Review of stratification issues in the liquid air storage tank for the liquid air energy storage integrated to PWR steam cycle

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Introduction

▣ For baseload power such as nuclear, negative pricing due to increased renewables can harm their economics as they are forced to lower their load.

▣ By integrating a large-scale ESS to the conventional nuclear plant, it can store the energy during off-peak hours and release energy when power is most needed, creating more revenue by price arbitrage.

▣ Liquid air energy storage (LAES) has been receiving attention recently, due to its high energy density and its freedom from geological constraints. KAIST research team has proposed an LAES integration layout for reference PWR steam cycle.

▣ LAES stores energy in cylindrical tanks of liquid air, a mixture of mainly nitrogen, oxygen, and argon.

▣ However, as idle time goes on for hours, possibly days, the mixture can potentially undergo stratification due to density and boiling point differences.

▣ The purpose of this paper is to review the available literature on stratification issues for cryogenic tanks and suggest implications for the LAES application.

Issues of tank stratification

▣ In previous literature, most of the stratification issues involving cryogenic liquid tanks have been addressed and studied for the liquefied natural gas (LNG) applications due to their safety and industrial implications.

▣ The paper approaches the review for LNG applications initially, and then to extend the speculations for LAES.

▣ The potential issues reviewed from the LNG applications are the following:

1) Rollover due to density stratification

- Historically, an event representing the possible dangers of rollover with LNG was the La Spezia incident in 1971, as shown in Fig. 2.
- Because there was insufficient mixing during the filling, and the difference of density between the two layers in the tank was around 0.7%.
- It has been reported that due to stratification which ultimately led to rollover, a 250-fold increase in boil-off gas (BOG) occurred, posing safety risks.

2) Conditions potentially leading up to tank stratification

- As it is explained in Scurlock (2015), the local temperature rise in the boundary layer is about 1K, according to experimental measurements of the LNG tanks.
- Hence, the buoyancy force of the boundary layer flow at the tank surface heated by the heat ingress becomes insufficient to penetrate across the liquid interface, causing the thermal overfill.
- Density stratification can take place by 1) composition differences between multi-component liquid layers, and 2) temperature differences between component layers.

Density difference between layers governed by:

$$\frac{d\rho}{dz} = \frac{dT}{dz}\left(\frac{\partial\rho}{\partial T}\right)_{x,P} + \frac{dx_1}{dz}\left(\frac{\partial\rho}{\partial x_1}\right)_{T,P} + \frac{dP}{dz}\left(\frac{\partial\rho}{\partial P}\right)_{x,T}$$

(Red: density gradient due to temperature, blue: density gradient due to concentration)

- It becomes important to investigate under what situations the composition differences may become significant and determine the charging scheme accordingly to avoid such a situation.

3) Implications of tank stratification on LAES operation

- Just as it is advised for LNG applications, complete mixing procedures and measures can be applied similarly for the LAES application to avoid such a risk.
- Tank stratification implies that the performance of the LAES discharging cycle may be deteriorated and/or altered during operation period.
- This is because the composition of the discharged liquid air will vary, causing the thermodynamic properties of the working fluid to change as well.
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Schematic of LAES integrated to PWR steam cycle

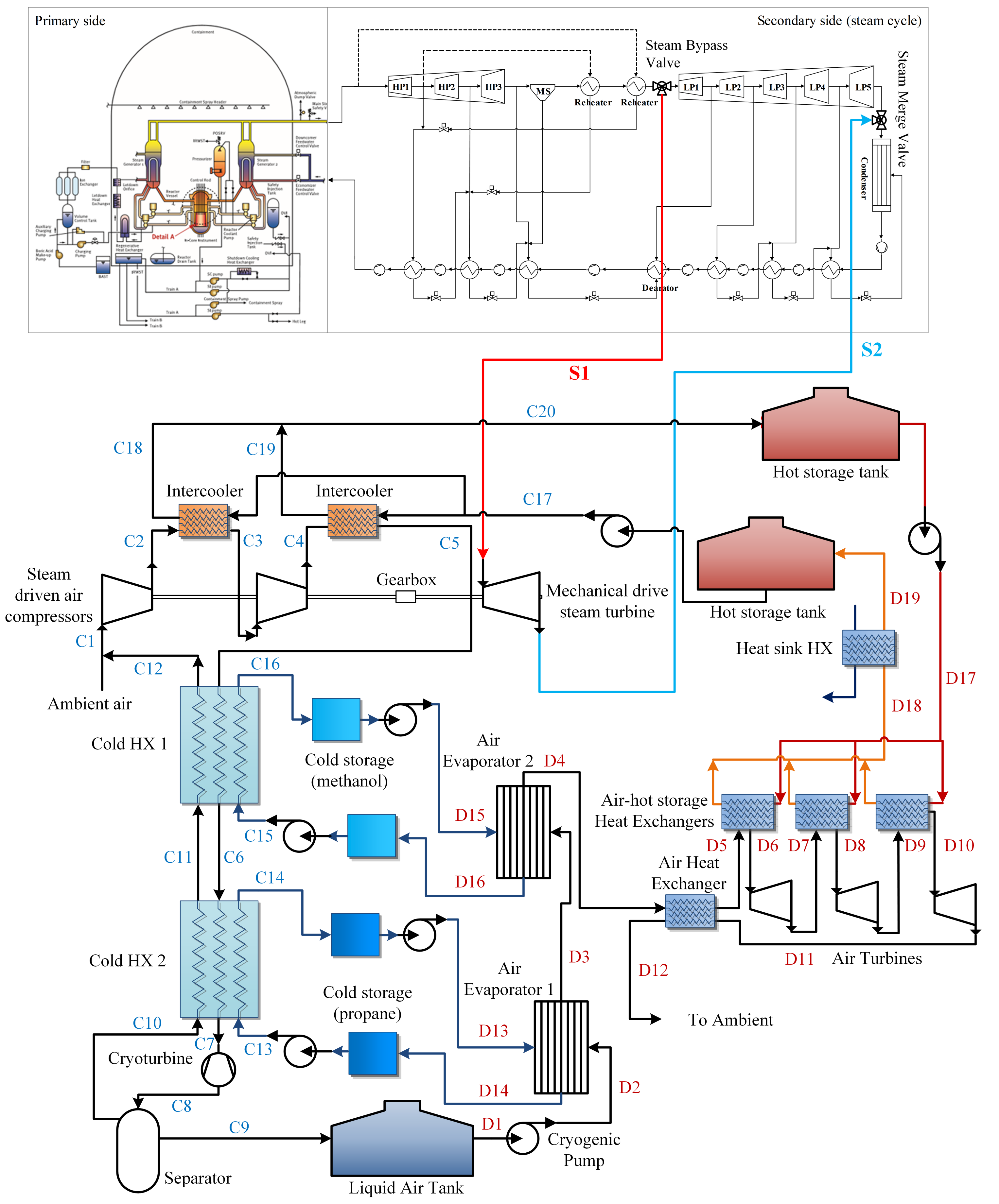

Fig. 1. Schematic of LAES integrated to PWR steam cycle

Tables and figures

Table 1. Representative properties of air and its constituents

	Air	Nitrogen	Oxygen	Argon
Molar mass (g/mol)	28.9586	28.01348	31.9988	39.948
Critical temperature (K)	132.5306	126.192	154.581	150.687
Critical pressure (MPa)	3.786	3.3958	5.043	4.863
Critical density (mol/m3)	11.8308	11.1839	13.63	13.407
Normal boiling point temperature (K)	78.903	77.355	90.188	87.302
Density at NBP (kg/m3)	877.81	806.6	1141.8	1396.2

Table 2. Derivative properties of saturated liquid cryogens at normal boiling points

	NBP (K)	ρ (kg/m^3)	$-(d\rho/dT)_{sat}/\rho$ (%/K)	$+(dT/dP)_{sat}$ (K/bar)	$-(d\rho/dP)_{sat}/\rho$ (%/bar)
Nitrogen	77.31	806.8	0.57	10.8	6.1
Argon	83.80	1394	0.47	7.1	3.3
Oxygen	90.19	1141	0.43	12.26	5.2
Methane	111.67	422.4	0.40	14.3	5.7
Ethane	184.55	488.5	0.20	18.1	3.6
Propane	231.1	581	0.19	29.2	5.55

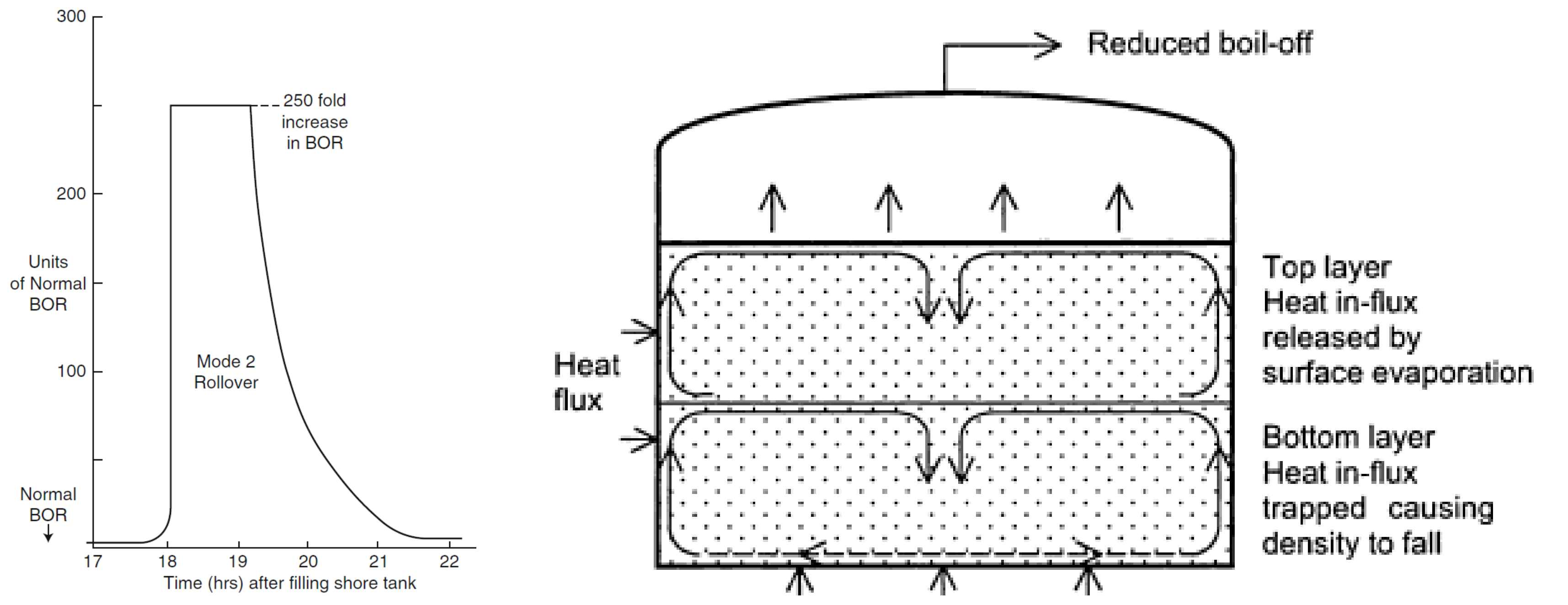

Fig. 2. Level of BOR with respect to time for the LNG tank (left) and schematic of rollover (right)

Summary and future works

▣ The research reviews and addresses potential issues of tank stratification for the liquid air energy storage integrated system.

▣ Moreover, the stratification issue can affect the LAES discharging cycle, in terms of heat transfer and turbine performance.

▣ Future works include experimental investigation of conditions under which stratification can occur during normal operations of LAES, as well as the modeling of the stratification phenomenon for liquid air.