A MODEL FOR LNG TANK ROLLOVER

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INTRODUCTION

Rollover has occurred in several liquefied natural gas (LNG) storage tanks. In all rollover cases described in the literature \(^1\) an unusually large amount of methane vapor evolved very rapidly. In one of the most dramatic cases, the La Spezia rollover of 1971 \(^2\), the consequent overpressure exceeded the nominal tank design pressure, but was relieved promptly by the opening of safety valves. Whereas the threat of rollover to the integrity of properly operated LNG storage facilities is very remote, the loss of valuable methane gas through large-scale venting during a rollover and the potential environmental impact may be undesirable.

It is believed that LNG tank rollover is due to the stable tank stratification that results when an LNG cargo is added to a tank that contains an LNG heel of different density and the two liquids are not mixed adequately during the cargo transfer; for example, in the transfer of a heavy cargo by a bottom-fill nozzle. (Density differences between cargo and heel are due to composition and temperature differences.) It is believed that soon after such an initial stratification is produced, natural convection induced by the heat leak into the tank causes the formation of distinct convection strata or cells. This kind of cell formation has been observed in heated salt solutions \(^4\). Figure 1 depicts a tank with \(n\) such cells. Once the cells are formed, turbulent transport of heat and mass across the cell interfaces drives adjacent cells toward density equilibration. However, because of the functional dependence of density on temperature and composition, adjacent cells can reach density equilibration before

![Diagram of stratified tank with cells](image-url)
temperature and composition equilibration. Temperature differences between cells are due to retained heat from the heat leak as well as to initial temperature differences between the cargo and heel. The cells are progressively higher in temperature toward the bottom of the tank. As density equilibration is approached by two adjacent cells, their interface begins to break up and the cells mix (rollover) and form a larger cell with average characteristics. This cell elimination process continues until the entire tank liquid becomes a single cell. When the last two cells mix (final tank rollover), the temperature of the evaporating top cell rises, sometimes sharply, which causes the very rapid and large boiloff rates that have been observed in LNG tank rollovers.

It is well known by now that the threat of rollover can be essentially eliminated if LNG tanks are built with both a top-fill and a bottom-fill nozzle. By use of the appropriate nozzle to transfer a given cargo, tank stratifications that could lead to an intense rollover can be avoided. There is, however, still a need for a mathematical model that describes properly the dynamics of the complex phenomenon of rollover and can accurately predict its occurrence and intensity. Such a model is a potentially powerful tool in the analysis of other rollover prevention strategies; for example, tank recirculation. The dynamic model presented here is based on the evolution of a cellular tank stratification as described above.

FORMULATION OF THE MODEL

The Equivalent Two-Component LNG Mixture

Consider a tank that contains a salt solution with a salinity gradient such that the tank has a stable density stratification. It has been demonstrated [4] that when the tank is heated from below a number of convection cells are formed as shown in Fig. 1, and that after the cells are formed, adjacent cells exchange heat and salt by interfacial turbulent transport (double-diffusive convection). A similar interfacial transport takes place in an LNG tank stratified as shown in Fig. 1. However, since LNG is a multicomponent mixture of methane (the solvent) and a large number of solutes (impurities), the interfacial transport is multidiffusive convection in this case. This is difficult to model, especially because the transport coefficients for LNG have not yet been determined. In the model presented here, LNG is represented by a simpler two-component mixture: methane (the solvent) and a fictitious solute that is equivalent, in a gross sense, to all impurities of a given LNG mixture. The interfacial transport is then modeled in terms of double-diffusive convection.

For the circumstances of interest, the density $\rho$ of an LNG mixture is essentially a function of only temperature $T$ and composition. Boyle [5] describes an interpolation method for the computation of $\rho$ when $T$ and the composition are given, and gives the required tables. (The method was first suggested by Klosek and McKinley [6], who did the original data reduction work from which Boyle compiled his tables.) It turns out that the computation suggested by Boyle can also be performed in terms of a fictitious two-component mixture of methane, with the original $x_1$ and a fictitious second component whose molecular weight $M_2'$ is given by

$$M_2' = \frac{1}{1 - x_1} \sum_{j=2}^{m} M_j x_j$$  \hspace{1cm} (1)

Consider now two LNG's (for instance, cargo and heel) that have different compositions and/or different temperatures $T_1$ and $T_2$. Let the corresponding densities computed by Boyle's method be $\rho_1$ and $\rho_2$. A fictitious two-component