RE–GASIFICATION SIMULATION OF NGH PELLETS INSIDE A TRANSPORT SHIP IN EMERGENCY

Go Oishi*, Kiyoshi Shimada
Akishima Laboratories (Mitsui Zosen) Inc
1-50, Tsutsujigaoka 1-chome Akishima, Tokyo 196-0012
JAPAN

Isao Yoshino, Takashi Nakata and Shinya Yuasa
Mitsui Engineering & Shipbuilding Co., Ltd
3-16, Nihonbashi 1-chome Chuo-ku, Tokyo 103-0027
JAPAN

ABSTRACT
Mitsui Engineering & Shipbuilding Co., Ltd. (MES) has been developing a natural gas hydrate pellet carrier. Rapid re-gasification of the pellets within the ship shall be required in emergency such as a breakdown of unloading devices in order to repair the devices under air circumstances after dissociating the pellets and excluding methane gas in cargo holds. A computer code, based on simplified Navier-Stokes equation and heat transfer relation including phase changes among solid, liquid and gas, has been developed to simulate re-gasification and dissolution process of NGH pellets due to water injection into cargo hold. Freeze-up of injection water, which might occur because of massive cold pellets, is major concern in re-gasification operation. Two ways of water injection are investigated in laboratory tests with simplified cargo hold models and methane gas pellets: one is vertical injection with spray from the hold top and the other is sideward injection from the hold wall. The simulation code incorporating water freezing model validated in the test has made it possible to grasp a phenomenon of re-gasification due to water injection in the huge cargo hold of an actual ship and to finally design an actual ship cargo hold equipped with an emergency re-gasification system. In addition, a concept design of a re-gasification NGHP carrier, re-gasification of which is carried out for normal operations in cargo holds without onshore re-gasification facilities, is newly introduced.

Keywords: gas hydrate pellet carrier, emergency re-gasification, water injection, Freeze-up

NOMENCLATURE

\( u, v, w \): Fluid velocity of \( x, y, z \) coordinate
\( \varepsilon \): liquid phase rate
\( T_w \): Water temperature
\( T_s \): Surface temperature of pellet
\( q_w \): Heat input into pellet
\( d_{p0} \): Initial diameter of pellet
\( d_p \): Diameter of pellet
\( P_w \): Water pressure
\( A_P \): Area of heat transfer
\( Nu \): Nusselt number
\( \lambda_w \): Thermal conductivity of water
\( \mu_w \): Viscosity coefficient of water
\( \rho_w \): Density of water
\( C_{p_w} \): Specific heat of water
\( g \): Gravitational acceleration
\( dt \): Time interval

* Corresponding author: Phone: +81 42 545 3112 Fax +81 42 545 3113 E-mail: go-oishi@ak.mes.co.jp
INTRODUCTION

Necessity of the development of small and medium-sized gas fields, many of which have been found in Southeast Asia, has been sharply rising due to strong demand for natural gas. A natural gas transportation chain with natural gas hydrate (NGH) is expected to be a great player in realizing the development. The present paper is related with re-gasification phase, the final phase of the chain, which consists of manufacturing, transportation, storage and re-gasification of NGH pellets.

Mitsui Engineering & Shipbuilding Co., Ltd. (MES) is developing a NGH carrier equipped with a mechanical unloading system for NGH pellet bulk. In case of breakdown of the unloading system, NGH pellets must be gasified safely and promptly, which could be done by injecting a large amount of water into cargo holds. It is, however, worried that water injection operations may malfunction due to freeze up of injection water passage, resulting from latent heat of the massive NGH pellets.

Therefore, re-gasification simulation code is under development, aiming to investigate how massive NGH pellets in the holds gasify with injection water and finally to seek a safe and prompt gasification system.

RE-GASIFICATION SIMULATION

Outline of simulation

The simulation has been done solving Navier-Stokes (NS) equation of incompressible flow and heat conduction equation by means of three-dimensional finite difference technique. It is assumed that physical quantities, such as flow velocities, pressure and temperature, are uniform in each cell and pellets situated in upper part of the hold go down successively, occupying vacancy of dissolved pellets up to a fixed solid occupying rate.

Heat transfer between NGH pellets and water flow and then phase change between water and ice is simulated based on dissolution test of crammed NGH pellets in water flow. Four phases, which are pellet, ice, water and gas, are dealt with, though dissociated gas is promptly removed from the analyzing cells. Flow of the simulation is shown in Figure 1.

Governing equations

Adopting Stokes approximation, NS equation is simplified as shown below: equation of continuity (1), equations of motion (2) to (4), equation of energy conservation (5) and heat convection equation (6). Unknown quantities to be solved are \( u, v, w \) (fluid velocities toward \( x, y, z \) coordinates), \( \varepsilon \) (liquid phase ratio), \( T_w \) (water temperature) and \( q_{in} \) (heat input into pellet).

\[
\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = \frac{\partial \varepsilon}{\partial t} \tag{1}
\]

\[
\frac{1}{\varepsilon} \frac{\partial \varepsilon u}{\partial t} = - \frac{1}{\rho_w} \frac{\partial P_w}{\partial x} - \beta, \tag{2}
\]
Diffusion terms in equations (2) to (4) are replaced by an empirical equation (Ergun equation [1]), which is derived for a flow through crammed particles as follows.

\[
\frac{1}{\varepsilon} \frac{\partial \nu}{\partial t} = - \frac{1}{\rho_w} \frac{\partial P_w}{\partial \nu} - \beta_x
\]

(3)

\[
\frac{1}{\varepsilon} \frac{\partial w}{\partial t} = - \frac{1}{\rho_w} \frac{\partial P_w}{\partial z} - \beta_z - g
\]

(4)

\[
\frac{\partial T_w}{\partial t} + u \frac{\partial T_w}{\partial x} + v \frac{\partial T_w}{\partial y} + w \frac{\partial T_w}{\partial z} = \frac{\lambda_w}{\rho_w C_p_w} \left( \frac{\partial^2 T_w}{\partial x^2} + \frac{\partial^2 T_w}{\partial y^2} + \frac{\partial^2 T_w}{\partial z^2} \right)
\]

(5)

\[
q_{in} = \frac{Nu A_p \lambda_w}{d_p} (T_w - T_S)
\]

(6)

Since Nu, heat transfer coefficient, in equation (6) is strongly related with co-existent bubble quantity, Nu should be specified with hydrate ratio of the pellets. Nu of the pellet whose hydrate ratio equals to zero, corresponds to that of Ranz equation [2] (NuI: Nu of crammed ice pellets), and Nu of the pellet whose hydrate ratio equals to 60%, is calculated by experimental results (NuP: Nu of fixed bed of NGH pellets) that was obtained by research of NGH gasification [3]. In-between Nu can be calculated by interpolating the two values above. Then, the temperature of the pellet is calculated from heat transfer obtained by the equation (6), and the dissociation rate of NGH pellets corresponding to the temperature can be obtained. For obtaining the dissociation rate of pellets, the value of Mitsui Zosen Technical Review (2006) was used [4, 5, 6].

**EXPERIMENT WITH MODELS**

**Outline of experiment**

Model experiments were carried out, where water was injected into the hold model filled with Methane Gas Hydrate (MGH) pellets as a substitute of NGH pellets. Purposes of the experiments are as follows.

a) observation of gasification process, aiming to find problematic phenomena, which may malfunction gasification operation

b) acquisition of fundamental data to validate the simulation code

Measured items are as follows.

1) amount of dissociated gas
2) quantity of injection water at the model inlet
3) water temperature in the reservoir
4) water temperature (9 points at the bottom of hold model and 4 points at the drain pipe)

Photos of MGH pellets, a freezing chamber, where the experiment was conducted, and the hold model are shown in Figure 2, Figure 3 and Figure 4, respectively.
Three patterns of water injection were tried in the experiment. Measuring points of water temperature are shown schematically in figures below.

**Flow type A**
Sideward injection from the hold wall (lower horizontal flow)

**Flow type B**
Vertical injection with spray from the hold top (sprinkling water)

**Flow type C**
Sideward injection from the hold wall and vertical injection with spray from the hold top (lower horizontal flow and sprinkling water combined)

Re-gasification experiment was conducted for three cases shown in Table 1.

<table>
<thead>
<tr>
<th>Case</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Flow type</strong></td>
<td>A</td>
<td>B</td>
<td>C</td>
</tr>
<tr>
<td><strong>Pellet weight</strong></td>
<td>51.2kg</td>
<td>51.6kg</td>
<td>50.8kg</td>
</tr>
<tr>
<td><strong>Filling ratio</strong></td>
<td>0.55</td>
<td>0.52</td>
<td>0.54</td>
</tr>
<tr>
<td><strong>Hydrate ratio</strong></td>
<td>58.3%</td>
<td>55.1%</td>
<td>62.0%</td>
</tr>
<tr>
<td><strong>Quantity of flow</strong></td>
<td>0.2L/s</td>
<td>0.2L/s</td>
<td>0.2L/s + 0.2L/s</td>
</tr>
<tr>
<td><strong>Temperature of injection water</strong></td>
<td>12.5°C</td>
<td>15.0°C</td>
<td>13.0°C</td>
</tr>
</tbody>
</table>
Results of experiments

Flow type A

Successive downward movement of the upper pellets to occupy the vacancy of dissolved lower pellets, which is assumed in the analysis, was not seen. Pellets frozen to the hold walls did not go down smoothly in the experiment, forming a tunnel flow without pellets. One reason for the phenomenon is that the hold model is a partial model and small compared with full-scaled hold and then a consolidated pellet pack bridged between walls. The downward movement of consolidated pellet pack might be successive in the full-scaled hold, different from in the small-scaled model.

Flow type B

A spray flow over the entire pellets has large heat transfer area on the pellets, which brought about strong freezing in the center part. Once pellet bulk strongly freezes in the center part, the spray flow has a tendency to detour along the walls without penetrating into the pellet bulk.

On the other hand the water flow between the wall and pellet bulk prevented the above-mentioned bridge formation. A photo of spray flow experiment is shown in Figure 8.

Flow type C

Flows on the walls in case 3 prevented bridge formation and gasification was as smooth as in case 2.

COMPARISON OF RESULTS

To confirm validity of the simulation code, calculation results are compared with the experimental results for the three cases. In these calculations, the number of cells representing calculating domain is 8,000. Time series of the calculation and the experimental result for case1, case2, and case3 are shown in Figure 9, 10 and 11, respectively. Drain temperatures in the Figures are shown as average values at the four points, 11 to 14.

In Figure 9, it is confirmed the experimental result of the gas flow rate was unstable. As a cause of the above result, it is considered that the gasification and the collapse of the pellet bulk occurred intermittently in the experiment, and the heat transfer between the pellet and the water flow was always not constant.

As seen in the Figures, it is confirmed that the experimental results and the calculation ones of the gas flow rate correspond roughly well to each other. As time elapses, the experimental water temperatures at the drain begin to separate from the calculation ones and the experimental gas flow rates abruptly decrease for case 2 and case 3. This is probably because the spray flow takes a short cut to the drains in the experiment, detouring consolidated pellet bulk.

Agreement between simulation and experimental results seems roughly acceptable, considering disagreements seen above may have resulted from peculiar phenomenon inherent in a small-sized model.
CONCEPT DESIGN OF ACTUAL SHIP

Concept design

Concept design of a NGH carrier equipped with a re-gasification system is proposed. Principal particulars and general arrangement of the carrier are shown in Table 2 and Figure 13, respectively.

Table 2 Principal particulars of NGH carrier and re-gasification system

<table>
<thead>
<tr>
<th>Ship</th>
<th>Lpp</th>
<th>250.0 m</th>
</tr>
</thead>
<tbody>
<tr>
<td>B</td>
<td>42.0 m</td>
<td></td>
</tr>
<tr>
<td>D</td>
<td>22.5 m</td>
<td></td>
</tr>
<tr>
<td>d</td>
<td>11.0 m</td>
<td></td>
</tr>
<tr>
<td>Cargo DW</td>
<td>about 57,000 t</td>
<td></td>
</tr>
<tr>
<td>Length</td>
<td>30.0 m</td>
<td></td>
</tr>
<tr>
<td>Width</td>
<td>35.0 m</td>
<td></td>
</tr>
<tr>
<td>Height</td>
<td>23.8 m</td>
<td></td>
</tr>
<tr>
<td>Hold</td>
<td>Pellet weight</td>
<td>about 12,000 t</td>
</tr>
<tr>
<td></td>
<td>Filling ratio</td>
<td>0.60</td>
</tr>
<tr>
<td></td>
<td>Hydrate ratio</td>
<td>80.0%</td>
</tr>
<tr>
<td></td>
<td>Quantity of flow</td>
<td>about 22,000 m³/h</td>
</tr>
</tbody>
</table>

Numerical simulation of actual ship

Simulation has been conducted for MGH pellets instead of NGH pellets. In this calculation, the number of cells representing calculating domain is 7,680. Though freeze-up of the water passage occurred neither in the experiment nor in the simulation for the model hold, it might occur for a cargo hold of the actual ship because of massive cold pellets inside. Therefore, re-gasification simulation for an actual ship has been executed. An example of time series of calculation result is shown in Figure 12.

As shown in Figure 12, freezing phenomenon of the injection water is seen but freeze-up of the water passage is not seen. Water level in the hold has risen up to about 5m right after the water injection started and has been stable, keeping stable gasification and dissolution of the pellets. However, the freeze-up of the water passage might occur even with relatively small quantity of ice, if the ice blocks one passage section.
CONCLUDING REMARKS
In respect to a NGH carrier, safe and prompt gasification is essential in case of breakdown of the unloading system. Gasification simulation code is under development, being satisfactorily validated with a model experiment. A sample simulation for a cargo hold of an actual ship has been executed, aiming to grasp how NGH pellets dissolve and freeze-up of the water passage occurs.

The present gasification simulation code will be upgraded and utilized, seeking safe and reliable gasification operation.

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