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NUMERICAL STUDY ON MIXING OF SPRAYED LIQUID IN AN LNG STORAGE TANK

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SUMMARY

This paper presents a numerical method to simulate the mixing of heavier LNG sprayed on lighter layer. Numerical results for evolutions of flow field and density field are obtained in a rectangular computational domain which includes the vicinity of the liquid surface. At the surface boundary, uniform distributions of the fluid velocity and the density are assumed. Detail structure of flow caused by impingements of liquid drops are neglected. But, to trigger a realistic motion, a series of random numbers is employed. It is used as an initial distribution of the density near the surface. This method successfully gives a realistic simulation of the mixing process. Numerical result for mixing velocity shows good agreement with experimental data.

INTRODUCTION

Density of LNG varies according to its composition. When we receive LNG with different composition into a partially filled tank, they sometimes separate into two layers. This stratification should be avoided because it may cause the roll-over accident. A widely accepted way to receive heavier liquid into lighter layer is called bottom feed method, where these liquids are mixed by jet flow from a nozzle placed at bottom of the tank. In these years, top feed method is adopted at several power stations, where heavier liquid is sprayed on the lighter layer through a ring-header placed in the top space of the tank. This method is believed to be more reliable to receive heavier LNG.

Many researches have been done related to the mixing in the bottom feed method both theoretically and experimentally (refs. 1 and 2), but no reports are found for the top feed method. Some researches have been done on impingement of single drop against liquid surface (refs. 3 and 4), but there seems no research dealing with many drops and/or mass transport. In the present study, mixing process of the top feed method is investigated numerically. A color animation video will be presented at the meeting to show an evolution of the density distribution.

MODEL AND METHOD OF COMPUTATION

In the present analysis, temporal change of the distributions of velocity and density are solved in a rectangular computational domain. This domain includes the vicinity of the liquid surface. Therefore, only beginnings of the mixing can be analyzed in the present study. Governing equations employed here are vorticity transport equation, stream function equation (Navier-Stokes equations) and mass transport equation. Buoyant force due to the density difference is modeled by using Boussinesq approximation. This system is governed by three nondimensional parameters: Grashof number Gr, Reynolds number Re and Schmidt number Sc. That is,

$$Gr = g(\Delta\rho/\rho_0)L^3/\nu^2$$
$$Re = UL/\nu \ , \quad Sc = \nu/D$$

where g denotes the acceleration of gravity, $\Delta\rho$ the density difference between heavier and lighter liquid, ρ_0 the density of the sprayed (heavier) liquid, L the reference length, U the receiving velocity, ν the kinematic viscosity and D the diffusion coefficient.

Uniform distributions of the inflow velocity and the density are assumed at liquid surface, i.e. top boundary. That is, flow due to the impingement of the drops are ignored because of small scale of the flow. A thin layer with uniform density is assumed to form near the surface as a result of quick mixing. However, a nonuniform initial distribution of density is given on a grid line just below the top boundary. A series of random numbers is used to make this nonuniformity. This trick enables to obtain realistically complex solution. Uniform distribution of the velocity is given at bottom boundary. Both side boundaries are modeled as no-slip wall.

The governing equations are discretised by using a finite difference method. The transport equations for the vorticity and the density are solved by an explicit time integration method. In the present problem, mass transport will be dominated by convection because of very small diffusion coefficient. To keep high accuracy for such complex flow, Kawamura-Kuwahara scheme (ref. 5) is used to approximate convection terms. The stream function equation is solved by using the ADI method in each time step.

Some essential input data used in the present computation are as follows: $Gr=1.1\times10^{10}$, $Re=47.4$, $Sc=794$, 40x120 grids, 20000 time steps. Peclet number Pe (=ReSc) is 3.76×10^4. The reference length L (=200mm) is a width of an experimental apparatus by which a visualization experiment was carried out. Physical properties are for brine. Computation time was about 3.5 hours on a computer FUJITSU FACOM VP-2100.

RESULTS AND DISCUSSION

In the early stage of computations, we did not use any artificial initial distribution of density. But there happened no convective mixing. It is a trivial solution with only diffusion. For the next trial, we gave a seed for an initial distribution of the density. Some small value was given at only grid point on the center line just below the surface. Figure 1 shows an evolution of the density distribution for initial 4 seconds. Because this is just a trial, the lower part of the computational domain was cut off. To avoid the complication of the figure, the contour line is plotted for 0.1 (nondimensional density) only.

In the beginning of the mixing, wavy motions appear in the vicinity of the liquid surface. These motions are similar to those seen in Rayleigh-Taylor instability (ref. 6). The characteristics of this wavy motion, such as wave length, are determined spontaneously. The amplitudes of the waves increases gradually. One of the plume stands out from the others, and a mushroom-shaped plume forms. This plume reaches bottom and spreads. The density distribution is perfectly symmetrical and not very complex in contrast with the following result. We have not seen such simple and beautiful patterns in the experiment. This simplicity may come from the unrealistic boundary or initial condition.

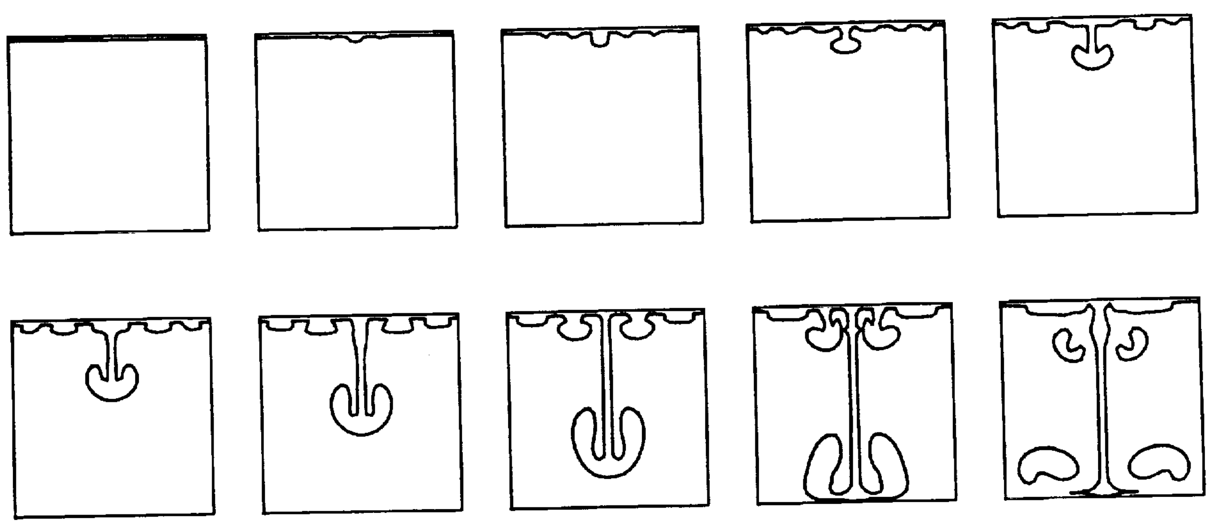

Figure 1.- An evolution of the density distribution for initial 4 seconds (a seed is given at a grid point only).

Figure 2 shows the density distributions for initial 8 seconds. The random numbers are used here for the initial distribution of the density. This evolution of the density will be also presented by the aid of a color animation video at the meeting. The color display makes it easy to understand the density distributions. In the beginning of the mixing, wavy motions appear as seen in figure 1 also. The amplitudes of the waves increases gradually, and some plumes of the heavier liquid grow. Two dominant plumes can be seen in the early stage of mixing. Finally, these mushroom-shaped plumes join into a vortical flow. After the dominant flow forms, following plumes are caught into the vortex one after another. The vortical flow develops further and the heavier part sinks downward. This feature of mixing is very similar to the observation in the experiment (ref. 7). It should be noted here that the position of the dominant plumes and the general behavior of mixing are not strongly affected by the artificial initial distribution of density.

Figure 3 shows an evolution of the density profiles in the vertical direction. The density is averaged in the horizontal direction. It is obvious that the front of the plumes moves downward. The density changes steeply at the front. This tells that the convetive mass transport is dominant compared with the diffusive transport there. The distribution is basically plateau shaped, though some unevenness is there. The heavier liquid seems to be mixed well within the vortex.

Figure 4 shows the position of the front of plumes as a function of time. The position of the front is defined here as the point where scaled density is 0.1. The velocity increases with time, and reach some value. An interest thing is that the front pause for a moment after 6 seconds mixing. This behavior was observed in the experiment also. The plume will go down with intermittent pauses. The numerical result for the average plume velocity shows good agreement with the experimental result.

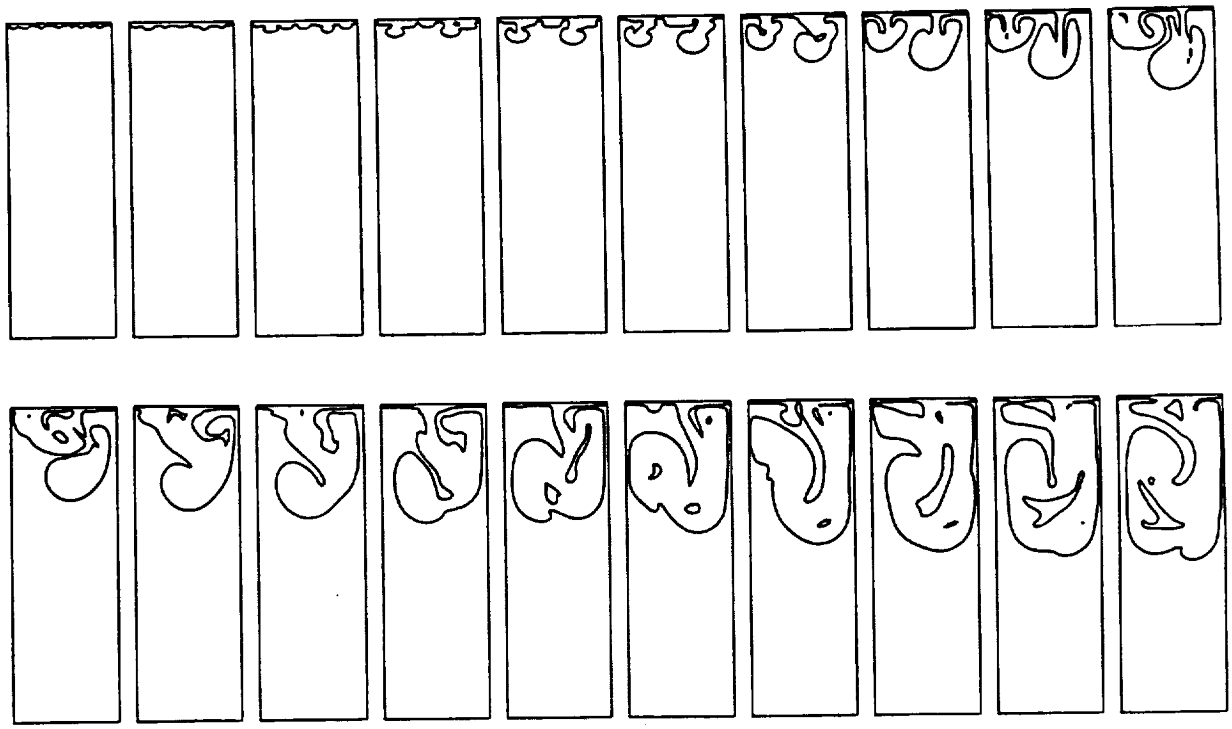

Figure 2.- An evolution of the density distribution for initial 8 seconds (a series of random numbers is used to specify initial distribution of density near free surface).

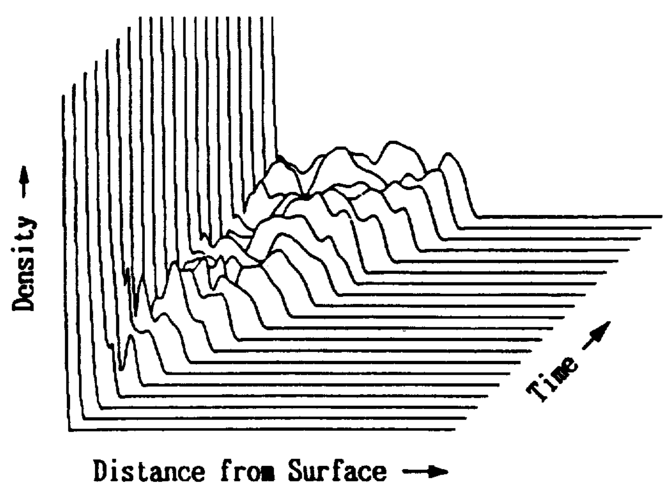

Figure 3.- A temporal change of the density profile.

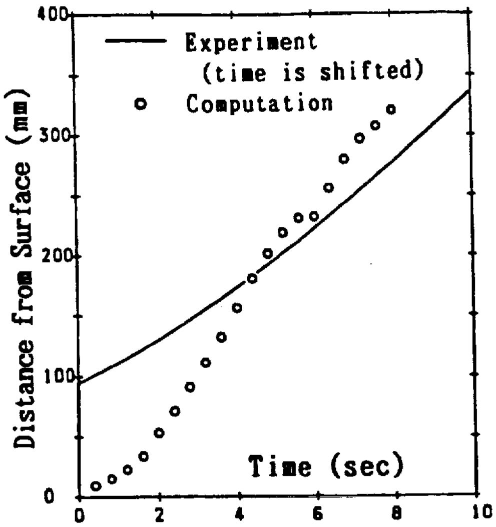

Figure 4.- Position of the front of the plumes as a function of time.

CONCLUSIONS

The mixing process of heavier liquid sprayed on the lighter layer has been analyzed numerically. The temporal change of the flow field and the density field are obtained. Realistically complex process is successfully predicted by using a series of random numbers for the initial condition. The present simulation catches the features, the momentary pause of the plumes' front, which is observed in the experiment. The numerical result for the plume velocity shows good agreement with the experimental result.

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