Analysis on Variation of Oxygen Loss Rate in AIP System

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Abstract—In view of the complex thermodynamic state inside the lox tank of SE/AIP oxygen supply system, the evaporation rate of liquid oxygen is proposed as the index of oxygen loss inside the oxygen tank (evaporation rate in short). A formula is derived from the thermodynamic point of view based on SE/AIP system usage record data calculate the evaporation rate of liquid oxygen, and on this basis, the influence law of evaporation rate is calculated and analyzed from three aspects.

1. Introduction
As an important fuel for SE/AIP system, liquid oxygen is stored in liquid form at low temperature and high pressure. In the process of storage and usage, as environmental heat flows into oxygen tank, liquid oxygen partly vaporize, which causes the tank pressure continue to rise. When tank pressure is close to the limit value, usually take the way of discharge or consumption to reduce the tank pressure to ensure safety, which results in loss of oxygen storage. In addition, considering the long time consuming loading process and high risk of liquid oxygen, it is greatly significant to reduce oxygen loss as much as possible in service cycle, which can reduce loading frequency of liquid oxygen, improve the fuel usage efficiency and improve the combat effectiveness of SE/AIP system.

2. Factors affecting oxygen loss from oxygen tank
The oxygen inside the SE/AIP system lox tank consists of liquid and gaseous oxygen, and the heat engine consumes gas oxygen. In normal circumstances, the pressure of gas oxygen used by heat engines certain. According to provisions of the SE/AIP oxygen supply system operation manual, the maximum pressure inside the tank should not exceed a certain value during storage process, which is subject to the pressure limit of tank material. However, if the liquid oxygen absorbs heat, and vaporized oxygen makes the pressure rise close to the limit value, it is necessary to relieve tank pressure, which results in oxygen loss. Since the volume expansion ratio of liquid oxygen vaporization is about 1:800 (liquid oxygen: gas oxygen) under atmospheric pressure[1], and liquid oxygen has poor compressibility(thermal expansion coefficient is only 9.53×10^{-3} /℃). According to the ideal gas state equation, the volume expansion ratio of liquid oxygen vaporization is as high as 1:17 even the temperature and pressure inside an oxygen tank is 170K and 3.0MPa. When the filling rate is 50%, the gas oxygen only accounts for 5.6% of the total oxygen storage in tank. Therefore, the rate of liquid
oxygen evaporating into gas oxygen can be used as an index to measure the oxygen loss rate when studying the oxygen loss in lox tank.

Ambient temperature, pressure and filling rate are the three most important factors affecting the evaporation rate\(^2\). Ambient temperature directly affects the temperature of oxygen tank outer wall: the difference between oxygen tank internal and external temperature increase with ambient temperature, as well as the heat transferred into cryogenic liquid oxygen, which makes evaporation loss increase. On the contrary, temperature difference and evaporation loss decrease with ambient temperature. The influence of pressure on liquid oxygen evaporation is mainly reflected in that pressure of saturated steam will increase with the pressure inside the tank, then the equilibrium temperature of liquid oxygen will rise, and the evaporation capacity will decrease with the heat transfer temperature difference, but at the same time, the latent heat of vaporization of liquid oxygen will decrease which makes evaporation speed up. When tank pressure decrease makes the saturated vapor pressure and equilibrium vapor pressure decrease, evaporation capacity increases with the heat transfer temperature difference. Besides, the increase of latent heat of vaporization makes evaporation speed down. Therefore, the change of tank pressure has two opposite effects on evaporation rate\(^3\). The effect of cryogenic liquid filling rate on evaporation loss is related to material and shape of the inner container\(^4\). When the thermal conductivity of inner container material is good, the effect of filling rate on evaporation loss is small. However, if the container is made of materials with poor thermal conductivity, the effect is very obvious.

3. Calculating method of liquid oxygen evaporation rate in lox tank

3.1 Liquid oxygen evaporation rate in lox tank

Evaporation rate in lox tank refers to evaporation rate of certain amount of liquid oxygen in tank after reaching thermal equilibrium under the standard state (101.3kPa, 273.14k). Evaporation rate calculated in hours is called hourly evaporation rate, and the evaporation rate calculated in a day (24h) is called daily evaporation rate. The formula of evaporation rate is as follows:

\[
\eta = \frac{m}{M} \times 100\%
\]

Where: \(\eta\) is the average evaporation rate of liquid oxygen in static unit time; \(m\) is the mass of evaporated liquid oxygen per unit time; \(M\) is the effective capacity of lox tank.

Since liquid consumption per unit time can be expressed by heat flow per unit time, Equation (1) can also be written as:

\[
\eta = \frac{1}{M} \frac{\Delta M}{\Delta t} = \frac{Q}{\gamma M}
\]

Where, \(R\) is the vaporization latent heat of cryogenic liquid; \(Q\) is the total heat leakage from the cylinder.

3.2 Relationship between temperature and pressure in lox tank

For the hermetic space in lox tank, the relationship between pressure and temperature\(^5\) is:

\[
\log P = A + \frac{B}{T} + C \log T + DT + ET^2
\]

Where, \(P\) is the steam pressure in lox tank; \(T\) is the temperature in tank; \(A, B, C\) and \(D\) are regression coefficients.

Assuming that the temperature distribution in tank is even and under saturation equilibrium state all the time, the coefficients \(C, D\) and \(E\) are 0. Equation (3) can be simplified as:

\[
\log P = 4.129 + \frac{374.5}{T}
\]
Wherein, T ranges from 223 to 303K.

3.3 Relationship between evaporation rate and temperature in lox tank

Since the process of vacuum-pumping cooling liquid and the process of free evaporation cooling in the container are two reverse processes. The evaporation capacity of liquid oxygen $\Delta M$ can be calculated by the formula of pumping, depressurizing and cooling process [6]:

$$\Delta M = M \left(1 - e^{-\frac{T}{c}}\right)$$

(5)

Where: $c$ is the specific heat of liquid oxygen; $\gamma$ is the vaporization heat of liquid oxygen; $M$ is mass of liquid oxygen in container; $\Delta T$ is the cooling temperature drop.

Evaporation loss during time $t$ is $\Delta M=tm$. Substituting Equation (1) into Equation (5), the following equation can be obtained:

$$\Delta T = -\frac{\gamma}{c} \ln(1-\eta t)$$

(6)

3.4 Relationship between evaporation rate, pressure and time in lox tank

Set the initial parameters in lox tank as $P_1, T_1$ and after a period, the state of lox tank becomes $P_2, T_2$. It is assumed that pressure and temperature in tank are always in the saturation state during the state change, then the time experienced in the process can be deduced according to the above analysis.

Substituting $P_1, T_1, P_2$ and $T_2$ into Equation (4), we can get:

$$\Delta T = \frac{374.5 \lg(P_2)}{(4.129 - \lg P_2)(4.129 - \lg P_1)}$$

(7)

Since $\lg P = \ln P / \ln 10 = \ln P / 2.303$, the static evaporation rate per unit time $\eta$ can be calculated in combination with Equation (6) and (7), as follows:

$$\eta = \eta^{-1} \left[1 - \left(\frac{P_2}{P_1}\right)^{\frac{862.5c}{(9.51 - \ln P_2)(9.51 - \ln P_1)}}\right]$$

(8)

According to literature [5], it can be seen that:

$$c = \frac{[A + B \frac{374.5}{4.129 - \lg P} + C \frac{374.5}{4.129 - \lg P}^2 + D \frac{374.5}{4.129 - \lg P}^3]}{32}$$

(9)

Substituting $A=46.432$, $B=3.9506 \times 10^{-1}$, $C=-7.0522 \times 10^{-3}$, and $D=3.9897 \times 10^{-5}$ into Equation (9), we can get:

$$c = 1.451 + \frac{4.623}{4.129 - \lg P} + \frac{30.908}{(4.129 - \lg P)^2} + \frac{65.486}{(4.129 - \lg P)^3}$$

(10)

$$\gamma = \frac{374.5}{\frac{4.129 - \lg P}{T_c}}$$

(11)

Substituting $A=8.04$, $n=0.201$, and the critical temperature of oxygen $T_c = 154.58$K into Equation (11), we can get:

$$\gamma = 251.25 (1 - \frac{2.429}{4.129 - \lg P}^{0.201})$$

(12)
If the initial pressure $P_1$, final pressure $P_2$ and process time $t$ from initial state to final state are known, the average liquid oxygen evaporation rate $\eta$ in tank during time $t$ can be calculated by Equations (8), (10) and (12).

4. Variation rule of liquid oxygen evaporation rate in tank

The influence of various factors on liquid oxygen evaporation rate can be analyzed by screening out typical data from data of SE/AIP oxygen supply system in use and substituting them into the model established in section above.

4.1 Influence of lox tank pressure on evaporation rate

Due to the temperature difference between interisland external tanks, the tank wall is constantly leaking heat keeps transfer, and the tank pressure will rise slowly without pressure relief. The influence of tank pressure on evaporation rate can be studied by calculating average evaporation rate under different pressure intervals. Three groups of typical data were selected from the original service data of SE/AIP lox tank. Matlab mathematical tool was used to calculate the hourly evaporation rate, and variation curves of evaporation rate are shown in Figure 1, Figure 2, and Figure 3.

Fig. 1 Curve of liquid oxygen evaporation rate varying with pressure (I)

Fig. 2 Variation curve of liquid oxygen evaporation rate with pressure (2)
From curves of liquid oxygen evaporation rate varying with tank pressure calculated based on the three sets of data, it can be seen that the evaporation rate increases with the tank pressure. Besides, there is an obviously sudden jump in evaporation rate after a certain pressure point. The pressures in three figures are 1.31MPa, 1.32MPa, and 1.94MPa respectively.

4.2 Influence of lox tank filling rate on evaporation rate

Since the evaporation capacity of liquid oxygen is very small when it is stored in tank, a set of continuous date shows that the filling rate of liquid oxygen varies little in tank. Therefore, the analysis of influence of filling rate on evaporation rate should not only ensure the consistency of other conditions as far as possible, but also select the use data of different time intervals. As shown in Fig. 4 and Fig. 5, lox tank usage data with filling rate of 7%, 25%, 79% and 90% when the external temperature is little different are selected as the basic data for calculation and analysis.

As can be seen from Fig. 4, the average evaporation rate at different filling rate changes steadily under different pressure, and evaporation rate decreases with the increase of filling rate. As can be seen from Fig. 5, the evaporation rate increases sharply when filling rate exceeds 90%, which is one order of magnitude higher than that below 90%, and the evaporation rate greatly fluctuates.

Fig. 4 Curve of liquid oxygen evaporation rate varying with pressure at different filling rates
4.3 Influence of external temperature on evaporation rate

The influence of the external temperature on the inside of the oxygen tank can be regarded as influence of the external tank temperature of the double tank on the evaporation rate of liquid oxygen. Due to daily maintenance requirements, the internal temperature changes little. Figure 6 shows the influence curve of different temperature on liquid oxygen evaporation rate.

5. Conclusion

In this paper, in the process of discussing the calculating method of the liquid oxygen evaporation rate in lox tank, the thermodynamic state in tank was assumed to be idealized, which simplifies the calculation. Conclusions are consistent with operating experience, providing reference for improving the usage efficiency of liquid oxygen in SE/AIP system.

Reference

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