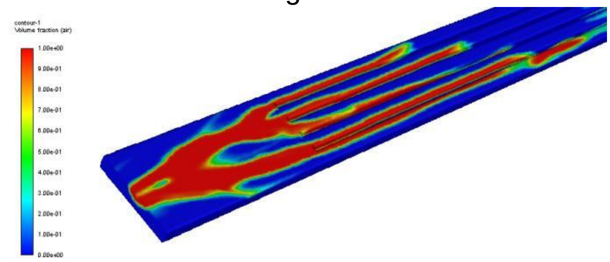
The pressure distribution on the outer surface of working condition 8 is shown in FIG. 6. There is little difference in pressure distribution between different channels. The pressure decreases uniformly along the flow direction of the channel, and the pressure loss is mainly concentrated in the mainstream area. The pressure distribution along the axial direction of the outer surface of the outermost channel is selected for statistics (see FIG. 7). The results showed that the pressure distribution is continuous, and the pressure drop curve in each flow region is basically linear. The slope of the curve in the main flow region is larger than that in the inlet and outlet region, and the pressure drop along the flow direction is about 4470Pa.



（a）working condition of 6



（b）working condition of 7



（c）working condition of 8

Figure 5 – Gas phase distribution in three working conditions

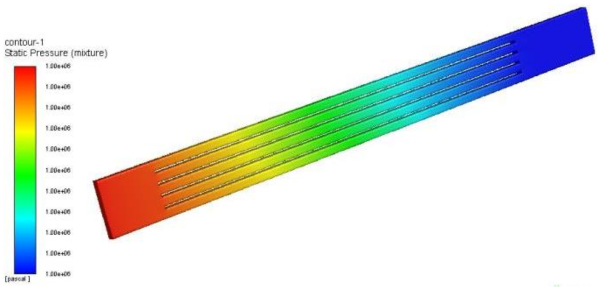


Figure 6 – Pressure drop distribution

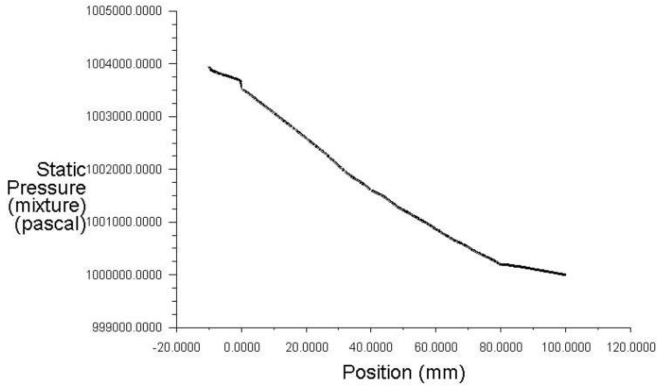


Figure 7 – Pressure distribution along the axis

4. Friction Factor Fitting

According to the full-factor experimental planning table, 9 groups of numerical simulation experiments were completed and experimental data were obtained, as shown in Table 3. With the help of Minitab analysis factor design module, the contour map of friction factors was obtained, as shown in Figure 8. It can be seen from the figure that with the increase of the oil mass flux and the decrease of the air mass flux, the friction factor decreases continuously. The fitting correlation of friction factors was obtained by regression analysis.

$$f = \Phi_L^2 \times f_L \quad (7)$$

$$f_L = 14.2/Re_L \quad (8)$$

$$\Phi_L^2 = 1 + \frac{2.6}{X_{tt}} + \frac{1}{X_{tt}^2} \quad (9)$$

$$X_{tt} = \left(\frac{\mu_L}{\mu_G}\right)^{0.1}\left(\frac{1-x}{x}\right)^{0.9}\left(\frac{\rho_G}{\rho_L}\right)^{0.5} \quad (10)$$

In the formula, f is the total friction factor, Re is the Reynolds number, ρ is the density, μ is the dynamic viscosity, x is the dryness, Xtt is the Martinelli factor, Φ_L^2 is the two-phase friction factor, subscript G and L respectively represent the air phase and lubricating oil phase.

Table 3 - Numerical simulation results

Working condition number	Oil mass flux (kg/(m^2·s))	Air mass flux (kg/(m^2·s))	Pressure drop（Pa）	Friction factor
1	600	3	9264	0.2347
2	30	0	283	2.8637
3	30	0	283	2.8637
4	30	3	509	5.1569
5	600	0	8471	0.2146
6	600	3	9462	0.2397
7	30	3	509	5.1569
8	315	1.5	4472	0.4110
9	600	0	8471	0.2146

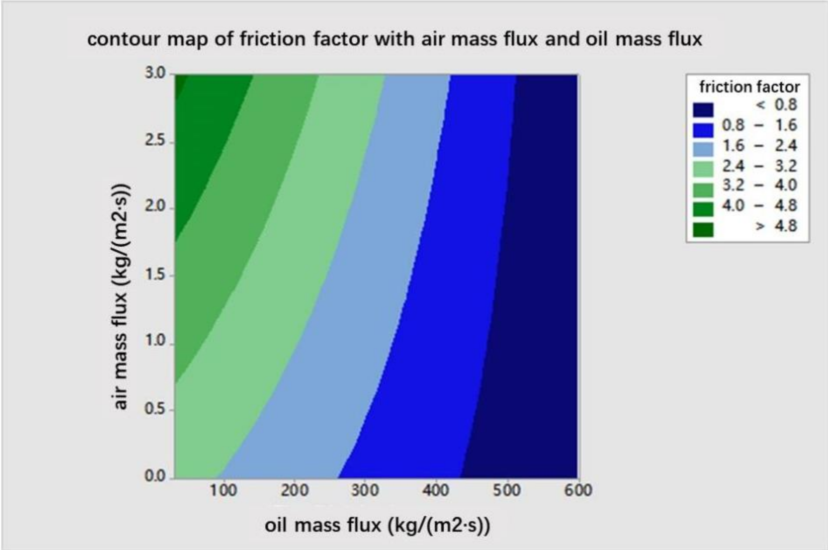


Figure 8 – Contour map of friction factors

5. Conclusion

Based on the single-tube model of flat tube finned air-oil heat exchanger, the characteristics of oil-gas two-phase flow were studied. And the full-factor experimental design was planned. Simulation analysis was conducted on 9 groups of working conditions. The results show that:

1) When the mass flux of the oil is large, it is easy to form a single bubble, which flows in the middle area of the channel. When the mass flux of the lubricating oil is small, it is easy to form stratified flow.

2) There is little difference in pressure distribution between different channels. The pressure decreases evenly along the flow direction of the channel, and the pressure loss is mainly concentrated in the mainstream area, and the pressure distribution is continuous.

3) With the increase of oil mass flux and the decrease of air mass flux, the friction factor decreases continuously.

6. Contact Author Email Address

PANG Xiaodong: 2352448335@qq.com

7. Copyright Statement

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