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Analytical Algorithm for Oxygen Concentration of Aircraft Fuel Tank in Various Inerting Stages

Yuhao Wei, Yang Pei and Yuxue Ge *

School of Aeronautics, Northwestern Polytechnical University, Xi'an 710072, China; weiyuhao0321@mail.nwpu.edu.cn (Y.W.); peiyang_yang@nwpu.edu.cn (Y.P.)

* Correspondence: ge_yuxue@nwpu.edu.cn

Abstract: Ullage washing is an efficient inerting method to keep the ullage oxygen concentration under the safe value, thus reducing the hazard and loss of fire and explosion of aircraft fuel tanks. In the conventional model of ullage washing, the initial derivatives of oxygen concentration that are used to solve the differential equations are selected subjectively by researchers and the empirical select influences the accuracy of the result. Therefore, this paper proposes an analytical algorithm that can calculate the ullage oxygen concentration without selecting any initial derivative value. The algorithm is based on a fuel tank ullage washing model regarding various inerting stages. It has been experimentally validated with an average relative error of 5.781%. Moreover, sensitive analyses carried out on the proposed model show that ground-based inerting can effectively reduce the ullage oxygen concentration in the climb phase. Increasing 5 min of pre-takeoff inerting duration can shorten the time of decreasing the ullage oxygen concentration to 9% after takeoff by 2.1 min.

Keywords: aircraft fuel tank; dynamics model; analytical algorithm; oxygen concentration; ullage washing

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1. Introduction

Fire and explosion of the fuel tank are the main causes of aircraft loss [1,2]. Expanded metal mesh filling, polymer foam materials filling, and fuel tank inerting are often used to reduce these losses [3,4]. Fuel tank inerting is the long-term maintenance of an inert atmosphere in the vapor space of the fuel tank during normal operation. The goal is to keep the oxygen concentration in the ullage lower than the Limiting Oxygen Concentration (LOC), which are 12% and 9% for commercial and military aircraft, respectively [5,6].

To predict the behavior of inert gases, ullage washing models were established according to experiment results. Flight tests on the A320 were conducted in 2003 by Federal Aviation Administration (FAA) to study the dynamics of center tank inerting [7]. Since the flight tests are very expensive, more studies were conducted through ground-based inerting experiments. Based on the experiments data, Burns [8] analyzed the influence of the quantity and purity of nitrogen-enriched air (NEA) on the ullage oxygen concentration. The conventional model of ullage washing was established based on the volume balance of inerting gases. Cai [9] investigated the inerting effectiveness regarding flow rate of NEA, inert gas concentration, and fuel load of the tank. Shao [10,11] tested the influence of the composition of N₂, CO₂, and O₂ on the inerting time of the fuel tank. Bae [12] tested the variation trend of oxygen concentration with time and found that concentration gradients within the fuel significantly increase the total amount of outgassing during depressurization. Peng and Feng [13,14] modeled the catalytic inerting system according to ground-based experiments and found that the fuel type can change the gas inflow rate. In practice, the ground-based inerting mainly happens before takeoff. However, studies on other flight phases are very few, for it is difficult to control the pressure and temperature in the ullage.

Mathematical methods could possibly involve dynamic factors into the study of fuel tank inerting [8]. Based on the conventional fuel scrubbing model, Pei [15] proposed an iterative model of fuel tank inerting in the battle environment by calculating the heat and oxygen transfer brought by projectiles. Shao [16] modified the conventional model by considering the ratio of the dissolved inert gases to analyze the relationship between bubble diameter and scrubbing efficiency. Feng [17] developed a numerical method that can assess the performance of the dissolved oxygen evolution in various conditions. Polynomial expressions of oxygen evolution time constant were fitted regarding temperature, pressure, and fuel load. Díaz Palencia [18] developed that model by using the traveling wave approach to consider the differences in the gas concentration of the fuel tank. The model was verified by the flight test data in [7]. However, when solving the differential equations of the inerting model, the initial derivatives of gas concentration are usually needed and selected subjectively by researchers. The accuracy of oxygen concentration results strongly depends on how much experience the researcher has.

To solve the above problems, this paper develops an analytical algorithm that needs no initial derivative of ullage gas concentration to solve the differential equations of the ullage washing model regarding various flight phases. By using this new algorithm, the uncertainty caused by inexperience can be controlled. In Section 2, the dynamic model of fuel tank inerting in form of an implicit ordinary differential equation is established based on the mass conservation law. In Section 3, the analytical algorithm of solving the ullage model without selecting the initial derivative is proposed. Finally, the method is experimentally verified and the influence of factors is analyzed in Section 4.

2. Ullage Washing Model

Ullage washing technology was used to ensure that the ullage oxygen concentration is below the LOC, thus reducing the hazard and loss of fire and explosion of the fuel tank. The ullage washing uses NEA with low oxygen concentration to replace the oxygen and fuel vapor in the ullage space. The process is shown in Figure 1.

Figure 1. The principle of aircraft fuel tank ullage washing.

The dynamic model of ullage washing is established based on the following assumptions.

- (1) There is only oxygen, nitrogen, and fuel vapor gas in the ullage space, and the distribution is uniform.
- (2) The NEA can immediately mix with the gas in the ullage space.
- (3) Dissolved oxygen and nitrogen in the fuel immediately reach equilibrium in response to changes in the partial pressures of oxygen and nitrogen in the ullage space [3].
- (4) It is assumed that the fuel flowing out from the tank does not contain dissolved oxygen, nitrogen, and other gases.

The mass change of oxygen in the ullage space of the aircraft fuel tank has three sources: the inflow of NEA, the outflow of air, and the overflow of oxygen from the fuel. Therefore, the mass flow rate of oxygen in the ullage space can be expressed as:

$$\dot{m}_o = \dot{m}_{Io} + \dot{m}_{OG_o} - \dot{m}_{Oo} \quad (1)$$

where $\dot{m}_o$ represents the mass flow rate of oxygen in the ullage space, kg/s; $\dot{m}_{Io}$ the mass inflow rate of oxygen, kg/s; $\dot{m}_{OG_o}$ the mass overflow rate of oxygen from the fuel, kg/s; and the mass outflow rate of oxygen, kg/s.

The mass flow rate of oxygen in the ullage space can be obtained by using the ideal gas law as,

$$\dot{m}_o = \left(\frac{p_U \cdot v_U \cdot z_{Uov}}{R_o \cdot T_U} \right)' \quad (2)$$

where p_U is the total pressure of gas mixture in the ullage space, Pa; v_U the volume of the ullage space, m³; z_{Uov} the ullage oxygen concentration; R_o the gas constant of oxygen, J/kg·K; and T_U the temperature of the ullage space, K. The superscript ' denotes the time derivative of a variable. The mass inflow and outflow rate of oxygen can be expressed as,

$$\begin{cases} \dot{m}_{Io} = \frac{p_I \cdot \dot{v}_I \cdot z_{Iov}}{R_o \cdot T_I} \\ \dot{m}_{Oo} = \frac{p_U \cdot \dot{v}_O \cdot z_{Uov}}{R_o \cdot T_U} \end{cases} \quad (3)$$

where $\dot{v}_I$ represents the volume inflow rate of NEA, m³/s; $\dot{v}_O$ the volume outflow rate of gas, m³/s; p_I the pressure of the inflow, Pa; z_{Iov} the oxygen concentration of NEA; and T_I the temperature of the NEA, K.

The mass overflow rate of oxygen from the fuel can be expressed by Henry's law as [3,19,20]

$$\dot{m}_{OG_o} = - \left(\frac{\beta_o \cdot p_U \cdot v_F \cdot z_{Uov}}{R_o \cdot T_F} \right)' \quad (4)$$

where v_F is the volume of fuel, m³; T_F the temperature of the fuel, K; and β_o the Ostwald coefficient of oxygen.

Therefore, Formula (1) can be rewritten as

$$\left(\frac{p_U \cdot v_U \cdot z_{Uov}}{R_o \cdot T_U} \right)' = \frac{p_I \cdot \dot{v}_I \cdot z_{Iov}}{R_o \cdot T_I} - \frac{p_U \cdot \dot{v}_O \cdot z_{Uov}}{R_o \cdot T_U} - \left(\frac{\beta_o \cdot p_U \cdot v_F \cdot z_{Uov}}{R_o \cdot T_F} \right)' \quad (5)$$

Similar to oxygen concentration, the mass flow rate of nitrogen can be expressed in as

$$\left(\frac{p_U \cdot v_U \cdot z_{Unv}}{R_n \cdot T_U} \right)' = \frac{p_I \cdot \dot{v}_I \cdot z_{Innv}}{R_n \cdot T_I} - \frac{p_U \cdot \dot{v}_O \cdot z_{Unv}}{R_n \cdot T_U} - \left(\frac{\beta_n \cdot p_U \cdot v_F \cdot z_{Unv}}{R_n \cdot T_F} \right)' \quad (6)$$

where z_{Unv} represents the ullage nitrogen concentration, z_{Innv} the nitrogen concentration of NEA, R_n the gas constant of nitrogen, J/kg·K; and β_n the Ostwald coefficient of nitrogen.

According to assumption (1), the sum of the concentrations of the three kinds of gas is 1,

$$z_{Uov} + z_{Unv} + z_{Ufv} = 1 \quad (7)$$

where z_{Ufv} represents the concentration of fuel vapor in the ullage space. It can be obtained by using the empirical formula of saturated vapor pressure [21,22]. Derivation of the above formula is

$$z'_{Uov} + z'_{Unv} + z'_{Ufv} = 0 \quad (8)$$

Formulas (5), (6), and (8) compose the dynamic model of ullage washing.

3. Analytical Algorithm

The conventional way of solving the implicit ordinary differential equations, like (5), (6), and (8), needs the initial values of the oxygen concentrations and their derivatives [23]. The accuracy of computed results depend on the empirically given values that are difficult to be properly set. This section proposes an analytical algorithm to solve the dynamic model without the assumed initial derivatives of gas concentration.

In most of flight process, the gas concentration in the ullage always falls because of fuel consumption, and the ullage is mainly under the pressurization or the exhaust process. During the descent phase, the gas concentration increases by injecting NEA to maintain the pressure difference between the ullage and the atmosphere. Therefore, the ullage washing can be concluded into 3 inerting stages, which are the descent phase, the pressurization process, and the exhaust process. The derivatives of variable, such as oxygen concentration and ullage pressure, can be calculated according to the state of each inerting stage based on Formulas (5), (6), and (8) to eliminate the uncertainty brought by the assuming the initial values.

The analytical algorithm of solving the dynamic model of ullage washing is illustrated in Figure 2. The algorithm has three main steps, as follows.

- (1) Identification of the inerting stage at the i th moment. During the descent phase, calculate the $z'_{Uov}(i)$, $z'_{Umv}(i)$, and $\dot{v}_I(i)$ by the descent phase calculation method. In other flight phases, if the fuel tank is pressurized, calculate the $z'_{Uov}(i)$, $z'_{Umv}(i)$, and $p'_U(i)$ by the pressurization process calculation method. Otherwise, calculate the $z'_{Uov}(i)$, $z'_{Umv}(i)$, and $\dot{v}_O(i)$ by the exhaust process calculation method.
- (2) Calculate $z_{Uov}(i+1)$ and $z_{Umv}(i+1)$ according to $z_{Uov}(i)$, $z_{Umv}(i)$, $z'_{Uov}(i)$ and $z'_{Umv}(i)$.
- (3) Repeating the previous two steps until the end of the flight to obtain the z_{Uov} regarding time.

Figure 2. Analytical algorithm flow chart to calculate the ullage oxygen concentration.

3.1. The Descent Phase Calculation Method

During the descent phase, atmospheric pressure p_{atm} can be higher than p_U , because p_{atm} increases with decreasing height while p_U decreases with fuel consumption. However, to keep the fuel tank functional, p_U should be bigger than p_{atm} . Hence, it is necessary to increase the pressure of the ullage space by injecting NEA. The variables that need to be calculated in this situation are z'_{Uov} , z'_{Unv} , and $\dot{v}_I$. The ullage washing model can be expressed as:

$$\begin{cases} f_o \cdot z'_{Uov} - \frac{p_I \cdot z_{Iov} \cdot T_U}{T_I} \cdot \dot{v}_I = g_o \\ f_n \cdot z'_{Unv} - \frac{p_I \cdot z_{Innv} \cdot T_U}{T_I} \cdot \dot{v}_I = g_n \\ z'_{Uov} + z'_{Unv} = -z'_{Ufv} \end{cases} \quad (9)$$

with

$$\begin{cases} f_o = p_U \cdot v_U + \beta_o \cdot p_U \cdot v_F \\ f_n = p_U \cdot v_U + \beta_n \cdot p_U \cdot v_F \\ g_o = -p'_U \cdot v_U \cdot z_{Uov} - \beta_o \cdot p'_U \cdot v_F \cdot z_{Uov} \\ \quad - p_U \cdot v'_U \cdot z_{Uov} - \beta_o \cdot p_U \cdot v'_F \cdot z_{Uov} \\ g_n = -p'_U \cdot v_U \cdot z_{Unv} - \beta_n \cdot p'_U \cdot v_F \cdot z_{Unv} \\ \quad - p_U \cdot v'_U \cdot z_{Unv} - \beta_n \cdot p_U \cdot v'_F \cdot z_{Unv} \end{cases} \quad (10)$$

By solving (9), as:

$$\begin{bmatrix} z'_{Uov}(i) \\ z'_{Unv}(i) \\ \dot{v}_I(i) \end{bmatrix} = A(i)^{-1} \cdot a(i) \quad (11)$$

where

$$A(i) = \begin{bmatrix} f_o(i) & 0 & -\frac{p_I(i) \cdot z_{Iov}(i) \cdot T_U(i)}{T_I(i)} \\ 0 & f_n(i) & -\frac{p_I(i) \cdot z_{Innv}(i) \cdot T_U(i)}{T_I(i)} \\ 1 & 1 & 0 \end{bmatrix} \quad (12)$$

$$a(i) = \begin{bmatrix} g_o(i) \\ g_n(i) \\ -z'_{Ufv}(i) \end{bmatrix} \quad (13)$$

with i standing for the i th moment. The iterative form of the ullage oxygen concentration can be expressed as:

$$z_{Uov}(i+1) = z_{Uov}(i) + z'_{Uov}(i) \cdot \Delta t \quad (14)$$

3.2. The Pressurization Process Calculation Method

To enhance the fuel supply performance at high altitudes, there is a pressure difference of 6.895~34.474 kpa between the ullage space and the environment [22]. If the pressure of the ullage space p_U is less than the sum of the atmospheric pressure p_{atm} and the pressure difference, the tank is in the pressurization process. In this situation, there will be no gas discharge and it usually occurs in the climb phase. The variables that need to be calculated in this situation are z'_{Uov} , z'_{Unv} , and p'_U . The ullage washing dynamic model can be expressed as:

$$\begin{cases} f_o \cdot z'_{Uov} + (z_{Uov} \cdot v_U + \beta_o \cdot z_{Uov} \cdot v_F) \cdot p'_U = h_o \\ f_n \cdot z'_{Unv} + (z_{Unv} \cdot v_U + \beta_n \cdot z_{Unv} \cdot v_F) \cdot p'_U = h_n \\ z'_{Uov} + z'_{Unv} = -z'_{Ufv} \end{cases} \quad (15)$$

with

$$\begin{cases} h_o = \frac{p_I \cdot \dot{v}_I \cdot z_{Iov} \cdot T_U}{T_I} \\ \quad - p_U \cdot z_{Uov} \cdot v'_U - \beta_o \cdot p_U \cdot z_{Uov} \cdot v'_F \\ h_n = \frac{p_I \cdot \dot{v}_I \cdot z_{Inov} \cdot T_U}{T_I} \\ \quad - p_U \cdot z_{Unv} \cdot v'_U - \beta_n \cdot p_U \cdot z_{Unv} \cdot v'_F \end{cases} \quad (16)$$

The iterative form of z_{Uov} is the same as (14).

3.3. The Exhaust Process Calculation Method

The exhaust process injects NEA into the ullage and exhausts the original gas. This process usually occurs in the pre-takeoff, climb, and cruise phase. According to assumptions (2) and (3), the ullage temperature, fuel temperature, and NEA temperature are equal and constant in a short time. Hence, only z'_{Uov} , z'_{Unv} , and $\dot{v}_O$ need to be calculated. The ullage washing dynamic model can be expressed as:

$$\begin{cases} f_o \cdot z'_{Uov} + p_U \cdot z_{Uov} \cdot \dot{v}_O = l_o \\ f_n \cdot z'_{Unv} + p_U \cdot z_{Unv} \cdot \dot{v}_O = l_n \\ z'_{Uov} + z'_{Unv} = -z'_{Ufv} \end{cases} \quad (17)$$

with,

$$\begin{cases} l_o = \frac{p_I \cdot \dot{v}_I \cdot z_{Iov} \cdot T_U}{T_I} - \beta_o \cdot p_U \cdot z_{Uov} \cdot v'_F \\ \quad - p_U \cdot z_{Uov} \cdot v'_U - (z_{Uov} \cdot v_U + \beta_o \cdot z_{Uov} \cdot v_F) p'_U \\ l_n = \frac{p_I \cdot \dot{v}_I \cdot z_{Inov} \cdot T_U}{T_I} - \beta_n \cdot p_U \cdot z_{Unv} \cdot v'_F \\ \quad - p_U \cdot z_{Unv} \cdot v'_U - (z_{Unv} \cdot v_U + \beta_n \cdot z_{Unv} \cdot v_F) p'_U \end{cases} \quad (18)$$

The iterative form of z_{Uov} is also the same as (14).

4. Validations and Discussions

4.1. Validation of the Ullage Washing Model under Pre-Takeoff Situation

The ground-based experiment in [9] is used to verify the proposed method under the pre-takeoff situation. The experimental conditions are illustrated in Table 1. Moreover, the results of the proposed method are compared with a conventional ullage washing model in [8], which ignores the oxygen evolution.

Table 1. The ground-based experimental condition used in [9].

Item	Value	Unit
The volume of the fuel tank	1.002	m ³
Fuel load	50%	-
The density of the fuel	786.6	kg/m ³
Ambient temperature	25	°C
Ambient pressure	101	kPa
The nitrogen concentration of NEA	99.8%	-
NEA mass flow rate	0.9	kg/h

Experimental and calculated results of ullage oxygen concentrations are shown in Figure 3. The calculated oxygen concentrations are consistent with the experimental results. The average relative error between the proposed model and the experiment is 2.768% and that of the model in [8] is 11.487%. By considering the oxygen evolution, the proposed ullage washing model performs better with the experiment results.

Figure 3. Experimental and calculated results of z_{Uov} in the pre-takeoff phase, with a fuel load of 50% and a NEA mass flow rate of 0.9 kg/h.

In this paper, it is assumed that the gas distribution in the ullage space is uniform and NEA can immediately mix with the gas in the ullage space. Therefore, the influence of the location of the measuring point on z_{Uov} is not considered in the proposed model. In the experiment in [9], the measuring point is located on the top of the fuel tank and away from the NEA injection port. The inerting effect of NEA will have a time delay, which causes the z_{Uov} calculated by the proposed model to be smaller than that measured in the experiment. For example, when $t = 0.7$ h, the proposed model gets $z_{Uov} = 0.0844$, which is smaller than the experimental $z_{Uov} = 0.0930$.

Figure 4 shows the calculated ullage oxygen concentration z_{Uov} regarding the NEA mass flow rate while keeping other experimental variables unchanged. When the NEA mass flow rates are 0.9 kg/h, 1.8 kg/h, 5 kg/h, and 9 kg/h, it takes 0.6487 h, 0.3244 h, 0.1168 h, and 0.0649 h, respectively, from the start of inerting until the oxygen concentration drops to 9%. The ullage oxygen concentration z_{Uov} decreases fast, with increasing NEA mass flow rate under the pre-takeoff situation.

Figure 4. The ullage oxygen concentration z_{Uov} regarding the NEA mass flow rate while keeping other pre-takeoff experimental variables unchanged.

Figure 5 shows the calculated ullage oxygen concentration regarding the fuel load while keeping other experimental variables unchanged. It takes 0.6487 h and 0.3313 h, respectively, for the oxygen concentration z_{Uov} to drop to 9% with fuel loads of 50% and 90%. The ullage oxygen concentration decreases fast, with increasing fuel loads under the pre-takeoff situation.

Figure 5. The ullage oxygen concentration z_{Uov} regarding the fuel load, while keeping other pre-takeoff experimental variables unchanged.

4.2. Validation of Ullage Washing Dynamic Model in Flight Phases

The flight test data and ullage washing model in [7] are used to verify the proposed method in the pre-takeoff, climb, and cruise phase. The working conditions are shown in Table 2.

Table 2. Working conditions of the understudied flight phases in [7].

Flight Phase	Working Condition
Pre-takeoff phase	Started with center wing tank not inerted (20% O ₂) and empty The onboard inert gas generation system started 10 mins before takeoff.
Climb phase	Climb from 0 to 11,887.2 m for 20 min
Cruise phase	Cruise at 11,887.2 m for 40 min

Experimental and calculated results of ullage oxygen concentration are shown in Figure 6. The average error of the ullage oxygen concentration between the proposed ullage washing model and the flight test is 0.0024 and that of the model in [7] is 0.0054. The average relative errors of the proposed model and the model in [7] are 5.781% and 13.137%, respectively. The results calculated by the proposed ullage washing model show a better agreement with the flight test data in understudied flight phases.

Figure 6. Flight test and calculated results of z_{Uov} in climb and cruise phases.

4.3. Effect of Model Parameters on the Oxygen Concentration

In this section, the ullage oxygen concentration is analyzed regarding the duration of the ground-based inerting, the volume inflow rate of NEA $\dot{v}_I$, the oxygen concentration of NEA z_{Iov} , and the fuel load of the tank. The z_{Iov} can be expressed as $z_{Iov} = k \cdot z_{A0}$, with k the scale coefficient and z_{A0} the atmospheric oxygen content. The flight phase conditions are shown in Table 3.

Table 3. Working conditions of the flight phases.

Flight Phase	Working Condition
Pre-takeoff phase	Ground-based inerting started 0, 5, or 10 min before takeoff
Climb phase	Climb from 0 to 10,000 m for 10 min
Cruise phase	Cruise at 10,000 m for 30 min
Descent phase	Climb from 10,000 m to 0 for 10 min

According to the proposed analytical method, there is no need to select the initial derivative of the oxygen concentration when solving the dynamic models. Only the initial value of z_{Uov} and the initial conditions of the ullage space are needed and illustrated in Table 4. Moreover, the understudied ranges of the ullage washing parameters are set according to the flight test in [7] and are also illustrated in Table 4.

Table 4. Initial states and understudied ranges of the controlled parameter of ullage washing.

Item	Value	Unit
Initial value of z_{Uov}	20.95%	-
Initial value of p_U	101,325	Pa
Initial value of T_U	300	K
The volume inflow rate of NEA $\dot{v}_I$	0.1, 0.15, 0.2	m ³ /min
Scale coefficient k	20%, 30%, 40%	-
Fuel load	40%, 60%, 80%	-

The ullage oxygen concentration z_{Uov} regarding the ground-based inerting duration is shown in Figure 7, with the boundary condition illustrated in Table 5. In the climb phase, the ullage oxygen concentration decreases with increasing height. It decreases slowly in the cruise phase when the altitude is unchanged at 10,000 m and then during the descent phase, it increases as the altitude decreases. When the ground-based inerting is 0 min, meaning no inerting before takeoff, z_{Uov} decreases from 20.95% to 9% for 8.493 min. When the ground-based inerting is 10 min, $z_{Uov} = 12.83\%$ when the aircraft takes off, and it costs only 4.268 min to decrease to 9%. In the climb and cruise phases, the pre-takeoff inerting leads to the low oxygen concentration in the fuel tank ullage. Adding 5 min of pre-takeoff inerting duration can shorten the time of decreasing the ullage oxygen concentration to 9% after takeoff by 2.1 min. During the descent phase, the z_{Uov} increases 6.33%, 6.38%, and 6.42%, with the ground inerting time of 0 min, 5 min, and 10 min.

The ullage oxygen concentration z_{Uov} regarding the volume inflow rate of NEA $\dot{v}_I$ are shown in Figure 8, with the boundary condition shown in Table 6. The z_{Uov} decreases slower in the pre-takeoff phase than in the climb phase. A high $\dot{v}_I$ can quickly change the z_{Uov} . When $\dot{v}_I = 0.1$ m³/min, 0.15 m³/min, and 0.2 m³/min, z_{Uov} drops to 9% for 15.044 min, 9.105 min, and 6.365 min, respectively, since takeoff. During the descent phase, z_{Uov} increases for 5.01%, 6.02%, and 6.38%, respectively.

Table 5. The boundary condition of the ullage oxygen concentration analysis regarding the ground-based inerting duration.

Item	Value	Unit
Ground-based inerting duration	0, 5, 10	min
The volume inflow rate of NEA $\dot{v}_I$	0.2	m ³ /min
Scale coefficient k	30%	-
Fuel load	80%	-

Figure 7. The ullage oxygen concentration regarding the ground-based inerting duration, with $\dot{v}_I = 0.2 \text{ m}^3/\text{min}$, $k = 30\%$, and the fuel load of 80%.

Figure 8. The ullage oxygen concentration regarding the volume inflow rate of NEA, with the ground-based inerting duration of 5 min, $k = 30\%$ and the fuel load of 80%.

Table 6. The boundary condition of the ullage oxygen concentration analysis regarding the volume inflow rate of NEA.

Item	Value	Unit
Ground-based inerting duration	5	min
The volume inflow rate of NEA $\dot{v}_I$	0.1, 0.15, 0.2	m ³ /min
Scale coefficient k	30%	-
Fuel load	80%	-

The ullage oxygen concentration z_{Uov} regarding the oxygen concentration of NEA z_{Iov} are illustrated in Figure 9, with the boundary condition shown in Table 7. In all flight phases, the low z_{Iov} results in a quick change to the z_{Uov} . When $k = 20\%$, 30% , and 40% , the z_{Uov} decreases to 9% for 5.034 min, 6.365 min, and 7.780 min, respectively, since takeoff. Every 10% reduction of k can shorten the time of decreasing z_{Uov} to 9% since takeoff by 1.37 min. During the descent phase, the z_{Uov} only increases 4.18% with $k = 20\%$, which can lower down the risk of tank fire.

Figure 9. The ullage oxygen concentration regarding oxygen concentration of NEA, with a 5 min ground-based inerting, $\dot{v}_I = 0.2$ m³/min, and the fuel load of 80%.**Table 7.** The boundary condition of the ullage oxygen concentration analysis regarding the oxygen concentration of NEA.

Item	Value	Unit
Ground-based inerting duration	5	min
The volume inflow rate of NEA $\dot{v}_I$	0.2	m ³ /min
Scale coefficient k	20%, 30%, 40%	-
Fuel load	80%	-

The ullage oxygen concentration z_{Uov} regarding the fuel load of the tank is shown in Figure 10, with the boundary condition shown in Table 8. The z_{Uov} changes fast when the fuel load is high, for it makes the ullage small. When the fuel loads are 40% , 60% , and 80% , the z_{Uov} drops to 9% for 10.373 min, 8.537 min, and 6.365 min, respectively, after takeoff. During the descent phase, the z_{Uov} increases a maximum of 6.38% , with a fuel load of 80% .

Figure 10. The ullage oxygen concentration regarding the fuel load of the tank, with the ground-based inerting duration of 5 min, $\dot{v}_I = 0.2 \text{ m}^3/\text{min}$, and $k = 30\%$.

Table 8. The boundary condition of the ullage oxygen concentration analysis regarding the fuel load.

Item	Value	Unit
Ground-based inerting duration	5	min
The volume inflow rate of NEA $\dot{v}_I$	0.2	m^3/min
Scale coefficient k	30%	-
Fuel load	40%, 60%, 80%	-

5. Conclusions

This paper establishes a dynamic model of ullage washing and proposed an analytical algorithm to solve it without using the initial derivative values. The model has been experimentally validated and used to carry out oxygen concentration analysis in the whole flight mission. The main conclusions are as follows:

- (1) Compared with experimental results, the average relative error of the oxygen concentration computed by the proposed model is around 5.78%.
- (2) Adding 5 min of pre-takeoff inerting duration can decrease the takeoff values of the ullage oxygen concentration and shorten the time of decreasing it to 9% by 2.1 min.
- (3) Every 10% reduction of NEA oxygen concentration can shorten the time of decreasing ullage oxygen concentration to 9% since takeoff by 1.37 min.
- (4) In all flight phases, the ullage oxygen concentration changes fast with the increasing volume flow rate of NEA and the fuel load. This is because lifting either of the two factors can directly squeeze the volume of the ullage space.

The proposed analytical algorithm can solve the ullage washing model without choosing the initial derivative value of oxygen concentration, thus it can eliminate the uncertainty caused by subjective selection. Future studies can be carried out by adding heat transfer inside the ullage washing model.

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Nomenclature

k	scale coefficient
$\dot{m}$	mass flow rate, kg/s
p	pressure, Pa
R	gas constant, J/kg·K
t	time, s, min or h
T	temperature, K
v	volume, m ³
$\dot{v}$	volume flow rate, m ³ /s
z	concentration of gas
β	Ostwald coefficient

Subscripts

$A, \text{ atm}$	atmospheric value
F	fuel
f	fuel vapor
I	inflow
n	nitrogen
O	outflow
o	oxygen
OG	overflow
U	ullage
v	volume

Abbreviation

FAA	Federal Aviation Administration
LOC	Limiting Oxygen Concentration
NEA	Nitrogen-Enriched Air

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