Analysis of the Influence of On-Board Temperature and Pressure Control System on Inert Gas Generating Performance of Hollow Fiber Membrane

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Abstract. Based on the typical on-board membrane separation system for fuel inerting, the mathematical models of temperature and pressure control subsystem and hollow fiber membrane were built with the coupled iterative numerical solution methods. While the temperature and pressure were controlled, the design area, nitrogen production effect of hollow fiber membranes were analyzed and compared with the situation of no temperature and pressure control in the full flight envelope by numerical simulation. Moreover, the root causes for those changes were found out. It shows that the method used in temperature and pressure control can increase the bleed air pressure and enhance the stability of temperature and pressure effectively. Compared with the situation of no temperature and pressure control, the temperature and pressure control method are able to decrease the demanded area of membrane by 42.3%–51.7%. And there is no need to adjust the membrane area for condition of low nitrogen production efficiency. But it also decreases the highest nitrogen production efficiency by 9.4% and increase the minimum oxygen concentration by 0.65%. The rate of flow has the most significant effect on nitrogen production. These phenomena are caused by the effects of the rate of flow, pressure, temperature and membrane area.

1. Introduction
According to the data of air crash in 50 years, the viability of the aircraft is affected by the safety of fuel tank greatly. Since the 1980s, the United States had begun research on aircraft fuel tank inerting systems [1] and made great achievement [2]. With the development of new type in China [3], the theoretical and experimental research on aircraft fuel tank inerting systems had been carried out without hesitation [4]. Among all kind of aircraft fuel tank inerting technology, onboard inert gas generating technology received extensive attentions because of its high reliability, long working life, low repair costs and few needs for support equipment on ground. This technology asks for bleeding air from an aircraft engine or an environmental control system and obtains nitrogen-enriched gas through an onboard air separation device, which is used for fuel tank washing [5]. After that, the oxygen concentration is able to keep a lower level than the oxygen demand for the possibility of combustion in the upper space of the aircraft fuel tank [6]. At present, many military aircrafts and civil aircrafts,
such as C5A, C17, KC135, F22, B737, B747 and A320 [7], have applied this technology.

The air separation device is the most critical part of the onboard fuel inerting system. In 1950, Weller was the first to establish a mathematical model of the cross-flow binary gas separation process based on the working mechanism of the fiber membrane for gas separation [7]. After that, Zhu Yulin and Jiang Guoliang established a mathematical model of the process of separating nitrogen and hydrogen with hollow fiber membranes and performed some experiments to confirm the theory [8]. Based on their research, Xu Renxian analyzed the pressure drop in the hollow fiber membrane with the gas separation model and contributed to verified the effectiveness of the mathematical model of the gas separation [9]. At the same time, the US Air Force conducted a large number of experiments on the inert gas generating performance of hollow fiber membrane in the 1980s. The data showed that the active temperature control can help to improve the nitrogen production efficiency by mostly about 15% and decrease the oxygen volume fraction of the product gas by mostly about 4%, and the active pressure control can help to improve the nitrogen production efficiency by mostly about 20% and decrease the oxygen volume fraction of the product gas by mostly about 6% [10]. Liu Xiaofang simulated the effects of ambient pressure, ambient temperature, altitude and gas temperature on the performance of inert gas generating system based on the inert gas generating system of some type of aircraft, which showed that factors such as pressure, temperature and mass flow determine the nitrogen production of the air separation device. George also found that the mass flow and gas temperature have a significant impact on nitrogen production by the experiments in 41 different working conditions [11]. Thomas made some research on the feasibility of onboard fuel inerting system applied to commercial aircraft. The result showed that it is closely related to the bleed air parameters[12]. Therefore, the active gas temperature control is an effective way to improve the nitrogen production effect of the onboard membrane separation system for fuel inerting [13]-[14]. However, there is still short of quantitative research on the combined effects of gas temperature control and gas pressure control for membrane separation system. The future design of onboard membrane separation system for fuel inverting needs to know well about the influence of flight envelope on effectiveness of nitrogen production and its internal cause.

This paper took the typical membrane separation system for fuel inverting as the research object. And it established the model of temperature and pressure control subsystem coupled with hollow fiber membrane which is used to compare the change of hollow fiber membrane design area, nitrogen production efficiency and oxygen volume fraction in the whole flight envelope with or without temperature and pressure control and analyze their internal factors. This paper will be able to provide technical reference for the design of onboard membrane separation system for fuel inverting.

2. Model building

2.1. Global structure
The onboard membrane separation system for fuel inverting designed in this paper has a temperature and pressure control subsystem with turbine and compressor. And the specific scenario is the following: this system bleeds air from the engine or the environmental control system and delivers the air to the air separation device after temperature and pressure control in order to obtain inert gas, and finally delivers inert gas to the fuel tank for washing. The system structure is shown in figure 1. This device bleeds air from the engine or the environmental control system. After that, the gas is divided into two part. One part of the gas is used to drive the turbine in order to run the compressor to adjust pressure, and the other one is divided into two part again. One part of the divided gas flows through the heat exchanger while the other one not. Then, these gases are mixed and delivery to the compressor. This device can adjust the gas flow delivery to the turbine by the valves V1 and V2 in order to control the pressure of gas products. And it can adjust the gas flow delivery to the radiator by the valve V4 in order to control the temperature of gas products. After temperature and pressure control, the final outlet gas is the gas product.
2.2. Mathematical Model

2.2.1. Mathematical model and parameters of temperature and pressure control subsystem. Turbine: The characteristic curve of turbine is shown in Figure 2. The relevant parameters can be obtained by this curve. For saving space, the process won’t be present here.

Compressor: The characteristic curve of the compressor is shown in Figure 3. The relevant parameters can be obtained by this curve. For saving space, the process won’t be present here.
Heat exchanger: The heat exchanger adopts a counter-flow plate type. This one is similar with the heat exchanger in paper [15]. The space between the parallel plate is 30mm, and the heat exchange area is 20cm$^2$. The Nu number of heat transfer is calculated by the Dittus-Boelter formula, and drag coefficient is obtained by the Blasius formula:

$$\text{Nu} = 0.023 \cdot \text{Re}^{0.8} \cdot \text{Pr}^{0.3}$$

(1)

Where $\text{Re}$ is the Renault number ($10^4 \leq \text{Re} < 1.2 \times 10^5$), $\text{Pr}$ is the pressure ratio (0.6 < $\text{Pr}$ < 120).

$$f = 0.079 \text{Re}^{-0.25}$$

(2)

Where $\text{Re}$ is the Renault number ($4000 \leq \text{Re} < 10^5$).

2.2.2. Mathematical model and parameters of hollow fiber membrane. Hollow fiber membrane can be divided into parallel flow, counter flow and cross flow according to the direction of intake and exhaust gas [15]. And this paper adopts the parallel flow type, which means the directions of intake and exhaust gas are the same. And the inner diameter of the hollow fiber membrane is 0.45 mm. The outer diameter of the hollow fiber membrane is 0.55 mm, and the length of the hollow fiber membrane is 0.98 m. The structure of the hollow fiber membrane is shown in figure 4. And it’s possible to adjust the membrane area by increasing or decreasing the number of hollow fiber membrane silk.

![Figure 4](image)

Figure 4. Parallel flow type of the hollow fiber membrane.

According to conservation of mass, permeation law and the pressure drop equation, their equations can be obtained. The first equation is about flow mass conservation:

$$q_{V,in} + dq_{V,in} + q_{V,out} + dq_{V,out} = q_{V,in} + q_{V,out}$$

(3)

Where $q_{V,in}$ is the inlet flow, $q_{V,out}$ is the outlet flow.

The second equation is about conservation of oxygen mass:

$$(q_{V,in} + dq_{V,in})\left(\varphi_{O_2,in} + dq_{O_2,in}\right) - q_{V,out}\varphi_{O_2,out} = -(q_{V,out} + dq_{V,out})\left(\varphi_{O_2,out} + dq_{O_2,out}\right) + q_{V,in}\varphi_{O_2,in}$$

(4)

Where $\varphi_{O_2,in}$ is the oxygen content of inlet flow, $\varphi_{O_2,out}$ is the oxygen content of outlet flow.

The third equation is permeability equation of oxygen:

$$J_1 \left( p_f \varphi_{O_2,in} - p_p \varphi_{O_2,out} \right) dz = -d \left( q_{V,in} \varphi_{O_2,in} \right)$$

(5)

Where $J_1$ is the penetration rate of oxygen, $A$ is the area of hollow fiber membrane, $L$ is the length of the hollow fiber membrane, $p_f$ is the pressure within the membrane, $p_p$ is the pressure of the membrane outside.

The fourth equation is permeability equation of nitrogen:

$$J_2 \left[ p_f \left(1 - \varphi_{O_2,in}\right) - p_p \left(1 - \varphi_{O_2,out}\right) \right] dz = -d \left[ q_{V,in} \left(1 - \varphi_{O_2,in}\right) \right]$$

(6)

Where $J_2$ is the penetration rate of nitrogen.

The fifth equation is about pressure drop:
\[
\frac{dp_f}{dz} = -\frac{128RT_q}{N\pi d_i^4} p_f
\]  
(7)

Where \( N \) is the number of hollow fiber membrane silk, \( T \) is the temperature of membrane, \( d_i \) is the inner diameter of membrane silk, is the deal gas constant.

The change of penetration rate of nitrogen and oxygen with temperature conforms to the pattern of Arrhenius [16]. So, the penetration rate can be obtained by formula (8) and formula (9).

\[
J_1 = 1.81 \times 10^{-7} \times e^{19.3 RT} 
\]  
(8)

\[
J_2 = 8.76 \times 10^{-7} \times e^{27.6 RT} 
\]  
(9)

In the boundary condition, the initial flow within membrane is equal to the bleed air flow. And initial oxygen content within membrane silk is 21%. The initial flow outside the membrane is 0. And the initial oxygen content outside the membrane can be obtained by formula (10).

\[
\left. \frac{\varphi_{O_2,\text{out}}}{\varphi_{N_2,\text{in}}} \right|_{z=0} = \frac{J_1 \left( p_f \left. \varphi_{O_2,\text{in}} \right|_{z=0} - p_p \left. \varphi_{O_2,\text{out}} \right|_{z=0} \right)}{1 - \left. \varphi_{O_2,\text{out}} \right|_{z=0}} = \frac{J_2 \left( p_f \left. \varphi_{N_2,\text{in}} \right|_{z=0} - p_p \left. \varphi_{N_2,\text{out}} \right|_{z=0} \right)}{1 - \left. \varphi_{N_2,\text{out}} \right|_{z=0}} 
\]  
(10)

Where \( \varphi_{N_2,\text{in}} \) is the nitrogen content of inlet flow, \( \varphi_{N_2,\text{out}} \) is the nitrogen content of outlet flow.

2.3. Calculation flow

The calculation flow is shown in Figure 5. The inlet temperature, inlet pressure, ambient temperature and ambient pressure are known conditions. When the temperature and pressure control subsystem is working, the mathematical model of the hollow fiber membrane can be solved by the classical Runge-Kutta method. And the model of the temperature and pressure control subsystem can be solved by Newton's iteration method. If the residuals of these equations are less than \( 10^{-6} \), the efficiency of nitrogen production and oxygen content of gas product can be obtained by formula (11) and formula (12).
The efficiency of nitrogen production by calculating
The efficiency of nitrogen production by experiment
The oxygen concentration by calculating
The oxygen concentration by experiment

\[
\eta = \frac{q_{V, in}|_{z=0}}{q_{V, in}|_{z=0}} \times 100\% \quad (11)
\]
\[
\varphi = \varphi_{O, in}|_{z=0} \times 100\% \quad (12)
\]

Where \( q_{V, in}|_{z=0} \) is the initial flow within membrane, \( q_{V, in}|_{z=0} \) is the outlet flow within membrane (\( m^3/s \)), \( \varphi_{O, in}|_{z=0} \) is the oxygen content of the outlet flow within membrane.

2.4. Model validation

This part is used to verify the reliability of the model. The structural parameters of the device are the same with the parameters in the paper [17]. The inlet flow of the product gas is 13kg/s, and the temperature of the membrane is 298K. Comparing the results of calculating with the data in the paper, the maximum error is less than 10%. The data is shown in Figure 6. Therefore, this model is able to reflect the change of efficiency of nitrogen production and oxygen content of gas product very well.

![Figure 6. Comparison between calculating results](image)

3. Simulation condition

Based on the flight envelope of large transport airplane and its flight parameters, the flight path is designed. And this flight path can be divided into static stage of the ground, takeoff roll stage, ascent stage, cruise stage and dive stage, which is shown in Figure 7.

The flight state parameters at every stage and the parameters of gas product are shown in Table 1. According to the requirements of fuel tank inerting in each flight phase, this system designs flow control device [18] in order to achieve the different working modes of flow and oxygen content of gas product. There are two kinds of working mode in this paper [19]. One of them is small flow mode with low oxygen concentration, and the other one is large flow mode with high concentration oxygen. No stage except dive stage adopts large flow mode with high oxygen concentration. Large flow mode with high oxygen concentration requires that oxygen concentration is less than 9%, and small flow mode with low oxygen concentration requires that oxygen concentration is less than 5%. In the flight of aircraft, the working mode of flow is changing. And different types of aircraft have different requirements of flow. In this paper, the required flow is changing between 0.0064m$^3$/s~0.172m$^3$/s. And this paper sets that the flow in small flow mode with low oxygen concentration is no less than 0.118 m$^3$/s, while the flow in large flow mode with high oxygen concentration is no less than 0.200 m$^3$/s. In the static stage of the ground, the flow is limited because of static condition of aircraft. In this stage, the flow is no more than 0.0901 m$^3$/s.
4. Simulation result

4.1. Contrastive analysis of temperature and pressure

Figure 8 is a graph showing changes in ambient temperature, temperature of bleed gas and temperature after controlled. The change of the temperature of bleed gas is similar to ambient temperature. And these changes fluctuate greatly, while the temperature after controlled changes smoothly. The maximum temperature of bleed gas is 493K, which exists in the takeoff roll stage. The minimum temperature of bleed gas is 413K, which exists in the ascent stage. The maximum ambient temperature is 299.6K, which exists in the static stage of the ground. The minimum ambient temperature is 216K, which exists in the cruise stage. The temperature control objectives in this system is 365±5K. The temperature of air flow can be controlled to 365K with closed-loop control of temperature. This temperature is suitable for the working of hollow fiber membrane.

Figure 9 is a graph showing changes in ambient pressure, pressure of bleed gas and pressure after controlled. The change of the pressure of bleed gas and ambient pressure fluctuate greatly, especially in the takeoff roll stage and ascent stage. The maximum pressure of bleed gas is 4.5bar, which exists in the takeoff roll stage. The minimum pressure of bleed gas is 2.4bar, which exists in the dive stage. The ambient pressure changes with altitude. The most unstable situation of pressure after controlled exists in adopting open-loop control [20]. The maximum pressure after controlled is 5.4bar, which exists in the takeoff roll stage and cruise stage. The minimum pressure after controlled is 4.2bar.

Table 1. Selected point parameter table

| Number | t/s   | the required flow/m³·s⁻¹ | the required oxygen concentration |
|--------|-------|---------------------------|----------------------------------|
| 1      | 0     | <0.0901                   | <5%                              |
| 2      | 1500  | ≥0.0901                   | <5%                              |
| 3      | 1800  | ≥0.118                    | <5%                              |
| 4      | 2100  | ≥0.118                    | <5%                              |
| 5      | 2440  | ≥0.118                    | <5%                              |
| 6      | 2640  | ≥0.118                    | <5%                              |
| 7      | 2700  | ≥0.118                    | <5%                              |
| 8      | 5150  | ≥0.118                    | <5%                              |
| 9      | 5250  | ≥0.200                    | <9%                              |
| 10     | 5350  | ≥0.200                    | <9%                              |
which exists in the static stage of the ground. The pressure of air flow can be controlled to 5.6bar with closed-loop control of pressure [21]. But the pressure after controlled is higher than pressure of bleed gas, no matter adopting closed-loop control or open-loop control of pressure.

![Figure 8. The characteristic curve of temperature](image)

![Figure 9. The characteristic curve of pressure](image)

4.2. **Contrastive analysis of the area of hollow fiber membrane**
Based on the simulation results, the minimum required fiber membrane area in the whole flight envelope is calculated. The calculation results are shown in Figure 10. And the maximum value will be taken as the actual area of the hollow fiber membrane. If the temperature and pressure were not controlled, the maximum required area of the hollow fiber membrane is 1.49 m$^2$, which exists in the static stage of the ground. And the minimum required area of the hollow fiber membrane is 0.78 m$^2$, which exists in the ascent stage. The required area of the hollow fiber membrane fluctuates with the flight stage greatly. If the temperature and pressure were controlled, the maximum required area of the hollow fiber membrane is 0.72 m$^2$ in the static stage of the ground with open-loop control. And the minimum required area of the hollow fiber membrane is 0.41 m$^2$ in this situation, which exists in the cruise stage. Compared with the situation without temperature and pressure control, the required area decreases by 42.3%–51.7%. And the change of required area of hollow fiber membrane with altitude is smooth.

![Figure 10. The chart of the required area of hollow fiber membrane](image)

4.3. **Contrastive analysis of the effects of hollow fiber membrane on nitrogen production**
The nitrogen production efficiency of the hollow fiber membrane and the oxygen concentration of the gas product are analyzed with or without temperature and pressure control. Since the requirements in every stage have to be met, the area of hollow fiber membrane is set as the maximum required area in
the whole flight envelope. When temperature and pressure are not controlled, the temperature and pressure of the membrane inlet are the temperature and pressure of the bleed air. When temperature and pressure are controlled, the temperature and pressure of the membrane inlet are the temperature and pressure controlled. The results are shown in Figure 11 and Figure 12. When temperature and pressure are not controlled, the nitrogen production efficiency of the hollow fiber membrane will change between 7.71% and 68%. And the oxygen concentration of the gas product will change between 0.1% and 8.5% in this situation. They fluctuate with altitude greatly, and the maximum values all appear in the dive stage. Although the results all meet the requirements in Table 2, the nitrogen production efficiency in the operating point 3 and 4 is lower than expectation. When temperature and pressure are controlled, the nitrogen production efficiency of the hollow fiber membrane will change between 31.44% and 58.6%. And the oxygen concentration of the gas product will change between 0.75% and 5.7% in this situation. The maximum values also appear in the dive stage. Though the minimum oxygen concentration of the gas product is larger while the nitrogen production efficiency of the hollow fiber membrane is smaller, the fluctuation becomes smoother than the situation of temperature and pressure are not controlled. And the nitrogen production efficiency will not be lower than expectation after temperature and pressure control.

![Figure 11. The oxygen concentration of the gas product in the whole flight envelope](image1)

![Figure 12. Full flight envelope line rich nitrogen gas volume fraction change chart](image2)

### 4.4. Analysis of causes

The changes of the nitrogen production effects with flow, area of hollow fiber membrane, pressure ratio of membrane can be obtained by the model of hollow fiber membrane, which are shown in Figure 13, Figure 14, and Figure 15. With the increase of flow, the nitrogen production efficiency of the hollow fiber membrane and the oxygen concentration of the gas product keep increasing. But they will reduce with the increase of pressure ratio. And they will also reduce with the increase of the area of hollow fiber membrane. The temperature of membrane effects them not that much [22].

According to these results, it’s possible to analyze the reason why the temperature and pressure control system plays such a special rule in nitrogen production. When the temperature and pressure are controlled, the required area of hollow fiber membrane is much less than the required area of membrane without temperature and pressure control. And its fluctuation is smoother. The reason why the area of membrane will reduce can be explained by the changes of temperature and pressure. With temperature and pressure control, temperature and pressure are obviously stable and the pressure in the hollow fibre module is significantly increased. Then the oxygen concentration of the gas product will reduce. Therefore, the required area of membrane is less than before with the same requirement of oxygen concentration of the gas product. The nitrogen production efficiency of the hollow fiber membrane and the oxygen concentration of the gas product with temperature and pressure control fluctuate much less than the results without temperature and pressure control, and the situation that nitrogen production efficiency becomes less than expectation won’t happen. This can be explained by follows: the temperature is much more stable and the pressure is higher with temperature and pressure control.
control than the situation without temperature and pressure control, which means it’s still possible to get the high nitrogen production efficiency and the low oxygen concentration of the gas product after decreasing the required area, but the maximum nitrogen production efficiency is less than before while the oxygen concentration of the gas product becomes higher. And the nitrogen production efficiency and the oxygen concentration of the gas product are obviously increased in the dive stage, no matter the temperature and pressure are controlled or not.

5. Conclusion
In this paper, the typical onboard membrane separation type of fuel tank inerting system is taken as the research object, and its model of temperature and pressure control subsystem and hollow fiber membrane are established with the coupled iterative numerical method. Through contrastive analysis of the effects of hollow fiber membrane on nitrogen production in the whole flight envelope, the required area of membrane, nitrogen production effect and their internal factors are analyzed. The main conclusions are as follows:

1) When adopting open-loop temperature and pressure control, it’s possible to control the temperature from 413K–493K to 365K and increase the pressure of the bleed air from 2.4bar–4.5bar to 4.2bar–5.4bar. And the pressure is able to controlled to 5.6bar stably with closed-loop temperature and pressure control.

2) Compared with the case of no temperature and pressure control, the required area of membrane will decrease by 42.3%–51.7% after temperature and pressure control. And it will change with the flight state.

3) In the dive stage, due to the obvious increase in flow, the nitrogen production efficiency and oxygen concentration of gas product will be increased greatly with or without temperature control.

4) These phenomena are caused by the positive and negative effects of flow, pressure, temperature and area of the membrane.

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