Experimental Study of an On-board Fuel Tank Inerting System

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Abstract. A simulated aircraft fuel tank inerting system was established and experiments were conducted to investigate the performance of the system. The system uses hollow fiber membrane which is widely used in aircraft as the air separation device and a simplified 20% scale multi compartment fuel tank as the inerting object. Experiments were carried out to investigate the influences of different operating parameters on the inerting effectiveness of the system, including NEA (nitrogen-enriched air) flow rate, NEA oxygen concentration, NEA distribution, pressure of bleeding air and fuel load of the tank. Results showed that for the multi compartment fuel tank, concentrated flow washing inerting would cause great differences throughout the distribution of oxygen concentration in the fuel tank, and inerting dead zone would exist. The inerting effectiveness was greatly improved and the ullage oxygen concentration of the tank would reduce to 12% successfully when NEA entered three compartments evenly. The time span of a complete inerting process reduced obviously with increasing NEA flow rate and decreasing NEA concentration, but the trend became weaker gradually. However, the reduction of NEA concentration will decrease the utilization efficiency of the bleeding air. In addition, the time span can also be reduced by raising the pressure of bleeding air, which will improve the bleeding air utilization efficiency at the same time. The time span decreases linearly as the fuel load increases.

1. Introduction

Aircraft fuel system is an essential part of an aircraft. There is a large amount of flammable fuel vapor and air mixture in the gas space of the aircraft fuel tank. This mixture is easy to fire or explosion with an ignition source case which will cause serious crash. FAA (Federal Aviation Administration) research report published shows the commercial aircraft fuel tank will be safe when the ullage oxygen concentration is less than 12%, even if there is a fire in the fuel tank it will not be lit [1]. The main function of the aircraft fuel system is to reduce the risk of combustion or explosion of the fuel tank [2].

At present, the working mode of aircraft fuel inerting system widely used in the world is that the bleeding air is separated into nitrogen en-riched air (NEA) and oxygen enriched air through hollow fiber membrane, and then NEA is passed into the fuel tank to reduce the ullage (empty space above the fuel) oxygen concentration[3]. The effectiveness of the system is effected with the bleeding air pressure, NEA flow rate, NEA oxygen concentration and flow distribution. At the same time, if the fuel load is different, the inerting effect will be different [4]. According to the inertia of the aircraft fuel tank, the time required for the ullage oxygen concentration reducing to the safe range is very important in predicting the safety of the fuel tank [5-9].
Burns from FAA carried out theoretical and experimental research on rectangular fuel tank with single NEA vent and single air vent, considering the NEA flow, NEA concentration and the fuel tank temperature effect of the inerting effect. The study showed that VTE was 1.5 to decrease the ullage oxygen concentration to 8% with NEA of 95% concentration [10]. In order to study the influence of ventilation mode, William established an experimental research platform using a 24% scale CWT as the research object, whose top cover can move, thus changing the NEA distribution the ventilation mode. They obtained an optimal NEA distribution mode through a large number of experiments, which can reduce the amount of total NEA under the same inerting conditions [11]. Airbus and NASA installed this system in the warehouse of A320 and Boeing 747SP respectively, and the inerting effectiveness was studied [12]. The results showed that it’s effective to inert the CWT by OBIGGS. However, the specific influence of bleeding air pressure, NEA flow rate and so on has not been studied deeply. This study attempts to figure out the influences of these parameters on the effectiveness of the aircraft fuel tank inerting system.

2. Equipment and procedures

2.1. Experimental setup
A simulated aircraft fuel tank inerting system has been established in this study, the schematic diagram of the corresponding experimental equipment is shown in Figure 1. High pressure air produced by the compressor passes through the filter, the pressure regulator and the heater to obtain the inlet gas in accordance with the experimental requirement, and then enters the hollow fiber membrane. A certain concentration of NEA from the hollow fiber membrane, is passed into the scale tank for inerting washing. At the same time, a small amount of gas from the tank is collected to measure the oxygen concentration, in order to detect the inerting effect of the fuel tank.

![Figure 1. Schematic diagram of experimental setup.](image-url)

The simulation fuel tank used in this experimental system is 25% length of a certain simplified aircraft fuel tank and the tank contains three compartments. The top of the fuel tank has a fuel inlet and a fuel outlet is arranged at the bottom, which is used for adding or reducing the amount of fuel. The left and right sides of the tank are arranged with one-way valves, which are designed for altitude experiments in the future. In ground tests, the two valve was used for gas emission in the tank. At the top of the tank, there are three inerting inlets, which are located in the center of each compartment. At the same time, there are 6 sample gas outlets at the top of the tank numbered 1~6, each compartment has two respectively. The size of the tank and the specific location of these inlets and outlets is shown in Figure 2. The sample gas outlets are distributed at the corner of each compartment, which can...
monitor the oxygen concentration of the area difficult to inert effectively. Large amount of fuel vapor in the sample gas will affect the measurement results of the oxygen concentration, so it is necessary to condense and separate the oil vapor from the sample gas. After that, the oxygen concentration is measured by the oxygen concentration measuring instrument.

![Diagram](image)

**Figure 2.** The size of the tank and location of inerting inlets and sample gas outlets.

### 2.2. Experimental procedures

Fuel tank inerting experiment requires that the oxygen concentration of the fuel tank before inerting is the same as the ambient oxygen concentration at first. So the ullage of the tank should be washed with air before inerting until the oxygen concentration of all the sample points are consistent with the surrounding air. Then start the air bleeding system, heat the compressed air and adjust the pressure, until the pressure and temperature at the entrance of the hollow fiber membrane reach the experimental requirements. Then regulate the flow control valve at the outlet of the hollow fiber membrane to make the oxygen concentration of NEA meets the requirement of the experiment. Regulate the flow regulating valve of the inerting branch so that the NEA flow rate reaches the required flow rate. At the same time, open the micro vacuum pump for sampling and monitoring the oxygen concentration of the sample points. With the inerting process, the oxygen concentration of the sample points continues to decline, until the oxygen concentration of all the sample points reaches 12%.

### 3. Results and analysis

#### 3.1. Distribution of flow

To inert multi compartment tank using NEA of the same flow usually has two kinds of flow distribution mode, concentrated flow washing and uniform distribution of flow. When loaded 50%, inert the tank using NEA of 6% oxygen concentration and 3 kg/h of flow rate, and the bleeding air pressure is 0.3MPa. The variations of ullage oxygen concentration with time at different distribution mode of flow are presented in Figure 3.

As shown in the figure, the ullage oxygen concentration gradually decreased as time increases, but there is a great difference in the trend of the concentration of the sample points in two different ways. Figure 3(a) is the curve of washing inerting under uniform flow distribution, we can see the oxygen concentration change trend of every sample point is relatively consistent, and the final oxygen concentration reached 12% successfully. The oxygen concentration of point 1 decreased more slowly than the other sample points at the beginning, this is because the distance of sample point 1 from the inlet of inert gas is farther than other points. At the same time, the oxygen concentration of gas spread to point 1 is relatively high as the distance, so the oxygen concentration of point 1 reached 12% at last. This phenomenon appeared in later experiments too, so the oxygen concentration of point 1 is regarded as the basis of the whole tank meeting the requirements of inerting.
Figure 3. Inverting effects under different conditions of NEA distribution.

Figure 3(b) is the curve of oxygen concentration when all the inert gas enter the tank from the middle compartment. As seen from the picture, the change of oxygen concentration of each sample point is quite different. The oxygen concentration of point 3 and point 4 located in the middle compartment decreased rapidly and reached 12% soon, and the final concentration was approximately stable at 6%. The concentration of point 1 and point 5 located in the compartments beside reduced slowly, and the final concentration can only drop to about 12%. The concentration of point 2 and point 6 decreased very slowly and finally stay at around 13%, which did not meet the inverting requirement. The phenomenon illustrates that concentrated flow washing will cause great differences throughout the distribution of oxygen concentration in the fuel tank and the emergence of inverting dead zone. Therefore, uniform distribution of flow should be chosen for the inverting of fuel tank with multi compartments. In the study of the influence of other factors, we have used this distribution mode of flow.

3.2. Flow rate of NEA

During the inverting experiments, the flow rate of the inert gas acts as an important factor and affects the time span of a complete inverting process directly. When loaded 50%, inert the fuel tank using NEA of 6% oxygen concentration, and the bleeding air pressure is 0.5MPa.

Figure 4. Inverting effects under different conditions of NEA flow rate.

The variations of ullage oxygen concentration with time at different NEA flow rate are presented in Figure 4(a). It is seen from the picture that when the flow rate is higher, the time that needed to make the ullage oxygen concentration reaching 12% is obviously reduced. Figure 4(b) exhibits the relationship between the time span and NEA flow rate. The time span of a complete inverting process is 330s at the 3 kg/h flow rate, reducing by 75% of the time span at 1 kg/h flow rate which is 1320 s.
When the flow rate increased to 5kg/h, the time span is 280s, only reducing by 15% compared to the time span at the 3kg/h flow rate. It can be seen that with the increase in flow rate, the time span decreases but the trend becomes weaker gradually.

3.3. Concentration of NEA
During the inerting experiments, the oxygen concentration of NEA acts as another important factor. When loaded 50%, inert the fuel tank using NEA of 3kg/h flow rate, and the bleeding air pressure is 0.3MPa. The variations of ullage oxygen concentration with time at different NEA oxygen concentration are presented in Figure 5(a). It is seen from the picture that when the NEA oxygen concentration is lower, the time that needed to make the ullage oxygen concentration reaching 12% is obviously reduced. Figure 5(b) exhibits the relationship between the time span and NEA oxygen concentration. The time span of a complete inerting process is 320s at 6% concentration, reducing by 42% of the time span at 9% concentration which is 555 s. When the NEA concentration decreased to 3%, the time span is 260s, only reducing by 19% compared to the time span at 6% NEA concentration. It can be seen that with the decrease in NEA concentration, the time span decreases but the trend becomes weaker gradually.

![Figure 5](image-url)

**Figure 5.** Inerting effects under different conditions of NEA concentration.

In addition, research showed that NEA oxygen concentration would have a marked impact on the performance of the hollow fiber membrane. So the efficiency of the bleeding air in the application of the fuel tank inerting system should also be taken into account. Therefore we define the nitrogen recovery rate of the hollow fiber membrane as \( \theta \) and its calculation method is shown in equation (1). \( N_2 \) % is the nitrogen concentration, \( Q \) is the flow rate. Higher nitrogen recovery rate means the higher utilization efficiency of the bleeding air.
\[ \theta = \left( \frac{N_2\% \times Q}{N_2\% \times Q} \right)_{\text{NEA}} \]

Figure 5(c) shows the relationship between the nitrogen recovery rate and NEA oxygen concentration. It can be known that the inlet air flow rate and the NEA flow rate of the hollow fiber membrane will decrease when the NEA oxygen concentration is decreased, and the nitrogen recovery rate will decrease. Moreover, it can be known that with the decrease of the NEA oxygen concentration, the decreasing trend of the nitrogen recovery rate is becoming stronger. This shows that when using NEA with lower oxygen concentration for inerting, the utilization efficiency of the engine bleeding air by the fuel tank inerting system is lower.

3.4. Pressure of bleeding air

The bleeding air can be supplied to the hollow fiber membrane at different pressure, and the air pressure has an important influence on the efficiency of the hollow fiber membrane. At the same time, the pressure of NEA at the outlet of the hollow fiber membrane is different, which will influence the inerting effect.

![Figure 6](a) (b) (c)

Figure 6. Inerting effects under different conditions of bleeding air pressure.

When loaded 50%, inert the tank using NEA of 6% oxygen concentration and 3 kg/h of flow rate. The variations of ullage oxygen concentration with time at different pressure of bleeding air are presented in Figure 6(a). It is seen from the picture that when the pressure is higher, the time that needed to make the ullage oxygen concentration reaching 12% is obviously reduced. Figure 6(b) exhibits the relationship between the time span and the pressure of bleeding air. The time span of a complete inerting process is 280s at the pressure of 0.5MPa, reducing by 25% of the time span at the pressure of 0.3MPa which is 375s. When the pressure increased to 0.7MPa, the time span is 255s, only
reducing by 9% compared to the time span at the pressure of 0.5MPa. It can be seen that with the increase in pressure of bleeding air, the time span decreases but the trend becomes weaker gradually.

Figure 6(c) shows the relationship between the nitrogen recovery rate and the pressure of bleeding air. It can be known that the inlet air flow rate and the NEA flow rate of the hollow fiber membrane will increase when the bleeding air pressure is increased, and the nitrogen recovery rate will increase. This shows that when using NEA with higher bleeding air pressure for inerting, the utilization efficiency of the engine bleeding air by the fuel tank inerting system is higher.

3.5. Fuel load

The inerting effectiveness is investigated by experiments in this section with different fuel loads of the tank using NEA of 6% oxygen concentration and 3 kg/h of flow rate, and the pressure of bleeding air is 0.3MPa.

![Figure 7(a)](image1)

![Figure 7(b)](image2)

Figure 7. Inerting effects under different conditions of fuel load.

Figure 7(a) presents the variation trends of ullage oxygen concentration as time increases when the fuel loads are 50%, 70% and 90% respectively. It is seen from the picture that when there is more fuel in the tank, the time that needed to make the ullage oxygen concentration reaching 12% is obviously reduced. The relationship between the time span and fuel load is shown in Figure 7(b). As we can see in the picture, the time span of a complete inerting process decreases linearly with the increase of fuel load.

4. Conclusions

In this research, experiments have been performed to inspect the influences of different operating parameters on inerting effectiveness of the established aircraft fuel tank inerting system. The following conclusions can be drawn.

For multi compartment fuel tank, concentrated flow washing inerting would cause great differences throughout the distribution of oxygen concentration in the fuel tank, and inerting dead zone would exist. When inerting under uniform flow distribution, the ullage oxygen concentration of the tank is consistent. The area far from the inlet of NEA is more difficult to inert, so the inlet of inert gas should be arranged in the middle of the compartment.

Results show that with the increase in NEA flow rate, the time span of a complete inerting process decreases but the trend becomes weaker gradually. When NEA oxygen concentration reduces, the time span of a complete inerting process decreases but the trend becomes weaker gradually. However, when using NEA with lower oxygen concentration for inerting, the utilization efficiency of the engine bleeding air by the fuel tank inerting system is lower. The time span can also be reduced by raising the pressure of bleeding air, which will also improve the bleeding air utilization efficiency. The time span decreased linearly with the increase of the fuel load.

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