Numerical Investigation of Oil Spill from a Tanker by Multiphase MPS Method

***Guangtao Duan and †Bin Chen**

State Key Laboratory of Multiphase Flow in Power Engineering, Xi'an Jiaotong University, Xi'an 710049, PR China

*Presenting author: ltpeach@stu.xjtu.edu.cn
†Corresponding author: chenbin@mail.xjtu.edu.cn

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Introduction

Crude oil leakage from a tanker is usually a serious disaster to the ocean. Predicting the behaviors of leaked oil is of great significance to the quick response and decision for the early stage of such disasters. The simulations of such flows are usually difficult by the conventional grid methods because there are three types of interfaces (water-air, water-oil, oil-air) required to be tracked. In this paper, the spreading of the spilled oil are investigated by a multiphase particle method, which is developed based on the Moving Particle Semi-implicit method (MPS) (Koshizuka & Oka, 1996). The numerical methods and simulated results are briefly presented in next section.

Numerical methods

When MPS is extended to a multiphase particle solver, multi-viscosity and multi-density models are necessary to model the interaction of different phase particles. The following multi-viscosity model (Eq. (1)) based on the harmonic mean inter-particle viscosity is adopted for viscosity term.

$$\langle \nabla \cdot (\mu \nabla \mathbf{u}) \rangle_i = \frac{2d}{n_0 \lambda} \sum_j \frac{2\mu_i \mu_j}{\mu_i + \mu_j} (\mathbf{u}_j - \mathbf{u}_i) w(|\mathbf{r}_j - \mathbf{r}_i|, r_e) \tag{1}$$

On the other hand, the multiphase Pressure Poisson Equation is discretized by the following multi-density model,

$$\left\langle \nabla \cdot \left(\frac{1}{\rho} \nabla P \right) \right\rangle_i^{k+1} = \frac{2d}{n_0 \lambda} \sum_j \frac{1}{2\rho_i \rho_j / (\rho_i + \rho_j)} \left(P_j^{k+1} - P_i^{k+1} \right) w(|\mathbf{r}_j - \mathbf{r}_i|) \tag{2}$$

where all the variables above are consistent with those in (Koshizuka & Oka, 1996). The harmonic mean inter-particle density can help to stabilize the simulations.

Oil spill model

The oil spill model is sketched in Figure 1. Initially, the left tanker is partly filled with oil (ρ=800 kg/m^3, μ=0.05 Pa·s) which will leak into the water (ρ=1000kg/m3, μ=0.001 Pa·s) in the right part from the damaged hole (width 0.02 m) on the tanker. Both the rate of oil leakage and its spreading on the sea surface are investigated by the multiphase MPS method.

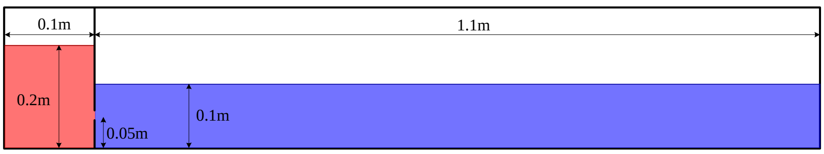

Figure 1 The oil spill model

Results and Discussions

The simulated snapshots of spreading of the leaked oil are presented in Figure 2. The corresponding evolution of the oil surface in the tanker and development of the spilled oil front are respectively shown in Figure 3 (a) and (b). As shown in Figure 3 (a), the leakage of oil is comprised of two stages. In the first stage (from t=0s to t=0.8s), the oil surface in the tank declines rapidly, as shown by the subfigures at t=0.2, 0.4, 0.8s in Figure 2. In the front of the spilled oil, mushroom-like twin-vortex happens at t=0.4s which is similar to the Rayleigh-Taylor instability. At t=0.8s, the oil surface in the tank has decreased to the stable position of oil surface. This stage is driven by the potential energy of the oil phase, which is arranged higher than the water surface initially. Therefore, a quasi-steady theoretical solution can be derived from the Bernoulli equation (Jeong et al., 2013). The comparison between the simulated results and Bernoulli solutions is shown in Figure 4, where TF indicates the ratio of actual leaking speed to that predicted by Bernoulli's equation. Therefore, TF is in fact unity if viscosity at the hole is neglected. TF=0.558 is an empirical value obtained from experiments (Jeong et al., 2013). As shown in Figure 4, the simulated results agree reasonably with those by TF=0.558, which validated the present simulations.

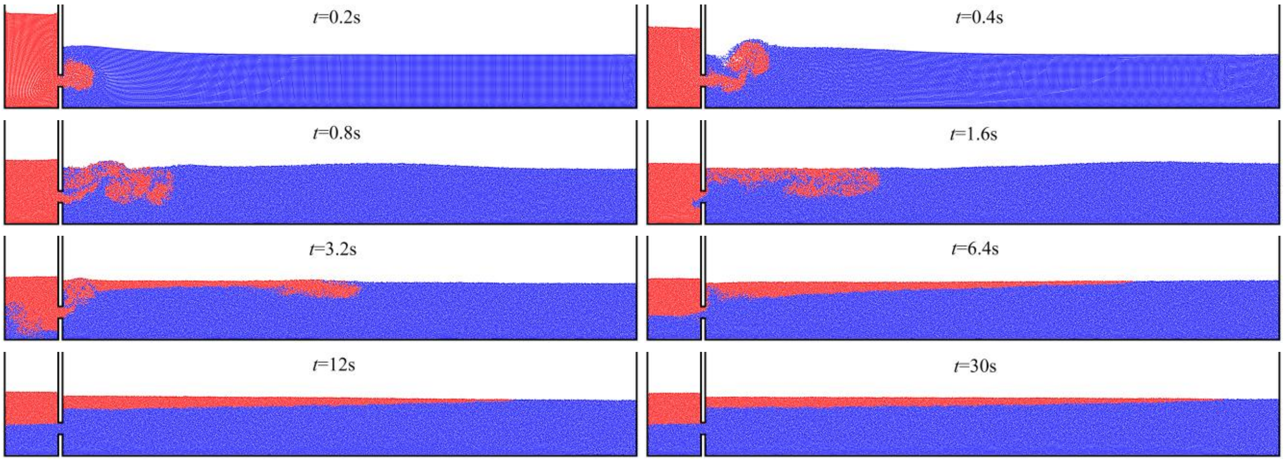

Figure 2 Snapshots of developments of leaked oil (particle arrangement: 600×100)

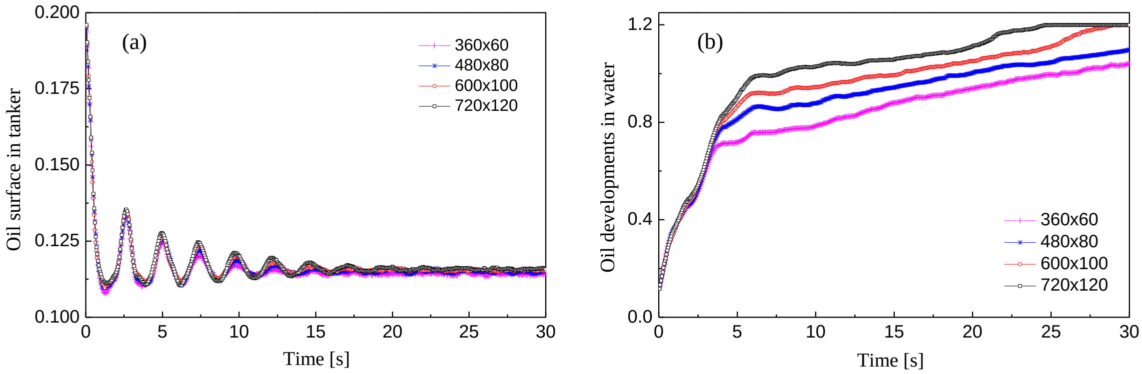

Figure 3 The developments of spilled oil by different particle arrangements: (a) evolution of oil surface in the tanker; (b) developments of leaked oil front in the water phase

In the second stage (from t=0.8s to t=12s), the leaking rate is slower than the previous stage. At t=1.6s in Figure 2, water begins to flow into the tank so that the light oil phase will be pushed away from the tanker. Water injection continues at t=3.2s and finally stops at t=12s when the top of the leaking hole is fully sealed by water. Accordingly, the oil leakage also stops at t=12s so there is only spreading of leaked oil from t=12s to t=30s. In this stage, the leaked oil is replaced by the injected water and the oil surface will not change. Note that the fluctuation of oil surface in Figure 3 (a) is caused by the sloshing of the water-oil system. When the periodic sloshing is ignored, the oil surface in the tank can be regarded as stable after t=0.8s.

The spreading of the leaked oil on water can also be classified into two stages, whose turning point happens between 5.0s and 7.5s as shown in Figure 3 (b). Firstly, the leaked oil will spread fast (basically from 0s to 5s) when there is a blunt front as shown at t=3.2s in Figure 2. The reason is that the release of the potential energy stored in the blunt front can drive the front move fast. However, when the blunt front disappears, the spreading of the spilled oil front will be much slower as shown by the slightly-inclined slope from 7.5s to 30s in Figure 3 (b). There are two possible reasons for the disappearance of blunt front. The first one is that the blunt front itself is very thin so it disappears, which is the ideal situation. The second one is that there is no enough particles to represent the blunt part, which usually happens when particle arrangements is not fine enough. In this situation, the blunt front exists for longer time when there are more particles to discretize the oil phase. As shown in Figure 3 (b), the finer the particle arrangement is, the later the turning point is. Therefore, all these simulations are not fine enough to reproduce the blunt front. The thickness of the blunt front in oil spreading is a key scale, which requires to be fully discretized in Direct Numerical Simulations (DNS) of multiphase flows. Besides, good convergence has been demonstrated for the evolution of oil surface in the tank as shown in Figure 3 (a).

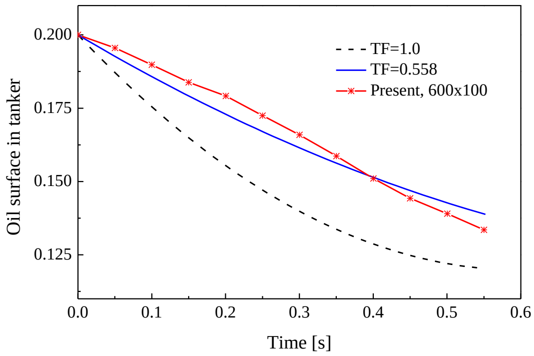

Figure 4 The decline of oil surface in the early stage of leakage is compared with theoretical prediction

Conclusions

The multiphase Moving Particle Semi-implicit (MPS) method is adopted to investigate the behaviors of leaked oil from a tanker. In the first stage of leakage, the rate of leakage is large under the strong drive of potential energy of the higher oil phase and the oil surface in the tank declines sharply. However, water injection into the tanker happens in the second stage, where the rate of leakage is relatively small and the oil surface keeps stable in the tank. The spreading process of leaked oil is also comprised of two stages. The leaked oil spreads fast under the influence of blunt front in the first stage of spreading while it moves much slower in the second stage. An experiment is being prepared to validate these simulation results.

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