

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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1. Introduction

In the scenario of increasing renewable penetration, the electric grid has become demanding of load-following and grid support capabilities. Due to the intermittency brought by the renewable sources, the need for more energy storage is growing, as well as the requirement for conventional power to reduce their load during the period of surplus supply.

To restore the reduction of cost-competitiveness during overproduction for conventional energy source such as nuclear power, the idea of integrating large-scale energy storage systems (ESS) has been explored [1-3]. 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.

Of the promising large-scale ESS technologies, liquid air energy storage (LAES) has been receiving attention recently [4]. Compared to compressed air energy storage or pumped hydro storage, LAES has higher energy density and is free from geological constraints [5]. With such potential, Li et al. (2014) proposed a concept of integrating LAES to a light-water reactor of 250MWe [6]. Also, the KAIST research team also proposed an LAES integration layout for a reference pressurized water reactor (PWR) [7].

As shown in Fig. 1, the layout bypasses steam flow from the inlet point of the low pressure turbine. Then, it is linked to the mechanical drive steam turbine coupled to the air compressors of the LAES charging cycle. This allows the PWR steam cycle to store energy at off-peak using the charging cycle, and then release energy by running a discharging cycle run on liquid air as the storage fluid. The liquid air tank, marked as red in Fig. 1, is thus the location at which the energy is stored between the charging cycle and the discharging cycle.

Liquid air energy storage involves the storage of energy in cylindrical tanks of liquid air, a mixture of mainly nitrogen, oxygen, and argon [8]. However, it has been known that the constituents of air as a mixture have varying densities with different boiling points, shown in Table 1. During the charging cycle, uniformly mixed liquid air is produced and stored inside the storage tank. As the idle time between charging and discharging modes exists in hours to possibly days, the mixture can potentially undergo stratification due to density and boiling point differences.

Though the mechanisms and types of stratification inside the liquid air tank of LAES are not fully understood, the issues of stratification in cryogenic tanks has been well investigated. However, they have been mostly studied for liquefied natural gas (LNG) applications, and thus, it remains uncertain under the LAES conditions.

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

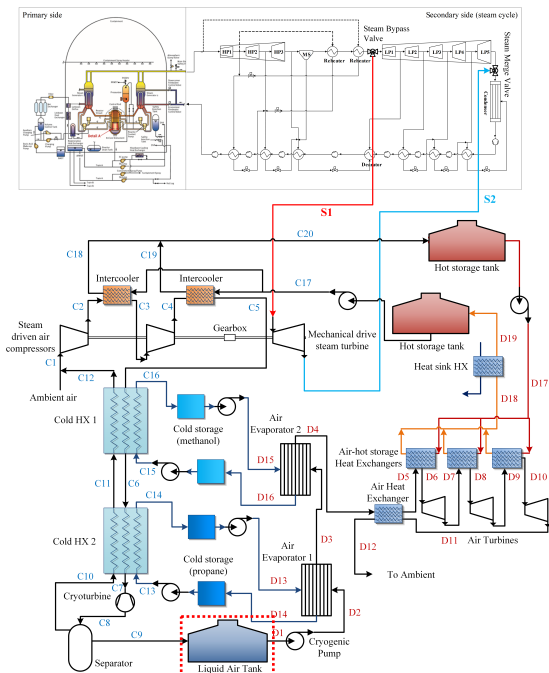


Fig. 1. Schematic of LAES integrated to PWR steam cycle [7]

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/m ³)	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/m ³)	877.81	806.6	1141.8	1396.2

2. Issues of tank stratification

In previous literature, most of the stratification issues involving cryogenic liquid tanks have been addressed and studied for the LNG applications due to their safety and industrial implications. Because the LAES research is relatively recent and does not have ample operational experiences, there has been no study on stratification applicable for liquid air tanks, specifically.

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

1) Rollover due to density stratification

Historically, an event representing the possible dangers of rollover with LNG was the La Spezia incident in 1971 [9]. 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. The representative graph of BOR with respect to time is shown in Fig. 2.

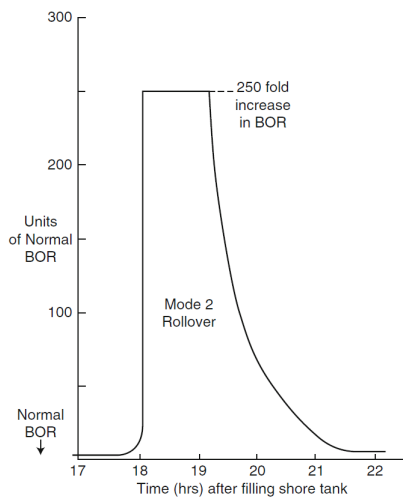


Fig. 2. Level of BOR with respect to time for the LNG tank during the La Spezia rollover event [10]

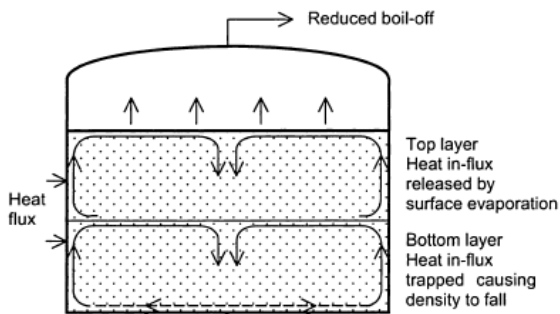


Fig. 3. Schematic of describing the mechanism of rollover for stratified cryogenic tanks [10]

As briefly portrayed in Fig. 3, the mechanism of the rollover due to stratification has been investigated as the following series of stages.

- 1) Firstly, there existed a density difference between the upper and lower layer due to minimum mixing during fueling, of about 0.7%.
- 2) Then, as the heat ingress from the insulation surface of the tank enters over time, it creates a boundary layer causing the heated liquid to travel upwards due to buoyancy force.

- 3) At the liquid-liquid interface, the density difference prevents the buoyancy force from driving the heated fluid upwards, and it becomes locked in the lower layer (thermal overfill).
- 4) As the upper layer undergoes surface evaporation, the concentration of the heavier molecular weight increases.
- 5) The reduction of density difference decreases between the two layers, leading to density equilibration by double-diffusive convection. This causes the uncontrolled rapid spontaneous mixing of layers.
- 6) BOR increases to a peak of 200 times by thermal overfill is released.

2) Conditions potentially leading up to tank stratification

The main assumption for leading up to the rollover event is density stratification of the cryogenic liquid tank. 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.

For LNG, with methane as its main constituent, the $-(d\rho/dT)_{sat}/\rho$ value is around 0.4% at the normal boiling point. Comparing to the case of liquid air, shown in Table 2, the derivative value for air constituents is slightly greater. This may imply that there needs a greater density stratification between the two layers at the liquid interface for the thermal overfill to occur.

It is therefore imperative to determine whether density stratification will occur under operating conditions inside the LAES tank. Density stratification can take place by 1) composition differences between multi-component liquid layers, and 2) temperature differences between component layers. Thus, if the LAES tank undergoes mixing of liquid air with different compositions and/or temperatures, density stratification may occur.

In the case for LNG tanks, the La Spezia incident occurred because of a loading mistake. This is explained by the filling of a methane-rich, low density liquid on top of the old liquid which underwent substantial preferential boiling of the lower boiling point component - methane.

Similarly, the situation may occur for the LAES system during charging. If it undergoes mixing by charging the fresh liquid air of higher nitrogen content with the stand-by liquid air which has undergone preferential boiling of nitrogen over time, unintended density stratification may occur inside the liquid air tank. Therefore, 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.

Another condition under which the stratification may occur is when a cryogenic liquid tank is topped up with a thermally subcooled liquid. Because the density of the subcooled liquid will be greater than the previously contained liquid in the tank at saturation, auto-stratification will take place immediately.

Table 2. Derivative properties of saturated liquid cryogenics at normal boiling points [10]

	NBP (K)	ρ (kg/m ³)	$-(dp/dT)_{sat}$ ρ (%/K)	$+(dT/dP)_{sat}$ (K/bar)	$-(dp/dP)_{sat}$ ρ (%/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

3) Implications of tank stratification on LAES operation

Abovementioned, the density stratification caused by a combination of the conditions can result in safety issues due to the rollover. 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. If the system operation fails to remove stratification in the liquid air tank, there can be safety issues, requiring special attention for nuclear integration.

Furthermore, 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. Consequently, the discharging cycle becomes vulnerable to the fluctuations of heat transfer performance in the evaporator as well as the performance output of air turbines.

3. Summary and future works

The paper reviews and addresses potential issues of tank stratification for the liquid air energy storage integrated system. Though they have not been specifically addressed for LAES in literature, important mechanisms concerning the rollover have been investigated for LNG applications. Similar considerations require attention in the recently explored LAES field. 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.

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