Numerical tracking of methane gas/hydrate and oil droplet in deep water spill

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Abstract:

The numerical simulation to track spilled methane gas and crude oil in deep water was carried out. The Lagrangian control volume method was applied to the methane gas tracking for jet/plume phase near a deep release point, and the Lagrangian parcel tracking was used for advection/diffusion phase above neutral buoyancy level. At all depth level, the conservations of mass, momentum and heat were considered and methane hydration was calculated by the reaction kinetics and equilibrium state of methane. On the other hand, the oil tracking was conducted with the simple Lagrangian parcel tracking, and the non-spherical shape and diameter distribution of oil droplet were considered. It was found that the rising velocity of hydrated methane was slower than that of oil droplet. When a strong steady current flow was assumed, crude oil branched according to the droplet diameter and did not clustered like methane gas.

Keywords: oil/gas blowout, methane hydrate, numerical simulation

Introduction

Oil/gas spill in deep water frequently occurs in the world, and the coastal area and marine environment around the accident site suffer huge damages from the pollution. As for the accident at oil platform, spilled materials are roughly divided into crude oil and natural gas. Crude oil droplets rise in seawater due to buoyancy and drifts on sea surface. On the other hand, a part of natural gas dissolves into ambient seawater and makes a stratified layer in deep water [1]. Oil/gas spill is not simple droplet/bubble rising phenomena but multi-component transport phenomena including physicochemical process. The general scenario of oil/gas blowout is schematically illustrated in Fig. 1. The blowout oil/gas makes a jet flow and methane gas, that is a main component of natural gas, forms hydrate according to the phase equilibrium relation. Then, oil and gas rise together and make a plume structure under the natural buoyancy level. In this plume phase, the methane hydrate decomposes under a certain thermochemical condition and a part of methane gas dissolves into seawater. On the edge of plume, the entrainment of seawater affects this process. The previous numerical studies [2-5] adapted this modeling, however, the dominant factor of spill behavior was not

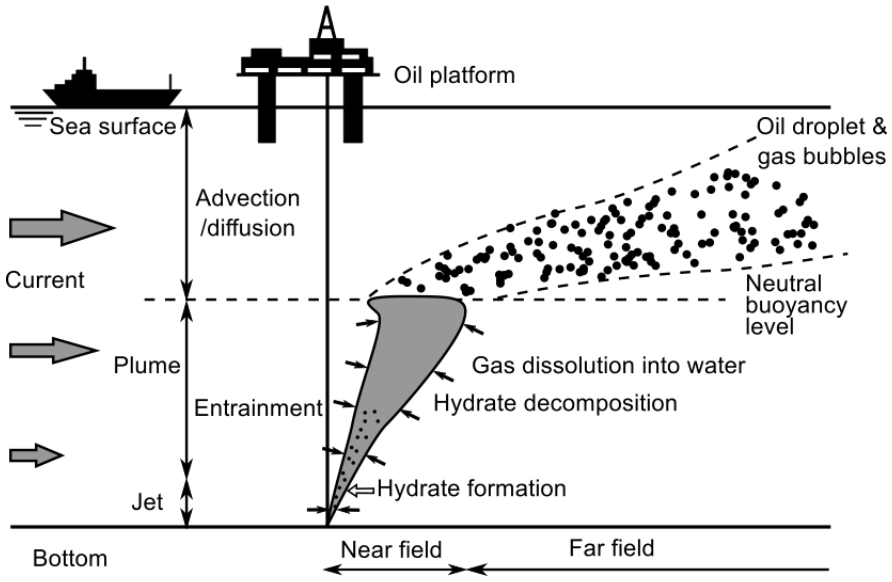

Figure 1: Schematic diagram of oil/gas blowout in deep water [2].

fully understood because this problem is multi-scale and multi-physics. Therefore, to understand the dominant chemical and physical dynamics in deep water spill, the effects of methane gas hydration and current flow on spill behavior were investigated.

Numerical method

Full simulation of deep water spill is difficult and complicated because spilled material consists of many hydrocarbons and it is complex multi-phase flow. As the first step of numerical prediction for spill, the methane gas and oil drop trackings were conducted individually by the following models.

Methane gas tracking model

As shown in Fig. 1, the plume phase and the advection/diffusion phase show a different behavior each other. The Lagrangian control method was used for the plume phase to reduce numerical cost and the random walk model, that was one of turbulent diffusion model, was used for the advection/diffusion phase, and the two models were linked at the neutral buoyancy level. The schematic of Lagrangian control volume method is shown in Fig. 2. The plume is divided into cylindrical control volumes, and the number of gas/hydrate particles, gas/hydrate fraction and methane concentration were calculated in each control volume. After the physical and chemical quantities in the control volumes were transferred at the neutral buoyancy level, Lagrangian gas/hydrate particles were released and tracked by the random walking in the advection/diffusion phase. The conservation law for mass, momentum and heat were considered in the both phases. The present numerical model considered the methane gas hydration and dissociation. The growth rate of methane hydrate was modeled by the following equation:

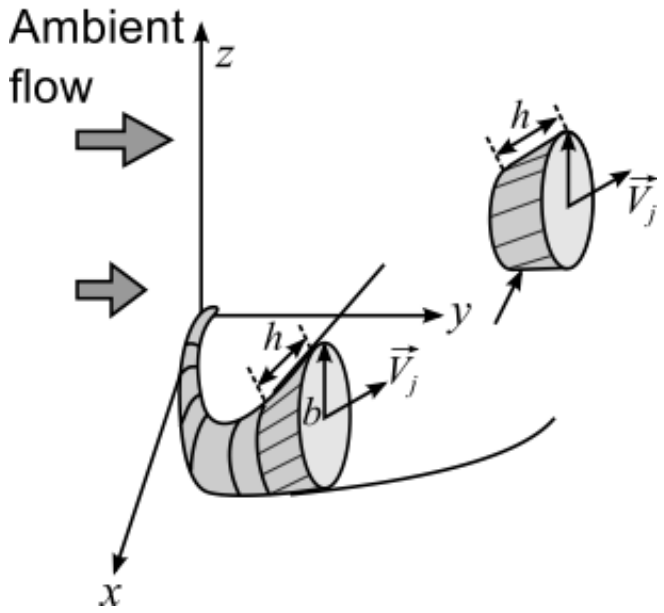

Figure 2: Schematic of Lagrangian control volume. *h* is the height of control volume, *b* is the radius of control volume, $\vec{V}_j$ is the rising velocity.

$$\frac{dn}{dt} = K \cdot 4\pi r_h^2 \cdot \Psi \cdot (f_{\text{dis}} - f_{\text{eq}}) \quad (1)$$

where dn/dt is the growth rate, K the reaction constant, $4\pi r_h^2$ the surface area of hydrate (r_h is the radius of hydrate shell), Ψ the effective surface area coefficient that considers the reaction enhancement of non-spherical hydrate shell, f_{dis} the fugacity under dissolved gas state and f_{eq} the fugacity under equilibrium state. The constant parameters, K and Ψ, in Eq. (1) were 0.65×10^{-5} mol/m^2·MPa·s and 38 [3], respectively, and the dependency of Ψ on numerical result will be discussed later in this paper. Hydrate dissociation was also modeled with a similar equation to Eq. (1).

Oil droplet tracking model

The simple Lagrangian tracking model was used for oil droplet because oil does not form hydrate and phase change is not occurred. The Lagrangian oil droplets were released at the blowout nozzle and tracked according to the momentum equation, and the non-spherical shape of droplet was considered at rising. The droplet diamter was not uniform and the diameter distribution according to the field experiment was given at the released point.

Numerical condition

The simulation was carried out with the condition of the deepspill experiment at the Norwegian Sea [6,7]. The deepspill project conducted the three release tests, methane gas, crude oil and diesel oil at -844 m depth, and the former two conditions were used in the present simulation. Ambient current speed

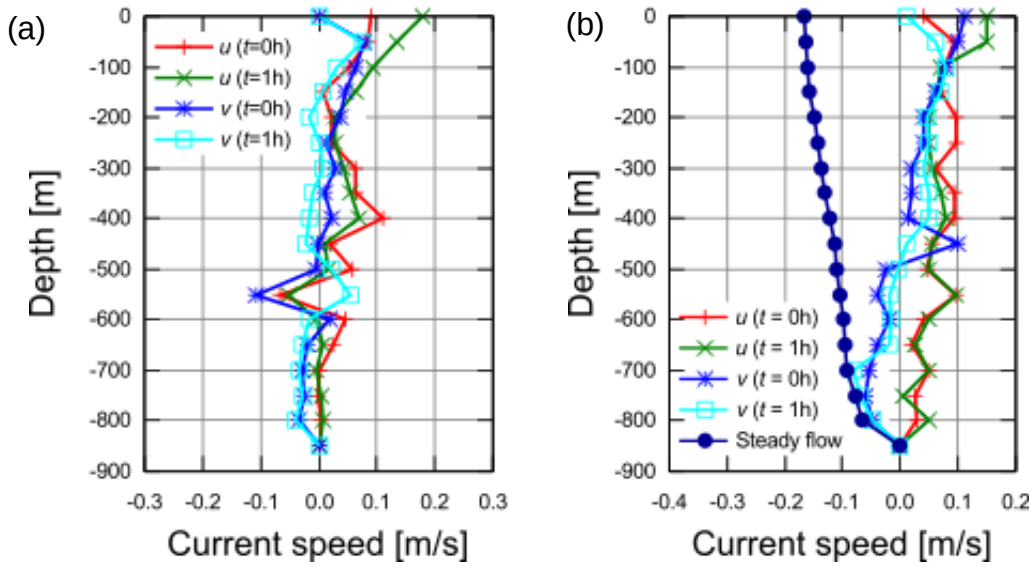

Figure 3: Current speed distribution in the Deepspill field experiment [3,7]: (a) methane gas, (b) crude oil.

distribution of the two conditions was shown in Fig. 3 and the current speed changed unsteadily. For comparison, no current flow and a simplified steady flow in the south direction (Fig. 3(b)) were also used. The other conditions such as temperature, bubble/droplet diameters and release rate are found in Refs. [3] and [7].

Results and discussion

Validation of simulation code

To validate the present simulation code, the numerical results were compared with the deepspill experiment results [7]. Figure 4 shows the spilled region in the vertical section. The numerical results indicate the outline of gas bubble and oil droplet trajectories and the experimental results were obtained from echo sounder where high sound intensity level corresponds with high concentration region of spilled component. The calculated gas region formed a plume under -700 m depth and advected over this level. On the other hand, the experiment measured wide gas distribution around the blowout level of -844 m depth. However, considering that methane gas easily diffuses out of plume and echo sounder data includes measurement error, it can be seen that the calculated distribution of methane gas shows a good agreement with the experimental results. Similarly, the calculated oil distribution shows a good agreement especially on the southern edge of spilled region. Therefore, we concluded that the simulation codes were valid and useful to predict the spilled region with sufficient accuracy.

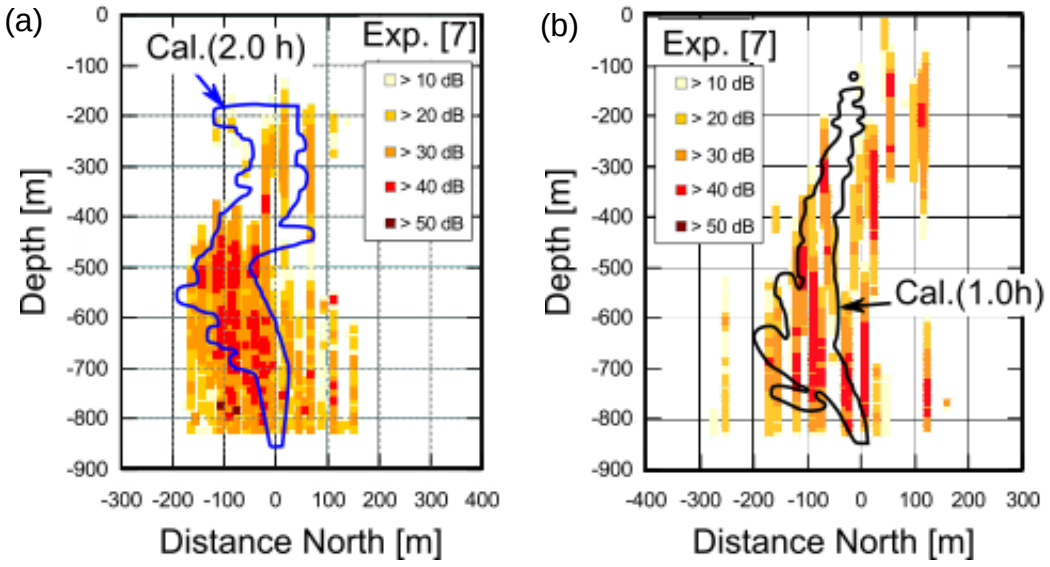

Figure 4: Spilled region in the vertical cross section (South-North direction): (a) methane gas, (b) crude oil.

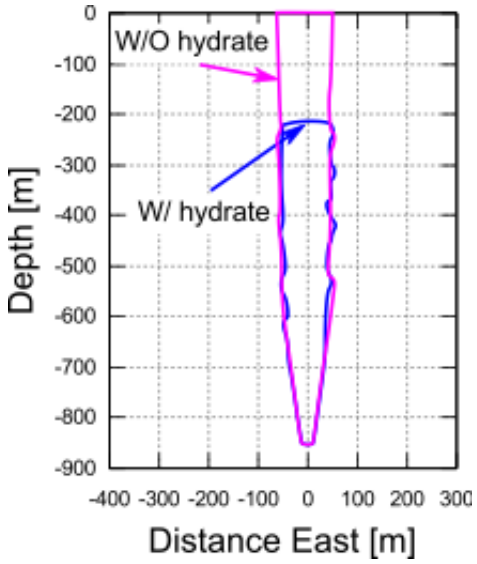

Figure 5: Effect of hydrate formation on spilled region in the vertical cross section after 1.5 hour blowout.

Effect of methane gas hydration

Methane gas hydration takes an important roll in deep water because the density of hydrate is different from that of gas. To discuss the effect of methane gas hydration on rising behavior, the simulation under no current flow was carried out. Figure 5 shows the effect of hydrate formation in the vertical section after 1.5 hour blowout. When hydrate formation was not considered, the rising velocity of methane was fast and a first released gas bubble reached at the sea surface after 1.5 hour blowout. On the other hand, when hydrate formation was considered,

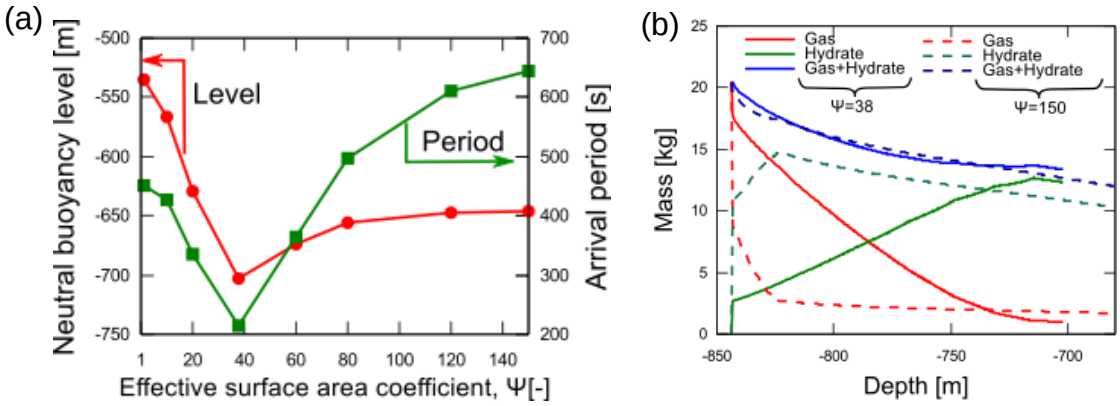

Figure 6: Effect of effective surface area coefficient on hydrate formation: (a) Dependency of neutral buoyancy level and its arrival period, (b) methane mass balance in plume phase depth.

hydrated methane only reached up to -200 m depth after 1.5 hour blowout because the rising velocity of hydrate was about 0.4 times of that of pure methane gas bubble. When the simulation with hydration was carried out for a long period, methane bubble and hydrate dissolved into seawater on the way of rising.

Methane hydration begins at jet/plume phase, and so the effect of hydrate surface structure on the growth rate of methane hydrate in Eq. (1) was investigated in the plume phase. The present study discusses the effective surface area coefficient, Ψ, that directly related with the growth rate. Cheng and Yapa [3] used $\Psi = 38$ for hydrate formation, however, this parameter took a large value, $\Psi = 150$, that was estimated from the laboratory experiment [8]. Thus, we changed the value of Ψ from 1 to 150 for the hydrate calculation. Figure 6 shows the effect of the effective surface area coefficient, Ψ, on hydrate formation. The neutral buoyancy level and its arrival period is shown in Fig. 6(a), and the both results took minimum values at $\Psi \sim 40$. To discuss this nonmonotonic curve, the methane mass balance in the plume phase for $\Psi = 38$ and 150 is shown in Fig. 6(b). The methane gas decreased and the hydrate increased because methane gas changed to hydrate as gas bubbles rose, and the total mass of gas and hydrate decreased because of dissolution into seawater. When hydrate formation was enhanced ($\Psi = 150$), gas and hydrate balanced rapidlly around -830 m depth, On the other hand, at the result of $\Psi = 38$, gas and hydrate balanced near -700m depth that corresponds to the neutral buoyancy level. For the simulation with $\Psi < 38$, the balanced state was not seen. Therefore, the critical value of Ψ was determined by the appearance of gas-hydrate mass balanced state in the plume phase.

Effect of current flow on total spilled region

Because real current flow is time-space dependent, it is important to investigate the effect of ambient current flow on spilled region. Figure 7 shows the spilled region in the vertical section after 1.0 hour blowout when the current speed conditions shown in Fig. 3(b) were used for the methane gas only and crude oil

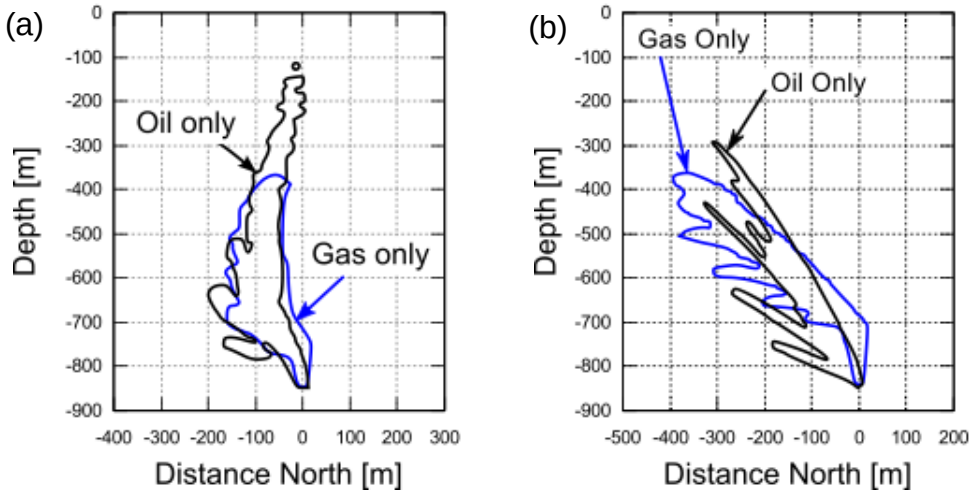

Figure 7: Effect of ambient current flow on spilled region after 1.0 hour blowout: (a) unsteady drift current, (b) steady southern flow. Current flow velocities are given in Fig. 3(b).

only releases. When the unsteady drifting current velocity was used (Fig. 7(a), the height of methane gas spilled region was lower than the oil spilled one because methane gas was hydrated on the way and the density of methane became smaller than that of oil. However, the horizontal distance of spilled region was not different because the current flow was drifted around the released point in the horizontal distance. Figure 7(b) shows the result with the steady southern flow (Fig. 3(b), dark blue) that was a strong current. The blowout methane formed a plume structure up to -700 m depth and was not affected by current flow. Then, at lower depth, a clustered methane hydrate rose and bent by current flow. Spilled oil branched according to oil droplet diameter and the horizontal distance of oil became smaller than that of methane gas even if the release period was 1.0 hour. Therefore, the contribution of each component must be considered in the modeling for real accidents because spilled material is oil/gas mixture at oil platform.

Conclusions

The numerical simulation for tracking methane gas/hydrate and crude oil droplet in deep water was carried out under the field experiment and simplified current flow conditions. The methane gas tracking model considered hydration in deep water, and the density change from gas to hydrate decreased the rising velocity of released methane. In the hydrate formation, the effective surface area coefficient of hydrate was an important factor and the gas-hydrate mass balance in the plume phase affected the prediction of neutral buoyancy level. The oil tracking model was simple compared with the methane gas tracking, however, the calculated spill region showed a good agreement with the experimental result. Under the strong current flow, the spill behaviors of methane gas and crude oil were different, and the combined model must be required to simulate a real field accident.

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