Current Status of Mixed LNG Storage Technology Development

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Back Ground

LNG demand in the world has been increasing and expected from current 170 million tons per annual. With this, the natural gas development, especially, unconventional natural gases, as known as shale gas, tight-sand gas, and coal bed methane, are increased.
In the result, various LNG will have been received and treated by LNG receiving terminal.
The current LNG storage tanks have bottom and top filling nozzle, and these nozzles are used for stratification prevention.
The concept of LNG receiving operation on the current LNG storage tanks is shown as Fig.1.
If cargo LNG density is higher than heel LNG density in LNG storage tank, the top filling nozzle (abbr; "T" in Fig.1) is used for receiving operation. And if cargo LNG density is lower than heel LNG density, the bottom filling nozzle (abbr; "B" in Fig.1) is used for it.
On the other hand, some Tokyo-gas primitive LNG storage tanks have only bottom filling nozzle.
Therefore, receiving way and the stratification condition of primitive LNG storage tanks have to be confirmed for diversified LNG sources.

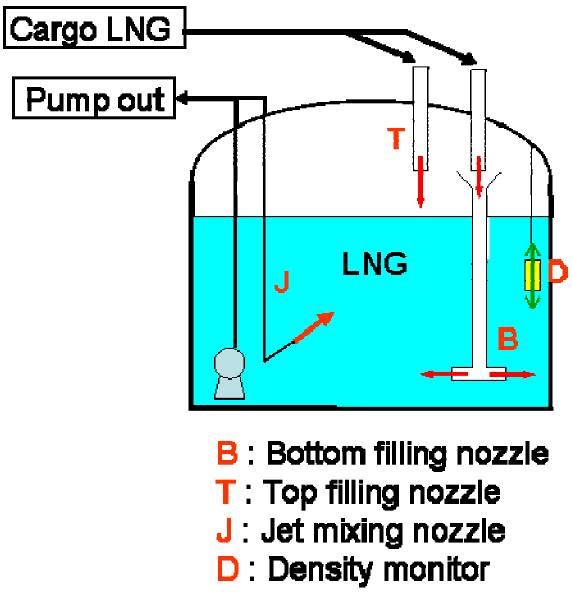

Fig.1 Facilities of LNG storage tank

Aims

LNG storing with different densities needs careful observation due to the possibilities of stratification followed by rollover. To prevent the damage to LNG facilities by rollover, the simulation of LNG stratification and rollover has become one of the essential technologies for those LNG receiving terminals.
Therefore, we study on tank reception procedures with bottom filling nozzle for different density LNG by using Computational Fluid Dynamics (CFD) simulation in order to confirm the bottom feed criteria to prevent stratification.

Methods

a. Analysis target

The analysis target is mixing behaviour between heel LNG and the cargo LNG with heavier density in LNG storage tanks. Especially, we focused behaviours of boil-off gas (BOG) spooled up with cargo LNG in bottom filling nozzle, because these spooled up BOG bubbles have not only buoyancy but also drag force of inter-phase friction.

Notable physical quantities are density, temperature, velocity, volume fraction and variation with time of void rate from BOG bubbles, boil off gas generation.

b. Analysis measure

Simulation with computational fluid dynamics is basically used, and actual measured data and experience is aided as necessary.

c. Software

- Heat transfer and fluid analysis software for the simulation of computational fluid dynamics
- Process simulation software for the estimation of LNGs properties

d. Hardware

- Parallel computer (8CPU is implemented)

e. Model and Condition

To develop a numerical model of mixing behaviour of different density LNGs in a vertical cylindrical tank, Multicomponent Multiphase Inhomogeneous Model in CFD software is used. In this study, three fluid model is introduced which consists of cargo LNG, heel LNG and BOG.

Governing equations are as follows.

Continuity equation:

$$\frac{\partial}{\partial t}(r_\alpha \rho_\alpha) + \nabla \bullet (r_\alpha \rho_\alpha \mathbf{U}) = S_{MS\alpha} \qquad (1)$$

where $\sum_{\alpha=1}^{N_P} r_\alpha = 1$ (2)

N_P =2, for LNG and BOG.

No inter phase mass transfer is assumed.

Momentum equation:

$$\frac{\partial}{\partial t}(r_\alpha \rho_\alpha \mathbf{U}_\alpha) + \nabla \bullet (r_\alpha (\rho_\alpha \mathbf{U}_\alpha \otimes \mathbf{U}_\alpha)) = -r_\alpha \nabla p_\alpha + \nabla \bullet \left(r_\alpha \mu_\alpha \left(\nabla \mathbf{U}_\alpha + (\nabla \mathbf{U}_\alpha)^T\right)\right) + \mathbf{S}_{M\alpha} + \mathbf{M}_\alpha \qquad (3)$$

where $\mathbf{M}_\alpha = \sum_{\beta \neq \alpha} \mathbf{M}_{\alpha\beta}$ (4)

Newtonian fluid is assumed.

Thermal energy equation:

$$\frac{\partial}{\partial t}\left(r_\alpha \rho_\alpha h_\alpha\right)+\nabla \bullet\left(r_\alpha\left(\rho_\alpha \mathbf{U}_\alpha h_\alpha-\lambda_\alpha \nabla T_\alpha-\sum_{i=A,B,C\ldots}^{N_C} \rho_{i\alpha} D_{i\alpha} h_{i\alpha,tot} \nabla Y_{i\alpha}\right)\right)=Q_\alpha+S_\alpha \qquad (5)$$

Compression work is neglected.

Component conservation law:

Behaviours between cargo LNG and heel LNG is described as this equation (6)

$$\frac{\partial}{\partial t}\left(r_\alpha \rho_\alpha Y_{A\alpha}\right)+\nabla \bullet\left(r_\alpha\left(\rho_\alpha \mathbf{U}_\alpha Y_{A\alpha}-\rho_\alpha D_{A\alpha} \nabla Y_{A\alpha}\right)\right)=S_{A\alpha}, \quad \sum_{i=A,B,C\ldots}^{N_C} Y_{i\alpha}=1 \qquad (6)$$

where, N_c =2, for cargo LNG and heel LNG.

Turbulence model:
Standard $k-\varepsilon$ turbulence model is used.
In this model, μ in Eq.(3) is written by $\mu=\mu_l+\mu_t$, while λ_α in Eq.(5) by $\lambda_\alpha=\lambda_{l\alpha}+\lambda_{t\alpha}$, where subscript l refers to laminar, t to turbulent. μ_t is determined by $k-\varepsilon$ model, while $\lambda_{t\alpha}$ is given by $\lambda_{t\alpha}=\mu_t C_{p\alpha}/P_{rt\alpha}$, where $P_{rt\alpha}$ is Turbulent Prandtl number.

Buoyancy:
Buoyancy caused by the density difference is essential in this model. For buoyancy calculations, a source term is added to the momentum equations as follows:

$$\mathbf{S}_M=(\rho-\rho_{ref})\mathbf{g} \qquad (7)$$

where ρ_{ref} is the reference density.

Physical properties:

Most LNG is composed of CH_4, C_2H_6, C_3H_8, C_4H_{10}, C_5H_{12} and N_2. On condition that p_0 is constant, each LNG is assumed as a pure substance of which all physical properties are constant, except for ρ_α (Eq.(8)), λ_F (Eq.(9)) and T_b (Eq.(10)).

$$\rho_\alpha=a_\alpha T+b_\alpha \qquad (8)$$

$$\lambda_F=cT_b+d \qquad (9)$$

$$T_b=er_\alpha+f \qquad (10)$$

where $a_\alpha, b_\alpha, c, d, e$ and f are constant.

Boundary conditions:
The liquid surface is assumed to be free- slip wall, while bottom and side-wall are no-slip. As liquid becomes deeper while filling, Moving Boundary option in the CFD software is used at the surface. The heat fluxes through tank walls, even in well insulated, cause convection and boil-off of the LNG. In this study, both the input heat fluxes and the removed latent heat caused by boil-off are taken into accounted, while the removed vapor mass is neglected. To estimate the rate of boil-off, Hashemi model[3] is used.

Hashemi model:

The boil-off rate m is given by

$$m = k_h C_h A(T_s - T_b)^{4/3} \tag{11}$$

Therefore, the heat flux through the surface caused by boil-off is $m l_F / A$ [W/m2].

Inter-phase friction force:

Ishii-Zuber Drag Model in CFD software is used as the model of drag force into interphase.

Interphase thermal transfer:

Two resistance model in CFD software is used. And Nusselt number is set by Ranz Marshall Model.

Calculation scheme

For transient term calculations, Second Order Backward Euler option in CFD software is used, while for advection term, High Resolution option is used.

Results

The density contour (Fig.2) shows that heavier LNG received from bottom filling nozzle is shaped as a gradual slope by buoyancy and a drag force by inter-phase friction force. Comparison of the calculated density and temperature profiles with the measurements by the actual receiving operation is shown in Figure 3, 4. These curves are matched very well.

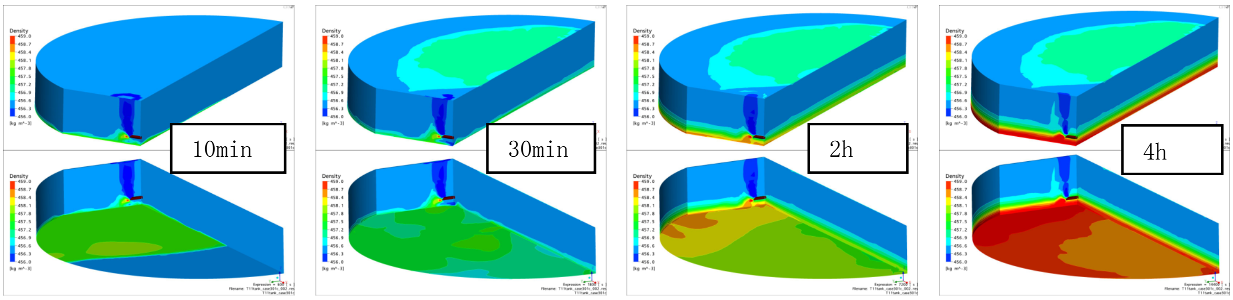

Fig.2 Density contour (10min, 30min, 2hour, 4hour)

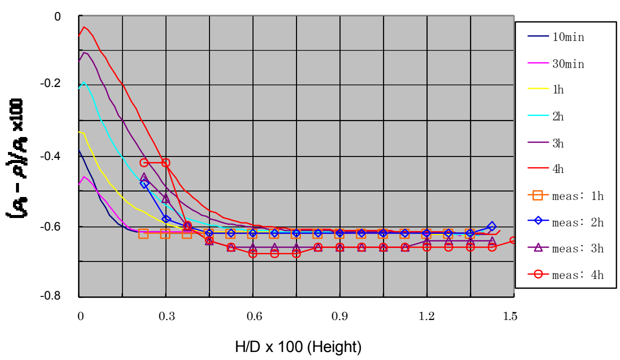

Fig.3 Comparison between calculated density profiles and measurements

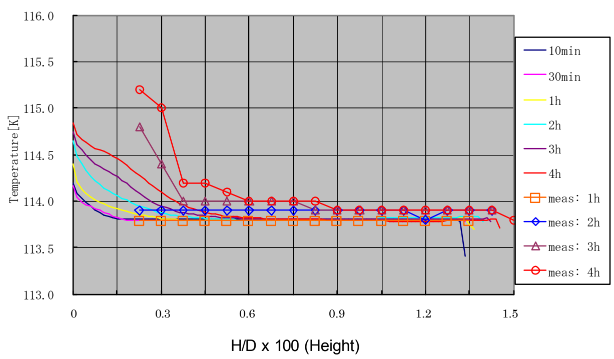

Fig.4 Comparison between calculated temperature profiles and measurements

Summary

The analysis result by two phase flow model is almost fit in the actual operation data.
The LNG terminals of Tokyo Gas continue to have flexibility for all kinds of LNG, which is a result of our strong experience of 40 years handling LNG, our development of technologies such as CFD simulation, and human resources who can manage the issues caused by the emerging changes in the LNG industry.

NOMENCLATURE

A : Section area of LNG tank [m^2]
C_h : Hashemi constant [kg/m^{2}K$^{4/3}$s]
C_P : Specific heat capacity at constant pressure [J/kgK]
D : Diffusion coefficient [m^2/s]
$\mathbf{g}$: Gravity vector [m/s^2]
h : Enthalpy [J/kg]
k_h : Correction coefficient of Ch [-]
$\mathbf{M}$: Interphase momentum transfer [kg/m^{2}s^2]
m : Boil-off rate [kg/s]
N_P : Total number of phases [-]
p : Pressure [Pa]
p_0 : Vapor pressure in LNG tank [Pa]
Q : Interphase heat transfer [W/m^3]
r_a : Volume fraction of phase a [-]
S : Heat source [W/m^3]
$\mathbf{S}_M$: Momentum source [kg/m^{2}s^2]
S_{MS} : Mass source [kg/m^{3}s]
T : Temperature [K]
T_b : Boiling point of LNG at the surface [K]
T_S : Bulk liquid temperature [K]
$\mathbf{U}$: Vector of velocity [m/s]
Y : Mass fraction of component [-]
l : Thermal conductivity [W/mK]
l_F : Latent heat of boil-off of LNG [J/kg]
m : Viscosity [Pa・s]
r : Density [kg/m^3]
A : Subscript, refers to component A
a : Subscript, refers to phase a

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