An effect of oxygen concentration on the evaporation rate of liquid air tank for nuclear integrated liquid air energy storage system

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1. Introduction

A nuclear integrated liquid air energy storage system has been proposed to improve the operational flexibility of nuclear power plants [1]. Liquid Air Energy Storage System (LAES) stores energy by producing liquid air and generates energy by evaporating the liquid air to drive air turbine. LAES is highly applicable to the nuclear industry due to its many advantages: high energy density(>100kWh/m^3), less geographical constraints, and good economy [2].

One of the characteristics of liquid air is that air is a mixture of N_2(78%), O_2(21%), and other molecules. Due to the different boiling points of each molecule, the composition of liquid air changes over time, called the 'weathering effect'. Since the boiling point of the N_2 is the lowest in the air, N_2 evaporates faster than other molecules. Therefore, the O_2 composition increases over time [3]. The increase in O_2 concentration causes the thermal properties of liquid air to change. Therefore, the effect of O_2 concentration should be reflected on the thermodynamic analysis of the liquid air tank.

The most important phenomenon in the liquid air tank is evaporation. Due to the low liquid point of air (-194°C), the liquid air is naturally evaporated by heat penetration. Therefore, the evaporation rate should be well estimated to evaluate the stored energy in the tank.

In this research, the effect of O_2 concentration on the evaporation rate of liquid air is investigated. Due to the weathering effect, the thermal properties of the liquid air will be changed. To evaluate the effect of weathering, the Tanasawa evaporation model is adopted, because this model can estimate the evaporation rate by reflecting the properties of the fluid. Based on the Tanasawa model, the effects of mixture composition and evaporation coefficient on the evaporation rate of liquid air are investigated.

2. Methodology

2.1 Evaporation model

The Tanasawa evaporation model is given by [4]:

$$\dot{m}''_{evp} = \frac{2\sigma_e}{(2-\sigma_e)}\sqrt{\frac{M}{2\pi R}}\rho_l h_{fg}\frac{T_{int}-T_{sat}}{T_{sat}^{3/2}} \cdots eq(1)$$

where $\dot{m}''_{evp}$ is evaporation mass flux [kg/m^2-s], σ_e is evaporation coefficient [1/s], M is molecular weight [g/mol], R is universal gas coefficient [J/mol-K], ρ_l is liquid density [kg/m^3], h_{fg} is latent heat [J/kg], T_{int} is interface temperature [K], and T_{sat} is saturation temperature [K].

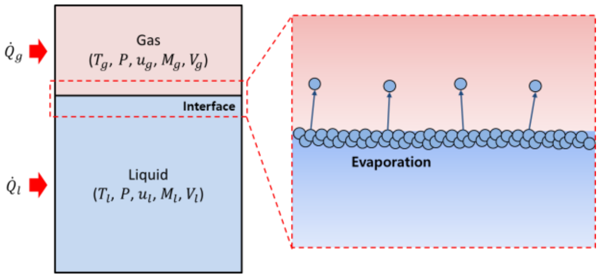

Fig. 1. Schematic of liquid air tank and interface

The present model calculates the evaporation rate by using the evaporation coefficient and the fluid state. First, the evaporation coefficient indicates the probability of the actual evaporated mass flux to the ideal evaporated mass flux. σ_e is generally defined by the user to match the experimental results well. The range of evaporation coefficients is very wide from 1e-8 to 1 [5]. Too high value of a σ_e will cause divergence, while a too small value may cause deviation between the actual value and the predicted value. Therefore, the evaporation coefficient should be chosen carefully. Second, fluid conditions are used to calculate the ideal evaporation rate. Density, latent heat and saturation temperature are calculated from the fluid state. On the other hand, interfacial temperature is highly dependent on the heat balance between upper layer (gas side) and the lower layer (liquid side) of the interface. In this study, the fixed interfacial temperature difference is assumed to see only the effects of other parameters.

3. Results

The effects of the O_2 concentration and evaporation coefficient are investigated. The test conditions are listed below:

Table. 1. Test conditions

Properties	Value
Fluid	Air (binary mixture)
O_2 vol%	21~30%
Molar mass of air	$x_{N_2}M_{N_2} + x_{O_2}M_{O_2}$
σ_e [1/s]	1e-8 ~ 1

Interfacial superheat [K] $\Delta T_{int} = T_{int} - T_{sat}$	0.1K

3.1 Effect on the thermal properties

Fig. 2 shows the change of thermal properties of the liquid air with O_2 volume concentration. The saturation temperature, latent heat, and liquid density increase with the O_2 concentration. The density of the liquid air is most affected.

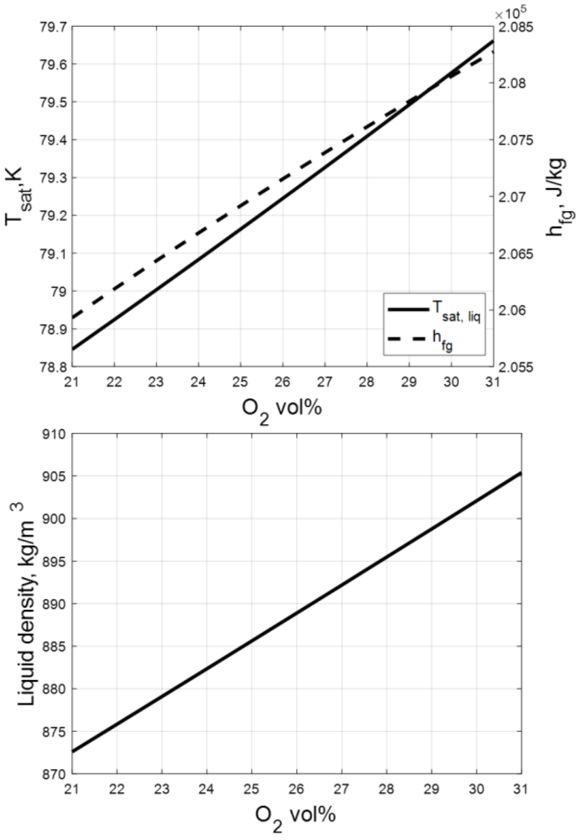

Fig. 2. (up) Saturation temperature and latent heat and (down) liquid density of liquid with O_2 concentration

3.2 Effect on the evaporation mass flux

Fig. 3 shows the effects of the evaporation coefficient and the O_2 concentration on evaporation mass flux. The evaporation mass flux increases exponentially with the evaporation coefficient. Therefore, a high value will overestimate the estimated evaporation rate, while a low value will underestimate it. In the light of O_2 concentration, the evaporation mass flux linearly increases. Based on the Tanasawa model, the effect of O_2 concentration on the increase in density and latent heat is greater than the effect on the increase in saturation temperature. Considering the weathering effect, the increase in evaporation rate can be further accelerated over time.

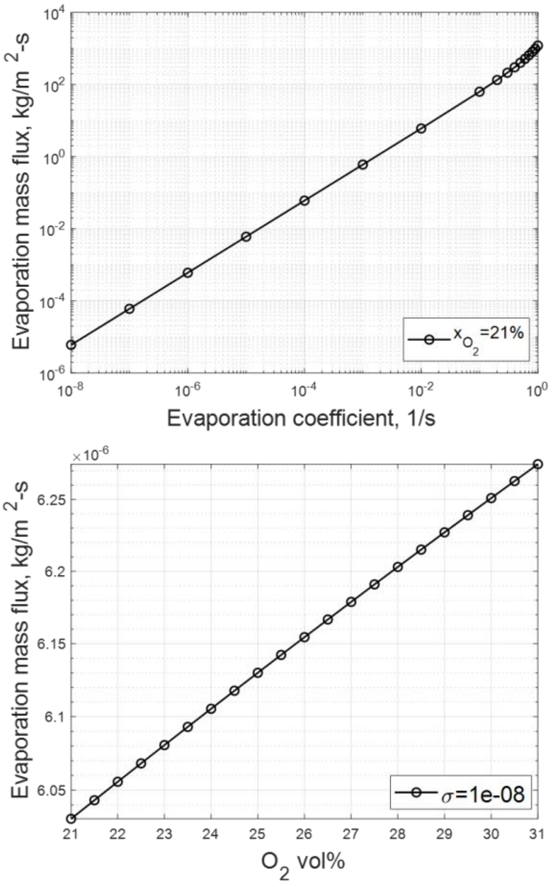

Fig. 3. Sensitivity of evaporation mass flux with evaporation coefficient and O_2 vol%

3.3 Heat of evaporation

Fig. 4 shows the heat of evaporation mass flux with O_2 concentration. Considering the effect of both latent heat and evaporation mass flux, the heat of evaporation increases gradually. When the O_2 concentration increases up to 31%, the heat of evaporation increases by almost 33% compared to base case. This result could be interpreted to mean that more heat is required for evaporation, but it could also be interpreted to mean that the evaporated liquid air transfers more heat to the gas region. Therefore, the increase of internal energy of the gas region is accelerated over time due to the weathering effect.

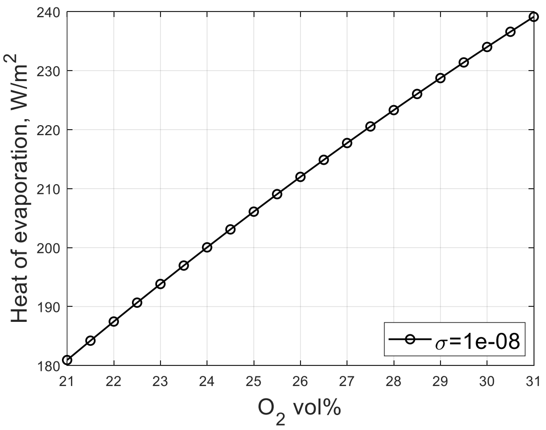

Fig. 4. Heat of evaporation with O_2 vol%

4. Conclusions

In this study, the effects of O_2 concentration on the evaporation rate of liquid air are investigated. The Tanasawa model is used for the evaluation. By using the Tanasawa model, the sensitivity of the evaporation rate with evaporation coefficient and O_2 concentration is evaluated. The evaporation rate increases dramatically with evaporation coefficient. For this reason, if too high value is chosen, the estimated evaporation rate will be enormous leading to divergence of simulation. On the other hand, low value causes underestimation. Considering the O_2 concentration, the evaporation rate increases linearly with O_2 vol%, because the effects of the increase in density and latent heat is greater than the effects of increase in the saturation temperature. This means that the evaporation rate is accelerated with time due to the weathering effect on liquid air. In the future, the overall modeling of liquid air tank will be carried out and the change of O_2 concentration will be investigated on a full-scale liquid air storage tank.

5. Acknowledgment

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