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LNG MIXING BEHAVIORS INCLUDING BUBBLES OBSERVED DURING THE BOTTOM FILLING OF HEAVIER LNG IN LNG MIXED STORAGE

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Tokyo Gas has succeeded in becoming the first in the world to observe and record visually the phenomenon where heavier LNG deposited from the bottom-filling nozzle in an LNG tank under operation did not remain at the bottom of the tank and moved against gravity to rise to the top.
The observation of this unique and physically contradictory phenomenon was performed under the condition where heavier LNG was intentionally deposited from the bottom-filling nozzle, unlike the ordinary operation to promote mixing. An LNG tank internal observation device, the only one in the world and developed by Tokyo Gas, made it possible to successfully observe and visually record the phenomenon. The results clearly show that heavier LNG rises from the bottom nozzle. It was also observed that bubbles appeared to mix with the LNG during the filling of the storage tank.
This paper describes LNG mixing behaviors focusing on these results.
In clarifying this phenomenon, depositing heavier LNG from the bottom of a storage tank, which is considered to always cause stratification, will become possible in a safe manner. With the detailed clarification of the mechanism and its application to a simulation model now being researched, it is expected that this achievement will contribute to further growth of the LNG industry through use of simulation technology developed by Tokyo Gas.

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1. Introduction

Tokyo Gas has succeeded in becoming the first in the world to observe and record visually the phenomenon where heavier LNG deposited from the bottom-filling nozzle in an LNG tank under operation did not remain at the bottom of the tank and moved against gravity to rise to the top.

In recent years, the LNG market has expanded and diversified rapidly in terms of production sites, LNG specifications, contract forms, and so on. Under such circumstances, LNG mixed storage technology provides great benefits enabling the storage of various types of LNG safely in a single tank.
In LNG mixed storage, it is necessary to avoid stratification which may cause rollover. In order to promote mixing, the depositing lighter LNG from the bottom of tanks and depositing heavier LNG from the top of tanks are the basic operations for filling storage tanks. However, because mixing behaviors depend on the specifications and filling conditions of each tank, stratification cannot be prevented from occurring in some cases under these basic operations. Therefore, Tokyo Gas simulates and predicts the performance of each tank for LNG mixed storage ahead of time.
Furthermore, heavier LNG is sometimes intentionally deposited from the bottom-filling nozzle, for example, in the case where a tank has no top-filling nozzle or for the purpose of suppressing the generation of Boil Off Gas (BOG) in new tanks with a top-filling nozzle, and so on. Based on common knowledge in physics, depositing heavier LNG from the bottom of a tank will always result in stratification. However, in certain conditions, stratification does not occur. Although Tokyo Gas fully understands the conditions for avoiding stratification through a large amount of operation data as well as testing data on actual tanks, the reason of this physically contradictory phenomenon is yet to be explained.
To study the mixing behaviors of depositing heavier LNG from the bottom of a tank, we therefore observed the inside of an LNG tank under operation using a tank internal observation device. Through this process, we discovered how heavier LNG moves against gravity and rises towards the surface.
This paper describes LNG mixing behaviors focusing on this observation result..

2. LNG Mixing Storage Technology

When LNG of a density different from that of heel LNG (the LNG already in the tank) is deposited into a tank, stratification may occur. Left untouched, this situation may result in rollover, which causes damage to LNG tanks. “LNG mixed storage” is to store various types of LNG safely in one tank without stratification.
Stratification is the formation of two or more layers in a tank due to differences in LNG density. As shown in Fig.1, once stratification occurs, each layer begins its own heat convection, and heat and mass are slowly transferred between the layers. When those layers disappear and mix together, the heat energy (enthalpy) accumulated in the lower layer is released in the form of a large amount of BOG over a short period. This phenomenon is called “rollover.” In the case where the amount of BOG exceeds BOG compressor capacity, a safety valve may be triggered or a tank can become damaged.

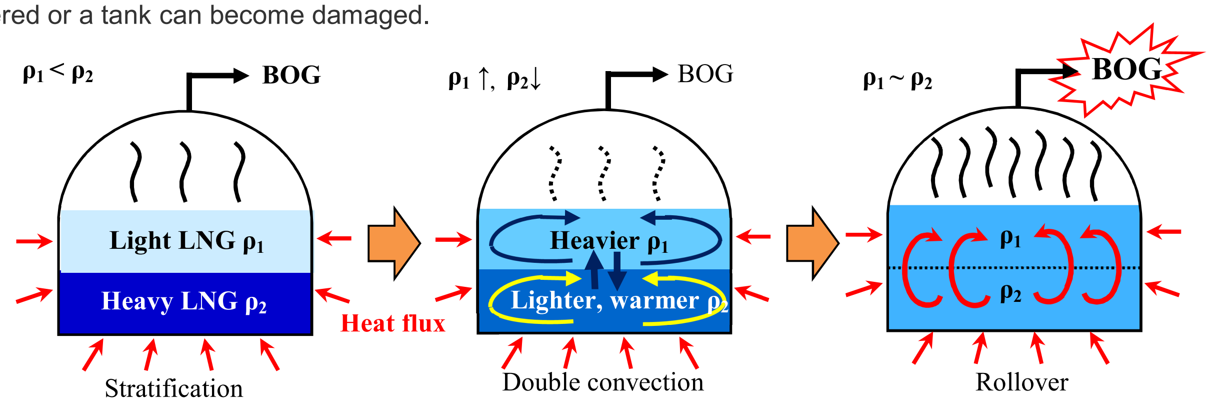

Fig. 1 Schematic of Stratification and Rollover

In LNG mixed storage, it is necessary to predict the mixing conditions of different-density LNGs in the tank quantitatively and use those figures as guidelines for operation.

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An LNG tank is often equipped with both top- and bottom-filling nozzles (Fig. 2). A filling operation that promotes further mixing is usually selected, such as depositing lighter LNG from the bottom of a tank or depositing heavier LNG from the top of a tank. Even in such operations, stratification may occur as mixing behaviors depend on tank specifications and filling conditions. Tokyo Gas utilizes a simulation technology based on numerical fluid dynamics (CFD: Computational Fluid Dynamics) to estimate ahead of time the LNG mixed storage performance of each tank (Ref. (1) to (5)). This simulation technology for prediction is the only such technology in the world and its reliability has been regularly enhanced through validation of large amounts of operating data and the 30 years of experience Tokyo Gas has in mixed storage.

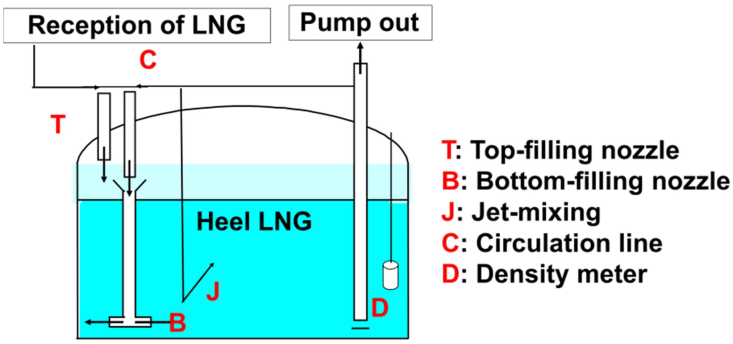


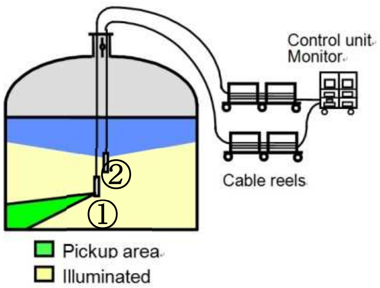
Fig. 2 Illustration of LNG Storage Tank

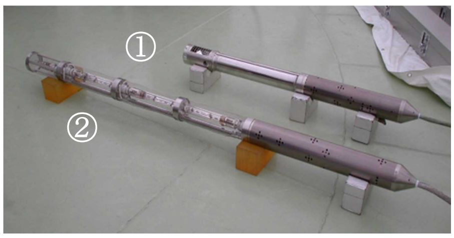
3. Depositing Heavier LNG from the Bottom of a Tank and Its Simulation

In addition to standard filling operations to promote mixing as mentioned above, heavier LNG may also be deposited from the bottom nozzle. This operation is selected, for example, in the case where an old tank has no top nozzle, or to minimize the generation of BOG even in the latest tanks that have a top nozzle.
Based on common knowledge in physics, depositing heavier LNG from the bottom of a tank is considered an extremely risky operation that intentionally triggers stratification. A famous incident at La Spezia (1971) occurred as a result of unintentionally depositing heavier LNG from the bottom nozzle (Ref. (6)). However, we know empirically the fact that even in depositing heavier LNG from the bottom of a tank, stratification will not occur under certain conditions. As with other filling methods, Tokyo Gas has researched conditions that can prevent stratification in specific tanks using large amounts of operation data and testing data in actual tanks. We have also been developing a simulation model in order to make possible prediction of this mixing condition in each tank. However, due to the lack of process data, it was not possible to understand this mixing phenomenon and develop a simulation model that can explain the reasons for this physically contradictory result.
We decided therefore to study this mixing phenomenon in depositing heavier LNG from bottom of a tank by directly observing the inside of a tank, which proved successful in actual use cases of depositing heavier LNG from the top of tanks (Ref. 1, a different filling method).

4. Observation Method

(1) Observation Device
We used LNG tank internal observation devices (Fig. 3, Ref. (7), (8), (9)) developed by Tokyo Gas for the first time in the world. This is the only device in the world capable of recording video of LNG in the form of both gas and liquid (LNG) in a cryogenic tank.





①: Camera unit(CCD)
4B, 1.2m, 18kg
②: Illumination unit
4B, 2.0m, 18kg

Fig. 3 Observation Device Used in LNG Tank Interior

(2) Observation conditions
LNG heavier than heel LNG was deposited from the bottom nozzle of the tank and the filling operation was directly observed using this device. In order to reduce the risk of stratification, the density-difference between the heel LNG and the LNG being deposited was set to 10 kg/m3 or less. Under these conditions, depositing from the top of the tank is generally selected in normal operation.

(3) Tank specifications
In order to deposit heavier LNG, which should originally be deposited from the top nozzle, from the bottom nozzle, we selected a tank with a density meter, a jet-mixing device, etc., that can deal with the risk sufficiently. Table 1 shows the main specifications.

Table 1: Observation Tank

Capacity [m^3]	Diameter [m]	Maximum Liquid level [m]	Top-filling nozzle	Jet mixing device	Density meter
130,000	64	40	Yes	Yes	Yes

(4) Measured data
Various sensors were also used in addition to the visual observation conducted with video equipment. The density distribution, liquid level, flow rate in the tank, etc. were measured.

5. Tank Internal Observation Result

(1) Observation result (video)
Internal observation of the LNG tank revealed the following behaviors of the heavier LNG in the tank (Fig. 4).

a. Rising of heavier LNG
There appeared “white turbidity” consisting of bubble-mixed LNG ejected from the bottom nozzle, but it disappeared as the heavier LNG rose. It could be observed that bubble-mixed LNG gradually changed in appearance to a “heat haze” while rising (Fig.4-1). This heat haze enabled observation of the path of the liquid flow rising in the tank against gravity.

b. Amount of bubbles ejected from the bottom-filling nozzle with deposited LNG
The amount of bubbles mixed with deposited LNG decreased as time passed, disappearing over several hours (Fig.4-1, 4-2, 4-3).

c. Change of flow direction
The direction of the flow was observed as gradually changing toward horizontal as time passed (Fig.4-1, 4-2, 4-3).

*Near the bottom nozzle in the early stage of filling.

*There appeared “white turbidity” consisting of bubble-mixed LNG ejected from the bottom nozzle, but it disappeared on the way up.

*Bubble-mixed LNG gradually changed in appearance to a “heat haze” while rising.

Fig. 4-1 Observation Image (1)

*One hour after Fig. 4-1.

*The amount of bubbles ejected from the nozzle with deposited LNG decreased, and the flow of liquid slightly changed to a horizontal direction as compared with the initial stage.

Fig. 4-2 Observation Image (2)

*Several hours after Fig. 4-2.

*Further decrease in bubbles ejected from the nozzle with LNG.

*The flow direction indicated by the heat haze changed to more horizontal.

*The number "43" written on the tank wall and previously hidden behind the heat haze in Fig. 4-1 and Fig. 4-2 gradually became visible.

Fig. 4-3 Observation Image (3)

(2) Measurement data (density distribution)

Measurement data obtained from the tank are as shown in Fig. 5 and 6.

As for the liquid density distribution, almost no density difference occurs in the tank. Despite depositing the heavier LNG from the bottom of the tank, it can be observed that the entire tank is well mixed without the heavier LNG lingering at the bottom.

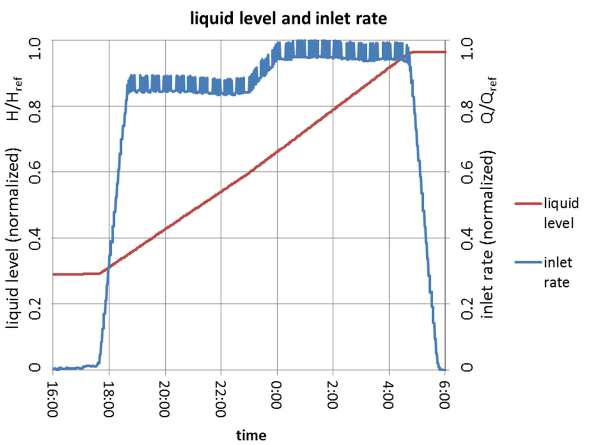


Fig. 5 Receiving Flow Rate and Liquid Level

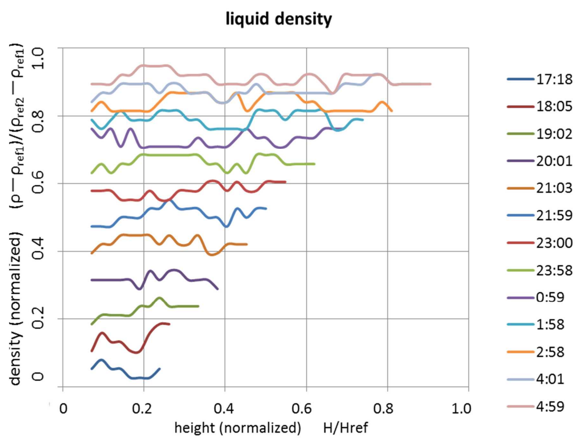


Fig. 6 Liquid Density Distribution in the Tank

6. Discussion

As shown in the previous chapter, it was observed that heavier LNG, which should physically stay around the bottom due to gravity, rose in the tank, and bubbles were ejected together with heavier LNG from the bottom-filling nozzle in the bottom-filling operation. Discussion on this phenomenon is as follows.

(1) Rising of heavier LNG
Bubbles were observed being ejected from the bottom-filling nozzle with the deposited LNG. It is considered that the buoyancy of the deposited LNG with bubbles lifts the heavier LNG as it is no longer heavier than the heel LNG (Fig. 7).

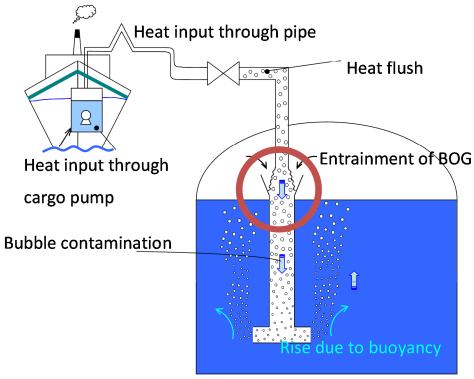


Fig. 7 LNG Behavior When Depositing LNG from the Bottom of the Tank

(2) Amount of bubbles ejected from the nozzle
Bubbles ejected from the bottom-filling nozzle with deposited LNG seem to consist of BOG partly generated due to flushing from heat input to the LNG through the cargo pumps, piping walls and so on. On the other hand, BOG was partly entrained through the funnel portion of the bottom-filling pipe (indicated by a circle in Fig. 7).
It was also observed that the amount of bubbles ejected from the filling nozzle decreases as time passed. It is considered that the bubbles collapsed due to head-pressure as the level of liquid in the tank became higher.

(3) Mixing behavior in the tank
According to the data of depositing heavier LNG from the bottom of the tank, it is shown that the liquid in the tank was well mixed throughout the process of filling (Fig. 6). The reason is considered as follows.

In the early stage of the filling operation, the density-difference between the heel LNG and the deposited LNG in the tank was large, however the amount of bubbles ejected from the nozzle was also large due to the lower liquid level of the deposited LNG. It is for this reason that mixing in the tank is promoted. On the other hand, in the latter stage of filling, the amount of bubbles decreased due to the high liquid level of the deposited LNG. However, mixing in the tank continued as the density-difference between the deposited LNG and surrounding LNG had sufficiently decreased.

(4) Application in simulation modeling
The amount of ejected bubbles from the bottom-filling nozzle changed depending on the liquid level, the liquid velocity, density-difference, etc. During the filling operation, the buoyancy acting on the deposited LNG also changed in accordance with to the amount of bubbles, density of surrounding LNG, and so on. Therefore, it is extremely difficult to predict whether the mixing will complete or ultimately lead to stratification. Detailed clarification of the mechanism and its application in a simulation model is being researched by Tokyo Gas. We expect that the mixing behavior of depositing heavier LNG from the bottom of the tank will be predictable by simulation.

7. Conclusions

The observation data successfully obtained by Tokyo Gas in video-recording an LNG tank under operation will lead to a deeper understanding of the mixing mechanism of depositing heavier LNG from the bottom of storage tanks.

The obtained data will add tremendous benefits to LNG mixed storage technology. For example, it will increase the flexibility of LNG procurement and LNG tank operation as it will enable reception of LNG with a wider range of density, as well as contribute to decision-making for more effective utilization of existing LNG tanks without the construction of new LNG tanks, BOG processing equipment, and so on. With this detailed clarification of the mechanism behind this phenomenon and its application to a simulation model now being researched, this achievement is expected to contribute to further growth of the LNG industry through use of simulation technology developed by Tokyo Gas.

8. References

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