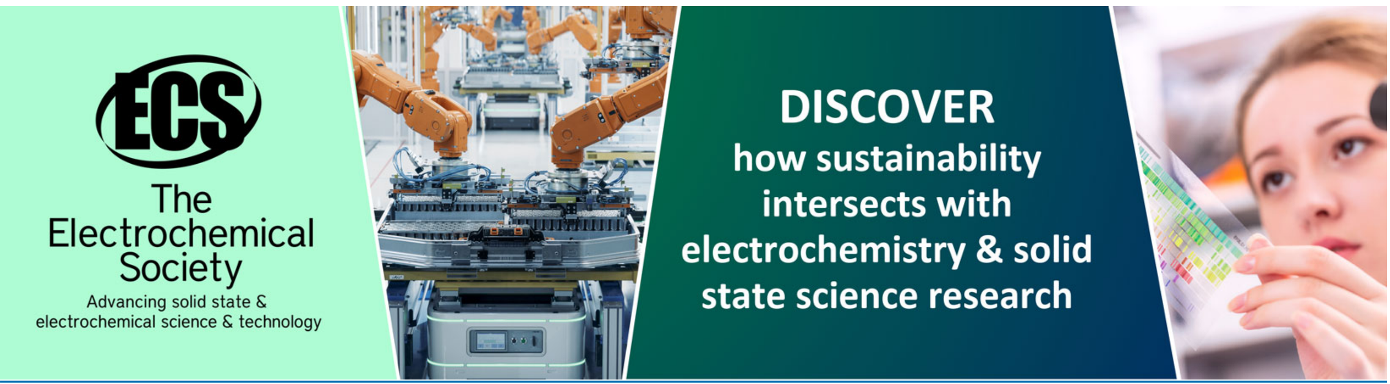
IOP Conference Series: Materials Science and Engineering

Simulation Calculation of Flow Characteristics of Air Separation System Based on Flowmaster



Simulation Calculation of Flow Characteristics of Air Separation System Based on Flowmaster

Yu Zeng[1], Bing Sun[2] and Haoyang Sun[1]

[1] Beihang University
[2] Aviation Industry Corporation of China

zengyu@buaa.edu.cn; 13810545207
sunbing0720@163.com; 18618405545
sunhaoyang@buaa.edu.cn; 15652909619

Abstract. The air separation system is an important part of aircraft fuel inerting system, which is responsible for the important task of supplying nitrogen-enriched air to the aircraft fuel tank. The flow characteristic of air separation device is the key problem of its design. In this paper, based on one-dimensional fluid simulation software Flowmaster, we did some research on the simulation model of membrane modules, established the simulation model of air separation system, obtained the simulation results of the flow characteristics and analyzed the results in detail. The results showed that under low pressure and flow conditions, compared with the experimental values, the relative error of nitrogen-enriched air and oxygen-enriched air flow rate was about 5%.In the case of high inlet pressure and flow, the pressure loss of the junctions and the long pipeline was larger, and the inlet pressure, outlet pressure and pressure loss of the 12 membrane modules were significantly different. The research work was of reference value for the design optimization of air separation system in aircraft fuel inerting system.

Keywords—Fuel inerting system, air separation system, pressure loss, flow characteristics, numerical simulation

1. Introduction

For modern military aircraft, fuel system fire disaster is the most common and the most serious potential danger, and the survival of fuel tank is of great significance to improve the survival of the whole machine. The fuel system mainly includes storage system, distribution system, measurement system, inertial system and many other complex subsystems[1]. The inerting system takes the high-pressure gas from the engine compressor and processes it into nitrogen-enriched air through the air separation system which is suitable for concentration of the fuel tank. Its function is to ensure that the oxygen concentration of the oil free space above the tank level is below 9%, to ensure the safe state of the oil tank. On the other hand, as the air pressure increases in the external environment during the landing, the inert gas is also used to increase the pressure in the tank to prevent excessive negative pressure.

The traditional aircraft fuel system research and design process often involves large workload, complicated tasks, inconvenient data usage, low efficiency, poor fault-tolerance, and difficulty in retrieving. With the continuous development of computational simulation technology, the designers usually choose the simulation calculation method to verify the feasibility of the complex system[2].

This paper mainly studies the flow characteristics of air separation system in fuel system based on fluid simulation software Flowmaster. As the world's leading one-dimensional fluid system simulation software facing the engineering, Flowmaster includes one-dimensional hydrodynamic system solver and fluid system simulation software package which is mature and complete, has received more and more application from aerospace, automobiles, ships, energy and chemical industry, hydraulic pump station and other industrial field. Flowmaster provides a set of simple and visual development environment to build elements and system. When building the simulation system, designers can call multiple pipelines and components more than 400 species, such as pipe, bend, T-branch tube, valve, pump, fan, heat exchanger, voltage regulator, fuel tank, spring, thermal bridge, control element and so on. By using Flowmaster, we can carry out accurate pressure, flow, temperature and flow velocity analysis of each node in the system, to help engineers complete and optimize the system design quickly. It can reduce production cost, improve product performance, shorten product development time and test times. [3-5]

2. Air separation system

Air separation system is loaded in aircraft inerting system, using hollow fiber technology, to separate oxygen and nitrogen in the air which is requested in pressure, flow, temperature and cleanliness, drain the enriched oxygen, and collect the enriched nitrogen for fuel tank inerting, to prevent serious disaster caused by aircraft fuel tank explosion and improve the survivability of the aircraft.

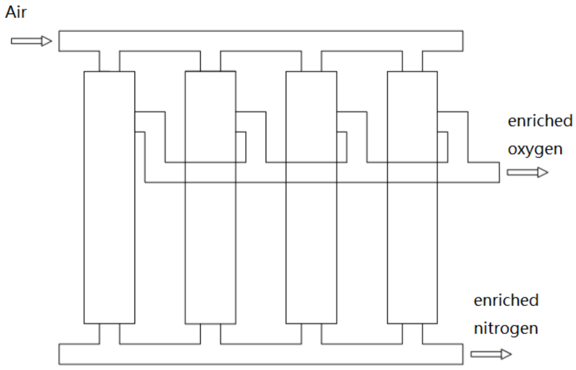


Figure 1. The upper layer of air separation system

The upper layer of air separation system is showed in Fig. 1, which is mainly composed of membrane modules, frames, pipelines, pipe supports, flexible clamp components and so on. In the air separation system, the air is bled from the environmental control system, entered into 12 membrane modules in the upper, middle and lower layers, where the separation of oxygen and nitrogen is achieved. The three -layer membrane modules are similar. The enriched oxygen bled from each membrane module is sent through the enriched oxygen pipe to the back of the aircraft cabin, the enriched nitrogen bled from each membrane module is collected into the enriched nitrogen pipe, adjusted into Nitrogen gas with different oxygen concentration and flow by a pressure regulator, and transported to the corresponding parts in fuel tank according to the system requirements.

3. Simulation model construction

3.1. Modeling purposes

The modeling purposes are formatted as follows:

- In view of the air separation system, how to utilize flow characteristics components in Flowmaster to build reasonable simulation calculation model of the air separation system and guide the subsequent simulation calculation and experiment of the air separation system is necessary.

- In view of the existing air separation system, there is a large pressure loss between the gas source and the entrance of 12 membrane modules. This paper will focus on two T-branch tubes and a 1.3 meters long and straight pipeline, analyze the pressure loss by the simulation calculation and put forward the reasonable optimization in order to improve process performance of the structure.

3.2. Construction of membrane module model

Membrane module is an important part of air separation system, which pipeline structure is composed of air inlet, enriched nitrogen outlet and enriched oxygen outlet. In practical application, experimenters usually control the flow of enriched nitrogen by adjusting valve opening at the nitrogen gas outlet to control the oxygen concentration of enriched nitrogen, enriched oxygen is bled directly into the atmosphere. oxygen concentration, gas flow ratio and flow characteristics of membrane module are all related to inlet pressure and enriched nitrogen pipeline pressure.

In order to study membrane module's flow characteristics of enriched oxygen pipe and enriched nitrogen pipe, two flow resistance components, the pressure loss coefficient of which respectively were known from the experimental data of the existing single membrane module, were adopted to match membrane module.

The pressure loss coefficient is related to inlet pressure and pressure loss (the difference between inlet pressure and enriched nitrogen pressure), The relation of them is:

$$\Delta p = \frac{KQ^2}{2A\rho} \tag{1}$$

Q is mass flow, A is the area of pipe section, ρ is the density and Δp is the pressure loss.

According to the experimental data of single membrane module provided by Hefei jianghang aircraft equipment company, there are 8 groups of flow resistance coefficient of Enriched nitrogen pipeline K1 and flow resistance coefficient of Enriched oxygen pipeline K2 under different inlet pressure and pressure loss shown in Table 1.

Table 1. K1 and K2 under different inlet pressure and pressure loss

Inlet pressure/MPa	Pressure loss/ MPa	K1	K2
0.4	0.01	10675.5	10124.1
0.5	0.015	3375.9	2863.3
0.6	0.015	1102.9	1669.2
0.4	0.015	3306.4	11269.0
0.5	0.025	1182.5	3008.9
0.6	0.025	410.9	1492.7
0.4	0.035	822.0	4844.1
0.5	0.05	271.2	2317.1

3.3. Simulation model

In view of the actual situation of air separation system, this paper builds the simulation model based on Flowmaster—one-dimensional thermal flow simulation platform. The simulation model is shown in Fig. 2.

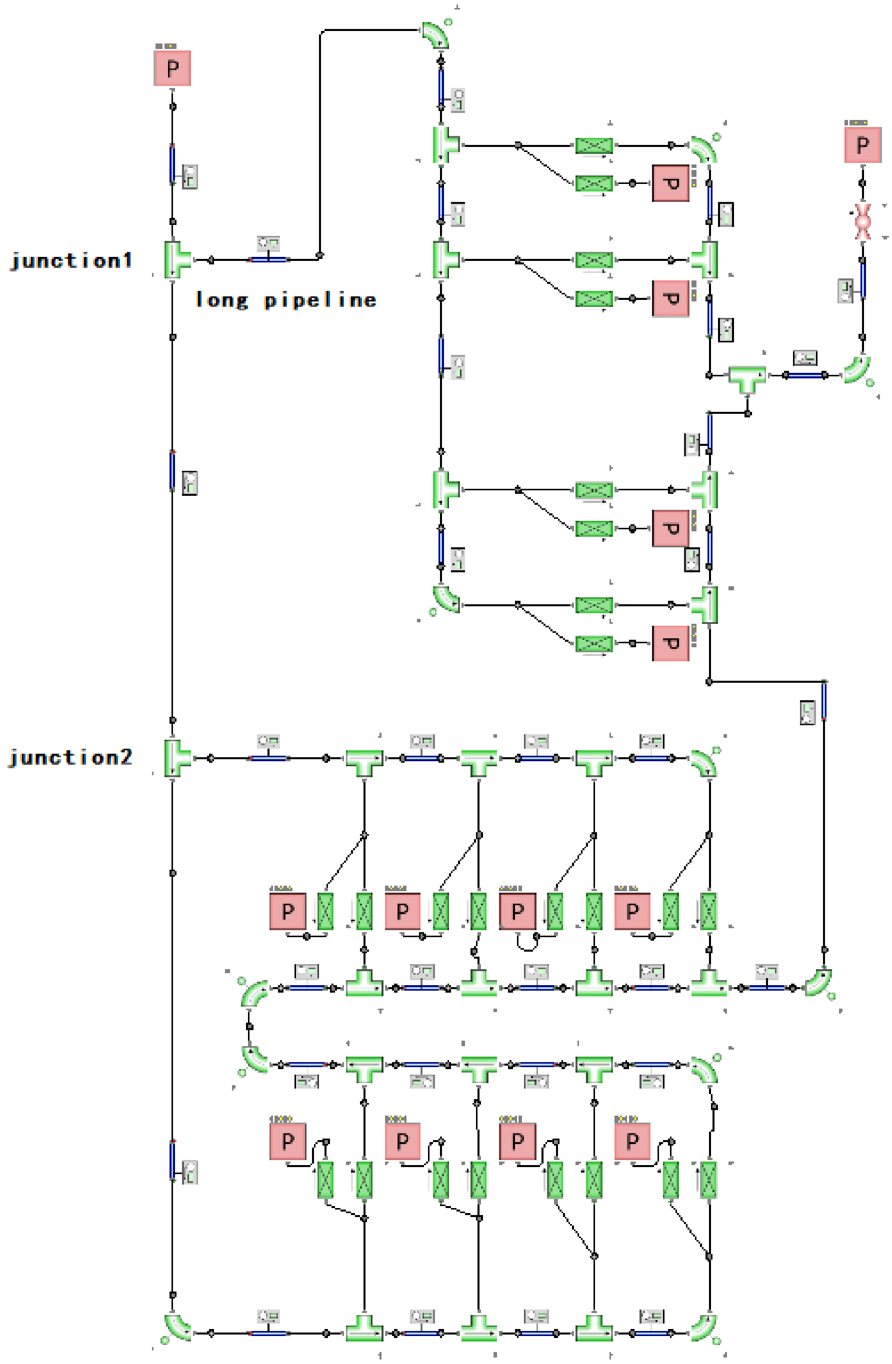


Figure 2. Simulation model of air separation system

The components in the model included pipe, bend, valve, source, T-branch tube, loss and so on. In the simulation model of air separation system, pressure source was adopted to simulate the air source of inlet and outlet, global valve was adopted to simulate flow control valve at the enriched nitrogen outlet. The 12 membrane modules were numbered 1~12, as shown in Fig. 2. The variable of simulation calculation was the opening of inlet pressure and the opening of flow control valve.

3.4. Component model selection and parameter setting

Table 2 introduces the model and the parameters to be set in the simulation calculation model according to the actual structure and components.

Table 2. The model and the parameters to be set

Components	Model	Parameters to be set
pipe	Pipe cylindrical	Length,diameter, Friction data
Constant pressure air supply	Source:Pressure	liquid type, total pressure
Flow resistance element	Loss:discrete	cross-sectional area, forward loss coefficient, forward loss coefficient
Valve	Valve:globe	Diameter,valve opening
Bend	Bend:circular	deflection angle, radius/diameter, roughness, diameter
T-branch tube	Junction:T(90°)	through pipe diameter, branch pipe diameter
medium	Dry air as real gas	No set up

4. Result and analysis

According to 8 groups of the experimental data of single membrane module, 8 groups of simulation calculations were performed.

In the simulation calculation, in the different air pressure conditions, flow resistance coefficient of membrane module was assigned in accordance with experimental data of single membrane module, the average pressure loss of the membrane modules was consistent with that of the single membrane module by changing the opening of the flow control valve, which ensured that the flow characteristics of the membrane modules were more consistent with the actual situation. The key parameters of simulation calculation of air separation system are shown in Table 3.

Table 3. Key parameters of simulation

Constant pressure air supply /MPa	The opening of flow control valve /%	Average pressure loss of the membrane modules /MPa	Average inlet pressure of the membrane modules /MPa
0.4	3.6	0.00999	0.398
0.5	6.33	0.01492	0.492
0.6	9.42	0.01501	0.583
0.4	7.1	0.01489	0.397
0.5	12.57	0.02496	0.489
0.6	19.72	0.02501	0.572
0.4	21.4	0.03505	0.390
0.5	59.3	0.04999	0.468

4.1. Analysis of pressure loss of T-branch tube and the long pipeline

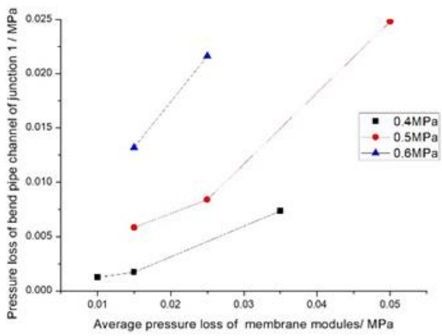


Figure 3. Pressure loss of bend pipe channel of junction 1

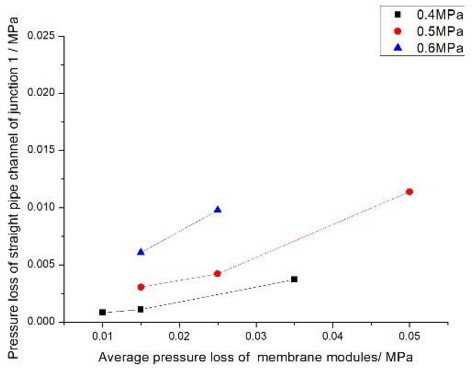


Figure 4. Pressure loss of straight pipe channel of junction 1

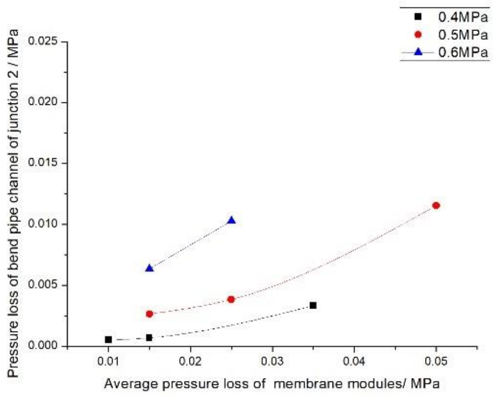


Figure 5. Pressure loss of bend pipe channel of junction 2

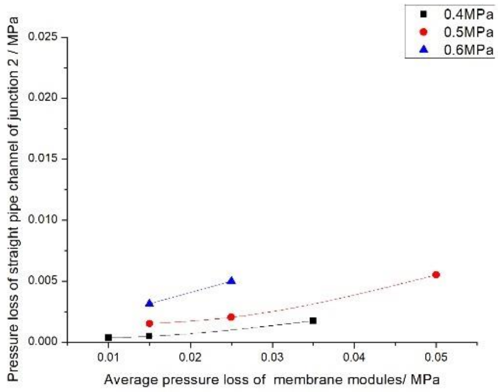


Figure 6. Pressure loss of straight pipe channel of junction 2

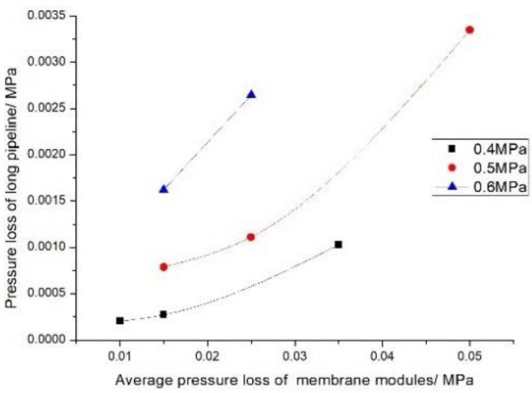


Figure 7. Pressure loss of the long pipeline

As can be seen from figure 3-7:

- The Pressure loss of bend pipe channel was greater than that of straight pipe channel;
- The junction 1 was in the front of the junction 2, and the flow rate of junction 1 was larger than that of the junction 2, so the pressure loss of junction 1 was greater.
- With the increase of air source pressure and flow, the pressure loss also increased.

- The pressure loss of junction was an order of magnitude greater than that of the long pipeline of 1.3 meters.

4.2. Analysis of simulation 8

The air source pressure and flow rate of simulation 8 were the largest in the 8 simulation experiments, and the differences between the 12 membrane modules were more obvious, which was convenient for analysis.

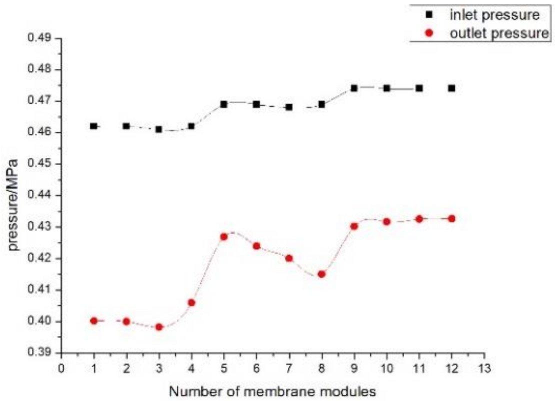


Figure 8. Inlet and outlet pressure of membrane modules in simulation 8

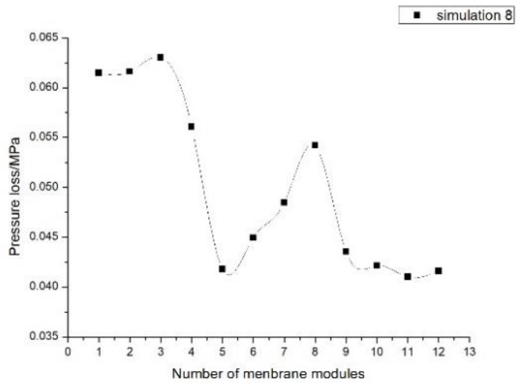


Figure 9. Pressure loss of membrane modules in simulation 8

It could be seen that when the inlet pressure and flow rate were larger, the inlet pressure, outlet pressure and pressure loss of each membrane module were very different. The following conclusions could be obtained from Fig. 8-9.

- The front pipe structure of membrane module in air separation system for had certain influence for inlet pressure of 12 membrane modules. As a result of the existence of two T-branch tubes, pressure loss of larger flow of T-branch tube was bigger, pressure loss of the bend pipe channel was bigger, so the inlet pressure of membrane module 1-4 was the minimum, the inlet pressure of membrane module 5-8 was secondary, and the inlet pressure of membrane module 9-12 was the maximum.
- The back pipe structure of membrane module in air separation system for had certain influence for outlet pressure of 12 membrane modules. Pressure loss of back pipe of membrane module1-4 was less than that of membrane module5-8, Pressure loss of back pipe of membrane module5-8 was less than that of membrane module9-12, so the outlet pressure of membrane module 1-4 was the minimum, the outlet pressure of membrane module 5-8 was secondary, and the outlet pressure of membrane module 9-12 was the maximum.
- The pressure loss of membrane module in air separation system was related with front pipe structure and back pipe structure. In a word, the pressure loss of membrane module 1-4 was the maximum, the pressure loss of membrane module 5-8 was secondary, and the pressure loss pressure of membrane module 9-12 was the minimum.

4.3. Simulation error analysis

The simulation values of the average flow of enriched nitrogen and enriched oxygen were compared with the experimental values of the single membrane module, and the error analysis was showed in Table 4-5.

Table 4. Error analysis of enriched nitrogen flow

Simulation number	Experimental values of enriched nitrogen flow /$m^3 \cdot s$^-1	The average calculation value of enriched nitrogen flow /$m^3 \cdot s$^-1	Relative error /%
1	0.00125	0.00122	2.25
2	0.00244	0.00240	1.94
3	0.00389	0.00393	1.13
4	0.00278	0.00252	9.13
5	0.00542	0.00516	4.74
6	0.00833	0.00837	0.45
7	0.00886	0.00782	11.78
8	0.01667	0.01515	9.09

Table 5. Error analysis of enriched oxygen flow

Simulation number	Experimental values of enriched oxygen flow /$m^3 \cdot s$^-1	The average calculation value of enriched oxygen flow /$m^3 \cdot s$^-1	Relative error /%
1	0.00523	0.00545	4.18
2	0.01001	0.01042	4.09
3	0.01312	0.01395	6.28
4	0.00502	0.00539	7.30
5	0.00997	0.01002	0.55
6	0.01412	0.01477	4.66
7	0.00808	0.00751	7.03
8	0.01199	0.01127	5.95

Table 4-5 showed that, under lower pressure and flow rate, the simulation error is within 5%; under higher pressure and flow, the maximum simulation error was 11.8%. In addition to the model error of the simulation calculation and the measurement error of the test, the main error was method error, the cause of which was that inlet pressure and pressure loss of each membrane module in simulation and experiment with single membrane were not the same, and the resistance coefficient of the membrane module K1 and K2 assigned different from the actual condition. A new idea was proposed that adopting the method of iterative calculation—according to the inlet pressure and pressure loss of membrane module in the last simulation calculation, assigning resistance coefficient of the membrane module K1 and K2 again and repeating the above operation until convergence.

5. Conclusion and optimization

The conclusion and optimization are formatted as follows:

- In the T-branch tube, the pressure loss of bend pipe channel was much greater than the pressure loss of straight pipe channel. As the pressure increased, it appeared a large pressure loss even influenced the experiment. Therefore, it was necessary to adjust T-branch tube to reduce the pressure loss.
- There was a 1.3-meter-long pipeline in experiment system, the pressure loss caused by which increase as the air source pressure increased. It is necessary that minimizing the length of the

pipeline or increase the diameter of it to increase its circulation area and reduce the pressure loss in the subsequent experiments.

- It is necessary to properly allocate the intake and exhaust mode of the membrane module, otherwise, the inlet pressure, outlet pressure and pressure loss of each membrane module will be different when the air source pressure and flow are high.
- The flow characteristics of membrane module were decided by the inlet pressure and the pressure loss of enrich nitrogen pipe. Therefore, we need a lot of experimental data and use interpolation to get the corresponding resistance coefficient K1 and K2. When sufficient experimental data are available for support, an iterative method can be used to analyze the flow characteristics of air separation system, which can obtain the accurate inlet pressure, pressure loss and resistance coefficient of each membrane module in the certain conditions of air source pressure and flow control valve opening, to avoid situations where the single assignment of resistance coefficient to all membrane modules is different from the actual working conditions.

References

[1] Langton R, Clark C and Hewitt M M 2009 *Aircraft Fuel Systems*(New York: Wiley–Interscience)

[2] Guangtuo G 2014 *J. Platform construction research for fluid numerical simulation of an airplane fuel system basing on flowmaster*. *Equipment Manufacturing Technology* **9** 42-44.

[3] Yi T, Guiping L and Guodong L 2009 *J Computer analysis of transport aircraft oxygen system based on flowmaster*. *Journal of Beijing University of Aeronautics and stronautics* **35** 1306-10

[4] Kexue Y 2008 *J Flowmaster Software Based on a Certain Type of Helicopter Fuel System Simulation*. *Helicopter technique* **4** 15-18

[5] Chao L, Zhihong L, Hong Shi and Yanlong J 2012 *J Simulation calculation of aircraft anti-ice system catheter based on Flowmaster software*. *Science & Technology Information* **32** 699-702