Simulation Platform on Flow and Heat Transfer of Aero-engine Secondary Air System

Ren Guo-zhe[1, a], Liu Zhen-xia[1,b], Zhu Peng-fei[1,c], Lyu Ya-guo[1,d]

[1]NorthWest Polytechnical University, Xi'an, 710072, China

[a]email: renguozhe7917@163.com, [b]email: zxliu@nwpu.edu.cn

[c]email: zhupengfei221@126.com, [d]email: yglu@nwpu.edu.cn

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Abstract. In order to analyze the flow and heat transfer characteristics of the secondary air system, a general simulation block library was developed and a characteristic analysis platform of secondary air system was constructed based on the tool box of MATLAB/Simulink. This platform could simulate all kinds of flow systems by dividing the system into finite correlative elements and nodes based on network algorithm. The fluid pressure, mass flow rate and temperature of the node and component in the network could be achieved. The calculation results of components library is in accordance with the results calculated by Flowmaster. Based on the net-arithmetic of flow and heat transfer, aero-engine secondary air system is decomposed into a net which is composed by the relevant typical components and nodes. The simulation platform could simulate and calculate the secondary air system quickly and precisely, and it could describe the steady state procedure of the secondary air system, and what's more, it provides an effective tool for the design and calculation of the aero-engine secondary air system.

Introduction

Aero-engine secondary air system is one of the most important system to ensure the high performance of the engine. It directly affects the working life and reliability of the aero-engine. The flow mass, temperature, pressure in the aero-engine secondary air system are crucial parameters in reflecting the performance of the system. The parameters of each node in the system must be determined in order to design, analyze and retrofit the aero-engine secondary air system, but it is unrealistic to use the experiment method since the non-independence and complexity of the aero-engine secondary air system. Therefore, simulation is an economical and efficient approach to study and analyze the characteristic of the flow and heat transfer in the aero-engine secondary air system.

From the currently published data, the abroad has been a relatively mature technology in the components and network computation of the aero-engine secondary air system [1-2], and they have developed the software and program for calculation and analysis, such as the SSME [3] of the United States NASA, GFSSP [4]especially, which has been widely used and developed continuously in the related field [5-10]. While, it is constrained to output as a result of the high value of the program and software. The Britain FMI company developed Flowmaster Software, which involved in wide range but it lacks the longitudinal depth and the mathematical model is too much simplified which cannot depict the physical characteristics overall, and the development process the user-defined components is too complicated. There has been certain progress in the aero-engine secondary air system calculating field, for example, the calculation program of air cooling system ASCP [11], which was compiled based on the Fortran Language and it cannot use visualized operation. Lv Yaguo[12] in Northwestern Polytechnical University has developed a general secondary air system calculating software, which is able to calculate only at the separately condition. It cannot depict and simulate continuously of the quasi-steady state when the boundary conditions changed.

In order to study and analysis of the quasi-steady state air system, and to obtain flow and heat transfer characteristics at corresponding state, and to improve the efficiency of air system modeling and analysis, this paper developed a system of air flow and heat transfer simulation module library and built up the air system pipe network flow characteristics and heat transfer characteristics of general simulation platform based on the flow network theory and MATLAB/Simulink toolkit. Typical components of module library and network algorithm was verified. At last, the network simulation model was established, and the key element, the flow and characteristics of the node parameters was calculated, and the accuracy and applicability of the platform were verified simultaneously.

Air system network

In this paper, one-dimensional method was used to deal with the flow and heat transfer characteristics of each flow units, which is to make the components typification based on the characteristics of the geometry and flow. A simplified network composed of many types of components in series and parallel are used to simulate the aero-engine secondary air system, and the connecting components are called` nodes. The pressure and temperature distribution and flow distribution of the entire network is obtained by iteration.

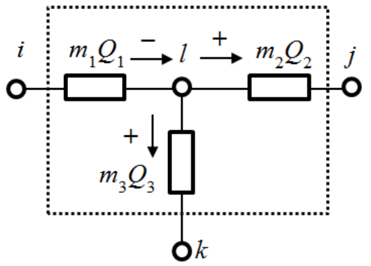

Fig.1 Calculation unit for three components

Each node and its adjacent elements can be regard as a calculation unit. As is shown in the figure 1, it is a three components calculation unit. For a flow heat transfer calculation unit, the element corresponding to the real structure. There is no flow and energy storage inside the element and node, which also satisfy the following control equation.

For components:

Flow equation:

$$\dot{m} = f\left[P_{in}, P_{out}, T_{in}, T_{out}, B\right] \tag{1}$$

Energy equation:

$$Q + \dot{m} \times C_P \times (T_{in} - T_{out}) = 0 \tag{2}$$

For nodes:

Continuous equation:

$$\sum \dot{m} = 0 \tag{3}$$

Energy equation:

$$\sum \dot{m} \times C_p \times T = 0 \tag{4}$$

In the above equation, $\dot{m}$ represents the mass flow of the element or node, P and T shows the pressure and temperature, respectively. C_P represents the specific heat capacity, B represents other quantity which contains the pressure, temperature parameters, such as geometry size, roughness, etc.; Q represents heat transfer.

Any air system can be abstracted as a flow network diagram which is composed of elements and nodes. In a complex flow system: supposing there are n nodes and m units, its temperature, pressure, flow rate can be described by m + n dimension nonlinear equations which consists of momentum equation and continuity equation and energy equation, and the mathematical model of the air system is nonlinear equations. For solving closed nonlinear equations can get the flow and heat transfer parameters of each element and node in the system.

Calculation of component and network

Calculation in component and node

For each component, the main parameters can be achieved based on the input conditions (the total pressure and total temperature of adjacent node), such as, mass flow, inlet and outlet Mach number, static pressure and static temperature. For each node, the total pressure of node is obtained based on the input conditions that are mass flow and total temperature. The algebraic sum of mass flow and heat flow in node is zero, that is to say, there is no mass and energy storage in node.

The calculation relations between component and node are as follows. The total pressure and total temperature calculated of node are transmitted to the adjacent component, which are input conditions of component. Firstly, the flow direction in component is determined by the pressure to obtain the inlet and outlet total parameters. Then, assuming the initial mass flow, the Mach number of inlet and outlet in component is calculated according to geometric parameters. Further the static parameters can be obtained by the Mach number and total parameters. Finally, using the method mentioned in the previous section the mass flow of component is calculated, which is compared with the assumed flow value. If the error is not satisfied with the accuracy requirements, it is necessary to re-assume a new mass flow value based on the calculated value until error meets the requirements. The mass flow and outlet total temperature calculated of component is transmitted to node. Similarly, with the iterative calculation of pressure in node the total pressure and total temperature is output.

Calculation module library and simulation process

The characteristic analysis platform of secondary air system constructed in this paper is needed to have the follow characteristic: openness, generality, modularity, visualization. Also, the platform can be used to analyze the flow characteristics and heat transfer characteristics of secondary air system easily, quickly and accurately. According to the requirements, the simulation platform is decomposed into independent but also linked with each other functional modules. Based on the mathematical models of physical components, the calculation models are built. All of these calculation models constitute the simulation library of secondary air system, including component module library, internal node module library and boundary node module library.

Component module comprises four sub-modules. Logic sub-module is used to judge and determine the inlet and outlet parameters of component; the function of mass flow sub-module is to calculate the flow and loss coefficient; the role of Mach number and heat transfer sub-module is to obtain the inlet and outlet Mach number of component, outlet temperature of fluid. Internal node module comprises sub-module without mass storage and sub-module without energy storage. The role of the two sub-modules is to maintain the conservation of mass and energy. Boundary node module is used to set boundary conditions in the network model, such as pressure, temperature, mass flow, etc.

Using the idea of fluid network algorithm, the fluid system is decomposed into a series of components and nodes. The continuity equation is established in node, while characteristic equation as well as energy equation is set up in component. These equations constitute a large equation group, which can be solved to obtain pressure, temperature and mass flow.

Before calculating of secondary air system, several significant data is required: a. boundary conditions, enter the calculation boundary conditions (mass flow, pressure, heat flow and temperature, etc.) on the boundary nodes; b. initial conditions, components and internal nodes are initialized (setting the initial value of pressure and temperature of nodes in order to improve the speed of computation); c. in Mask interface of components, enter value for the geometrical and characteristic parameters.

Model validation

Component validation calculation

First of all, the component module library developed is verified. The flow characteristic curves (flow-versus-pressure drop) of several common components are shown in the section below, and the calculation results of platform are analyzed comparing with Flowmaster.

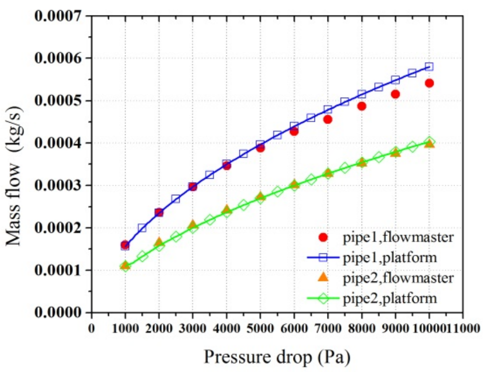

Figure 2 mass flow rate of pipe

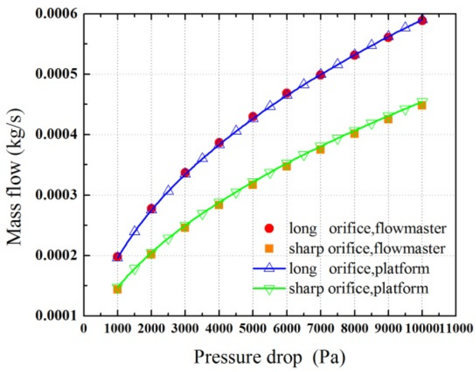

Figure 3 mass flow rate of orifice

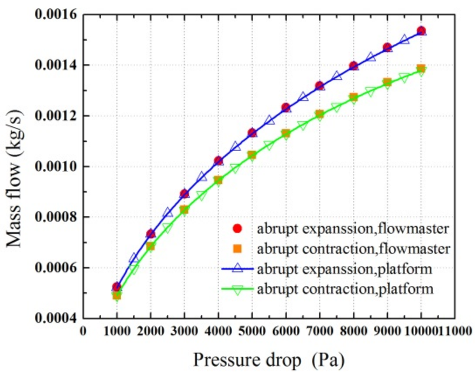

Figure 4 Mass flow rate of abrupt expansion and contraction

Figure 2 shows the comparison results of simulation platform and Flowmaster for pipe. Geometric parameters of pipe1: 2mm in diameter, 50mm in length; Geometric parameters of pipe2: 2mm in diameter, 100mm in length. As can be see, the results of platform agree well with Flowmaster for pipe2, while there is a bigger error for pipe1, the maxim error is 7.2%. Figure 3 shows the comparison results of simulation platform and Flowmaster for long orifice and sharp orifice. Figure 4 shows the comparison results of simulation platform and Flowmaster for abrupt expansion and abrupt contraction. The results indicate that the results of platform agree well with Flowmaster, the maximum relative error of less than 1.5%, therefore it has certain credibility.

Network validation

In order to verify the accuracy of component modules in system and network algorithms, the simulation model is built by the platform and Flowmaster, respectively. Finally, the mass flow of components and pressure of nodes are obtained and analyzed comparatively.

In figure 5, the circles represent nodes, green for boundary nodes (P1, P2, P3) and orange for internal nodes (1~13); the arrows indicate the direction of air flow; other symbols represent different types of components. There are many common components of secondary air system, such as pipe, abrupt expansion, abrupt contraction, long orifice, sharp orifice, etc. P1 is inlet total pressure node, likewise, P2 and P3 indicate outlet total pressure node. Limited by space, the geometric parameters of each component are not described in detail.

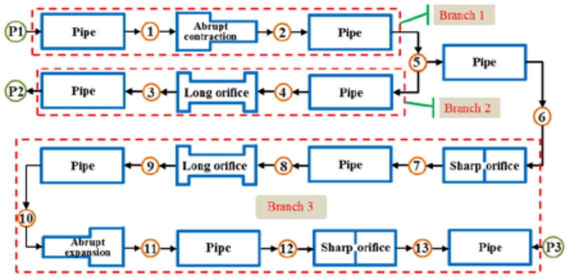

Figure 5 Sketch of network validation

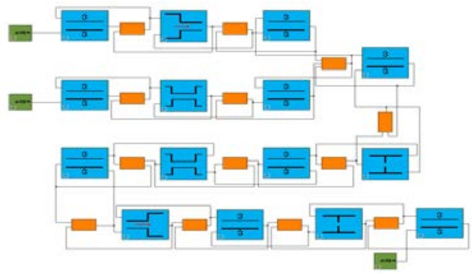

Figure 6 Network build in platform

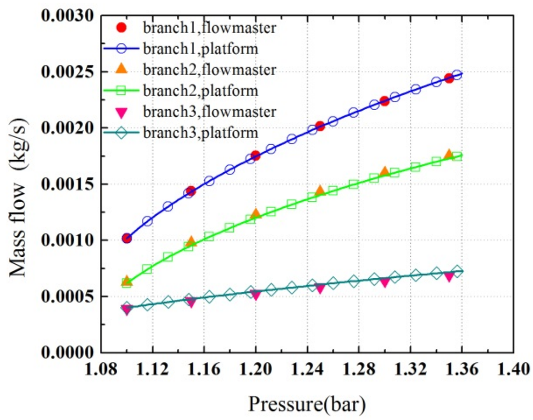

Figure 7 Calculation results for mass flow rate

The network diagram which is shown in Figure 7 is based on the platform in this paper. Using the vector of input conditions, when the import node (the outer node P1) pressure value varies from 1.1bar to 1.36bar, the calculation values of each branch flow is shown in Figure 7. The flow characteristics is calculated and obtained by using the Flowmaster software under 6 conditions of the inlet pressure: 1.10, 1.15, 1.20, 1.25, 1.30, 1.35bar, respectively, at the same time. As can be seen, the two calculation results are in good agreement. The maximum relative error of branch 1, branch 2 and branch 3 is: 0.3698%, 2.365% and 3.970%, respectively.

When the inlet pressure is 1.20bar, the calculation values of some typical node are shown in Table 1. From the table 1, the values of chosen nodes are very close to the calculation pressure, and the maximum relative error appeared in node 6, which has only 0.127% error.

Table 1 Calculation results for pressure of example 1(Pa)

Node	Platform	Flowmaster	Relative error
2	116644.1	116787	0.122%
4	115617.0	115752	0.117%
5	115769.2	115909	0.121%
6	115658.1	115805	0.127%
10	101175.4	101235	0.0589%
12	100896.3	100893	0.00327%

Conclusion

Based on the idea of network computing in this paper, the general simulation model library of aero engine air system is developed, and the general simulation platform of secondary air system is set up. The element model and network calculation has been verified. Furthermore, the following conclusions can be reached:

The element library has a good quality of versatility and scalability. The platform uses visual modeling method which is easy to operate and satisfies the simulation calculation of the aero-engine air system and the other pipeline systems. The input of the boundary conditions can use vector input, which can be used to calculate quasi-steady state and can simulate of a range of different conditions.

The verify calculation results of elements and the verify results of network are compared to the software Flowmaster, which shows that the calculation has a high precision and the biggest error of the flow characteristics of the straight-pipe elements is 7.2%, and the error of the other typical elements is less than 1.5%, and the error of the calculation of network verify calculation is less than 4%.

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