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Analysis of Evaporation of Liquid Ammonia in a Vertical Cylindrical Storage Tank

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Abstract**—**The present study addresses the problem of ammonia evaporation during filling of a vertical cylindrical tank and the influence of various external factors on the stability of storage by determining the conditions for minimum evaporation. Numerical simulation is carried out by solving the governing equations namely, continuity, momentum, energy, and diffusion of species. The effect of temperature of surrounding air, the filling speed of the reservoir and the temperature of the filling liquid ammonia on the evaporation rate is investigated. Results show that the temperature of the filling liquid has little effect on the liquid ammonia for a short period, which, in fact, is function of the filling speed. The evaporation rate along the free surface of the liquid is non-uniform. The inlet temperature affects the vapor ammonia temperature because of pressure increase. The temperature of the surrounding air affects the temperature of the vapor phase rather than the liquid phase. The maximum of evaporation is reached at the final step of filling. In order to minimize loss of ammonia vapors automatically causing losses in quantity of the liquid stored, it is suggested to ensure the proper insulation for the walls and roof of the reservoir and to increase the filling speed.

Keywords**—**Evaporation, liquid ammonia, storage tank, numerical simulation.

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I. INTRODUCTION

THE massive storage of flammable and/or toxic substances in many industrial facilities is mainly in metal tanks with welded construction installed on the ground. To meet the wide variety of industrial liquid products to store, various shapes of tanks with different designs, are manufactured to accommodate the most rationally and economically as possible the characteristics of the product to store [1].

The geometry of the reservoirs closely depends on the nature of the stored product and its volatility at the storage temperature. Once the volatility is known, different storage modes can be considered. They can be classified depending on the pressure and temperature of the stored liquid, taking into account the relationship between these two parameters. We may deal with volatile liquids that do not boil at the room temperature or volatile liquids that boil at temperature below or equal to the room temperature.

Besides loading and unloading operations, the stability of ammonia stored in cryogenic tanks is significantly affected by heat exchange with the surrounding environment. Assessment of heat transfer across the tank walls is extremely important for the prediction of the evaporation phenomenon of ammonia, which greatly affects the quantity and quality of the stored product. When a tank is filled with two types of ammonia, one is previously stored in the tank and the other is newly loaded, their densities are different because of the evaporation effect. Stratification in liquid level can occur. Heat transfer across the walls may result in a sudden release of large quantities evaporated gas (boil-off gas). This phenomenon called rollover is accompanied by a rapid increase in pressure, which can sometimes damage the tank. Barzegar and Dehghan [2] carried out a numerical simulation to analyze this phenomenon. In order to minimize losses of ammonia vapors automatically causing losses in quantity of the liquid, the researchers conducted several tests on the effect of heat transfer at the sidewalls as the work of Aszodi et al. [3]. These authors measured the temperature and the void fraction in the liquid, which makes their experimental results very interesting. Other works like the one of Chen et al. [4] who developed a thermodynamic model to analyze the different mechanisms of heat transfer. The properties and composition of ammonia were simulated. The authors proposed to use electric generators and condensers to reduce the pressure in the tank and eliminate losses due to evaporation. Kim et al. [5] used a dynamic hybrid model composed by continuous dynamic states to estimate the evaporation rate. Their analysis relies on energy and mass transfer between stratified layers of ammonia in the storage tank using discrete dynamic states to describe the evaporation.

The objective of the present study is to investigate the evaporation phenomenon of liquid ammonia in cryogenic cylindrical tank. Operating conditions that allow avoiding the risk of excessive evaporation of ammonia due to boundary conditions and introduction of warm ammonia in the tank during loading operation are determined by means of numerical simulation of the evaporation phenomenon within the tank.

II. PROBLEM STATEMENT

Let us recall that ammonia is a liquid stored at about 240 K (-33 °C) at atmospheric pressure, i.e. conditions close to the boiling point. This boiling point increases as the lightest components evaporate. A heat balance at the free surface is quite complex since it involves not only the latent heat transfer due to vaporization, but also sensitive heat transfer because of radiation and convection in the gas phase.

We consider in the present analysis a vertical cylindrical storage tank as shown in Fig. 1.

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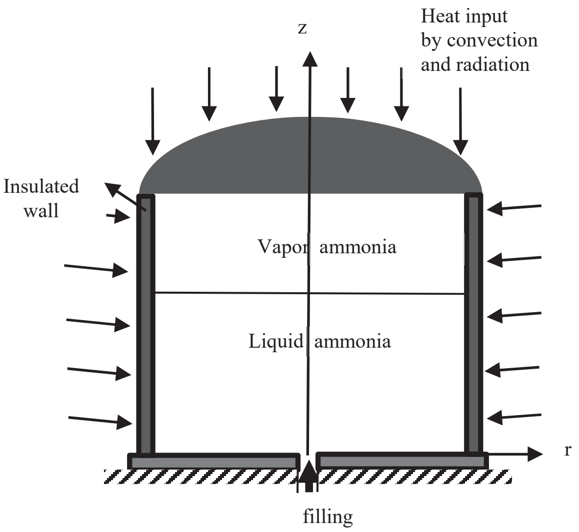

Fig. 1 Schematic of the storage tank

The governing equations, i.e. continuity, momentum, energy and species concentration equations, which describe heat and mass transfer during the evaporation phenomenon, are written in a dimensionless form as:

A. In the Liquid Zone

Continuity:

$$\frac{\partial}{\partial z^*}\left(u_z^*\right) = 0 \tag{1}$$

Momentum:

$$\text{r direction: } \frac{\partial P^*}{\partial r^*} = 0 \tag{2}$$

z direction:

$$\left[\frac{\partial u_z^*}{\partial t^*} + u_z^* \frac{\partial u_z^*}{\partial z^*}\right] = \left(-\frac{\partial P^*}{\partial z^*}\right) + \frac{2}{R_e}\left(\frac{\partial^2 u_z^*}{\partial {z^*}^2}\right) + \frac{G_r}{R_e^2} T^* + H_r \frac{g}{V_0^2} \tag{3}$$

Energy:

$$\left[\frac{\partial T^*}{\partial t^*} + u_z^* \frac{\partial T^*}{\partial z^*}\right] = \frac{1}{R_e P_r}\left[\frac{1}{r^*}\frac{\partial}{\partial r^*}\left(r^* \frac{\partial T^*}{\partial r^*}\right) + \frac{\partial}{\partial z^*}\left(\frac{\partial T^*}{\partial z^*}\right)\right] \tag{4}$$

B. In the Vapor Zone

Energy:

$$\left[\frac{\partial T^*}{\partial t^*}\right] = \frac{1}{R_e P_r}\left[\frac{1}{r^*}\frac{\partial}{\partial r^*}\left(r^* \frac{\partial T^*}{\partial r^*}\right) + \frac{\partial}{\partial z^*}\left(\frac{\partial T^*}{\partial z^*}\right)\right] + E_c\left[\frac{\partial P^*}{\partial t^*}\right] \tag{5}$$

Species concentration:

$$\rho\left[\frac{\partial C}{\partial t} + u_z \frac{\partial (C)}{\partial Z}\right] = \rho\, D\left[\frac{1}{r}\frac{\partial}{\partial r}\left(\frac{r\,\partial C}{\partial r}\right) + \frac{\partial}{\partial z}\frac{\partial C}{\partial z}\right] \tag{6}$$

where the dimensionless variables are defined as follows:

$r^* = r / H_r$; $z^* = z / H_r$

$P^* = P / \rho V_0^2$; $V^* = u_z / V_0$

$T^* = (T - T_0) / \Delta T$; $t^* = t . V_0 / H_r$

The height of the tank, H_r, is taken as a reference length.

C. Initial and Boundary Conditions

At t=0, ammonia concentration, temperature and vapor pressure are uniform and constant in the tank.

$$t = 0 \quad \rightarrow \quad \begin{cases} T_{(r,z,0)} = T_0 \\ C_{(r,z,0)} = C_0 \\ P_{(r,z,0)} = P_0 \end{cases} \tag{7a}$$

The pressure in the liquid phase is

$$P_{(r,z,0)} = P_{atm} + \rho g z \tag{7b}$$

Furthermore, the continuity equation allows writing the velocity of the free surface of the liquid as:

$$V_{free\ surface} = V_{inlet} \cdot \left(\frac{S_{inlet}}{S_{tank}}\right) \tag{7c}$$

The boundary conditions are shown in Fig. 2.

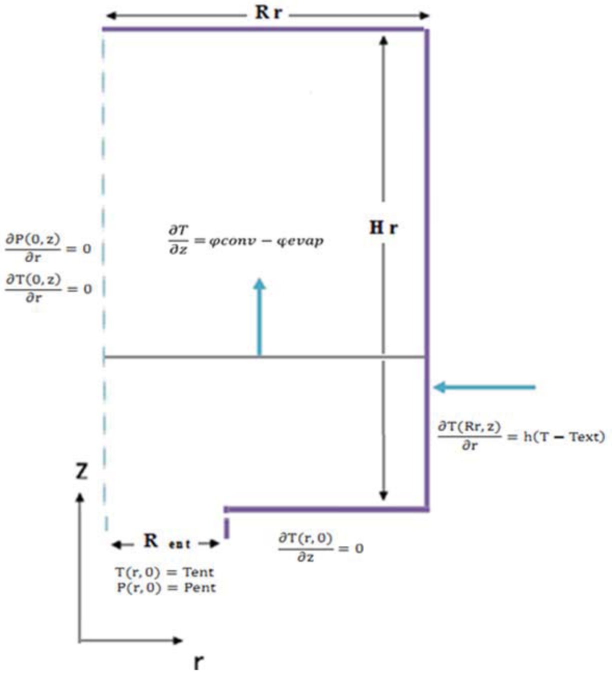

Fig. 2 Computational domain and boundary conditions

III. NUMERICAL PROCEDURE

The control volume method is adopted to solve the governing equations (1)-(6) along with the corresponding initial and boundary conditions. A generalized form of the transport equation may be written as:

$$\frac{\partial \rho \emptyset}{\partial t} + div\left(\rho \emptyset \vec{u}\right) - div\left(\Gamma\, \overrightarrow{grad}\,(\emptyset)\right) - S_\emptyset = 0 \tag{8}$$

The power law differencing scheme is used to discretize the convection-diffusion terms of (7). The velocity-pressure coupling is handled making use of the SIMPLE (Semi Implicit Pressure Linked Equations) algorithm. The combined between

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the iterative Gauss-Seidel method and the Thomas algorithm is used as the solution method. Convergence is assumed achieved once the relative error on each dependent variable is less than 10^{-5}.

The algorithm for the storage case is as follows:

1. Discretize the computational domain with a fixed mesh.
2. Initialize the fields of concentration and temperature.
3. Calculate at the interface, the unknown temperature, concentration, latent heat of vaporization and the velocity of the free surface of liquid.
4. Assume the position of the interface depending on the adopted the grid at an arbitrary time.
5. Determine the properties (density, thermal conductivity, dynamic viscosity) at each node according to its position in the liquid or gaseous phase.
6. Solve the concentration equation in the gas phase with the initial interfacial condition.
7. Calculate the density for the new domain for ammonia vapor.
8. Solve the energy equation in two subdomains (gas and liquid) and check for convergence.
9. Calculate the pressure for all nodes.
10. Check the convergence of concentration at the interface through the interfacial balance.
11. Verify the accuracy of the time (the evaporation rate obtained by the concentration equation is it the same as the displacement of the interface?)
12. Display the result.

IV. RESULTS AND DISCUSSION

We have developed a computer program to solve the equations of concentration and energy coupled by interfacial balance equation accounting for the evaporation phenomenon. An equation of state for the gaseous ammonia is used to link temperature and pressure in the gas phase. Two cases were considered: one for the stagnant liquid except the interface that moves due to evaporation; this is a moving boundary problem, the second case dealt with the charging of the storage tank from the bottom. The filling action sets in motion the liquid and must be taken into account in the program.

The simulation results are organized and presented in two parts. The first one concerns the pure ammonia storage in the reservoir, whereas the second one deals with the filling of the storage tank.

Fig. 3 illustrates the effect of external temperature on the evaporation rate of ammonia. It is depicted that the evaporation rate increases rapidly in a linear way once the evaporation starts. Then, it stabilizes for a while before increasing again but with a smaller speed. It is clear that the higher external temperature induces a higher evaporation rate. However, it should be pointed out that its effect is not of much importance. An increase of 40 °C in external temperature generates only about 10% increase in the evaporation rate and 14% increase in pressure as displayed in Fig. 4.

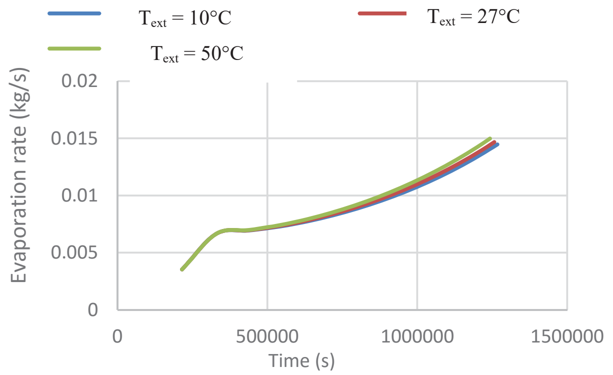

Fig. 3 Effect of surrounding temperature on the evaporation rate of ammonia, liquid height = H_l = 19.5 m

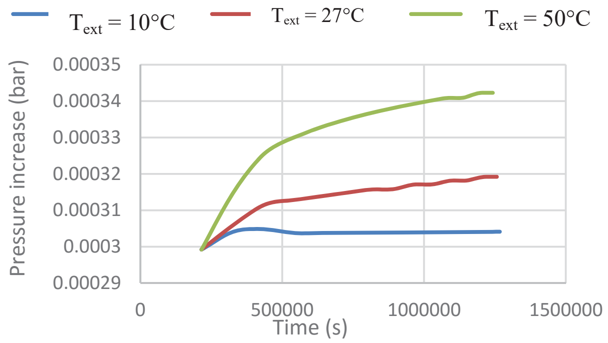

Fig. 4 Effect of surrounding temperature on pressure in the tank, liquid height = H_l = 19.5 m

In the case of charging the tank, a liquid height of 3.5 m is considered. The effect of the temperature of the filling fluid is exhibited in Fig. 5.

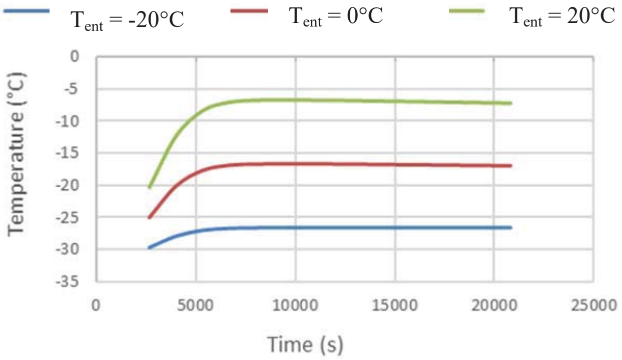

Fig. 5 Effect of temperature of filling fluid (Tent) on liquid temperature at height H_l = 3.5 m, Vent = 37 m/s and Text= 300 K

It is shown that the effect of filling the tank with higher temperature fluid raises the temperature in the tank during the first hour then it stabilizes at a constant value.

V. CONCLUSION

The aim of the present study was the analysis of the influence of certain parameters such as the external conditions and the filling rate on the evaporation rate and the evolution of the pressure in the storage tank. The numerical predictions would allow determining the operating conditions to prevent industrial risks associated with the boil-off phenomenon of ammonia.

Several parameters namely the external temperature, the inflow rate during charging the tank and the temperature of the added ammonia are influencing the evaporation of liquid ammonia and are explored. The numerical predictions show that higher inflow temperature yields a pressure increase of the vapor ammonia. The external temperature affects more the vapor phase of ammonia rather than the liquid phase. Recommendations that could be made for reducing losses of the liquid ammonia stored concern the good insulation of the reservoir walls and roof as well as the increase of the charging speed.

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