Three Dimensional Numerical Simulation of Oil Containment Process by Flexible Oil Booms in Inland Waters

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Abstract. The deformation of oil containment boom in inland waters and the hydrodynamic process are investigated based on multiphase CFD (Computational Fluid Mechanics) model and the structure analysis model by system coupling. The velocity field near the flexible boom under water current is compared with those behind the rigid boom. The process of spilled oil interception by oil boom is simulated through employing the VOF (volume of fluids) method to tracing the oil-water two phase flows and the variation of oil slick shape is investigated.

1. Introduction

Inland water oil spills which are not so large scale compared with marine oil spills can still cause serious damage to natural resources and to those whose livelihoods depend on these resources. With regard to the bio-environmental impact, inland water oil spills could directly slay the organism such as animals, plants and even the smallest micro-organisms by the toxicological reaction and hypoxia effect [1].On the other hand, spilled oil could experience series of physical and chemical changes, such as spreading, drifting, evaporation, emulsification, dissolution, and participate in the biological cycle through the food chain and eventually endanger the human society. Therefore, it is important to improve techniques and equipment that facilitate spill clean-up for inland water oil spills [2]. Effective use of skimmers or in situ burning for an oil spill generally requires that the spill first be contained using booms which are frequently used in inland water conditions due to the simple water conditions compared to sea water conditions. However, the booms often fail to hold the oil even in simple inland water situations due to hydrodynamic forces, which will significantly boost the clean-up costs. Therefore a better understanding of the oil containment process by oil booms is required. As is pointed out by FENG [3], there are mainly six failure mechanisms for the oil boom as shown in Figure 1: entrainment failure, drainage failure, critical accumulation failure, splash-over, boom submergence and boom planning. The last three failure modes are usually caused by the wind and wave effects which commonly happened in sea conditions and not so frequently for inland water conditions. So only the first three failure modes are talked about here. The entrainment failure as described by Leibovich [4] and Milgram et al. [5] is caused by breaking of Kelvin-Helmholtz water-oil interfacial waves at sufficiently large relative velocity. The drainage failure usually takes place when the boom draft is insufficient to contain the oil slick and some oil goes underneath the boom as shown in Cross and Hoult[6]. As shown in many experimental results [7-8], a third failure

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mechanism-critical accumulation usually takes place in highly viscous oils of kinematic viscosities exceeding 3000cSt, independently of the boom draft.

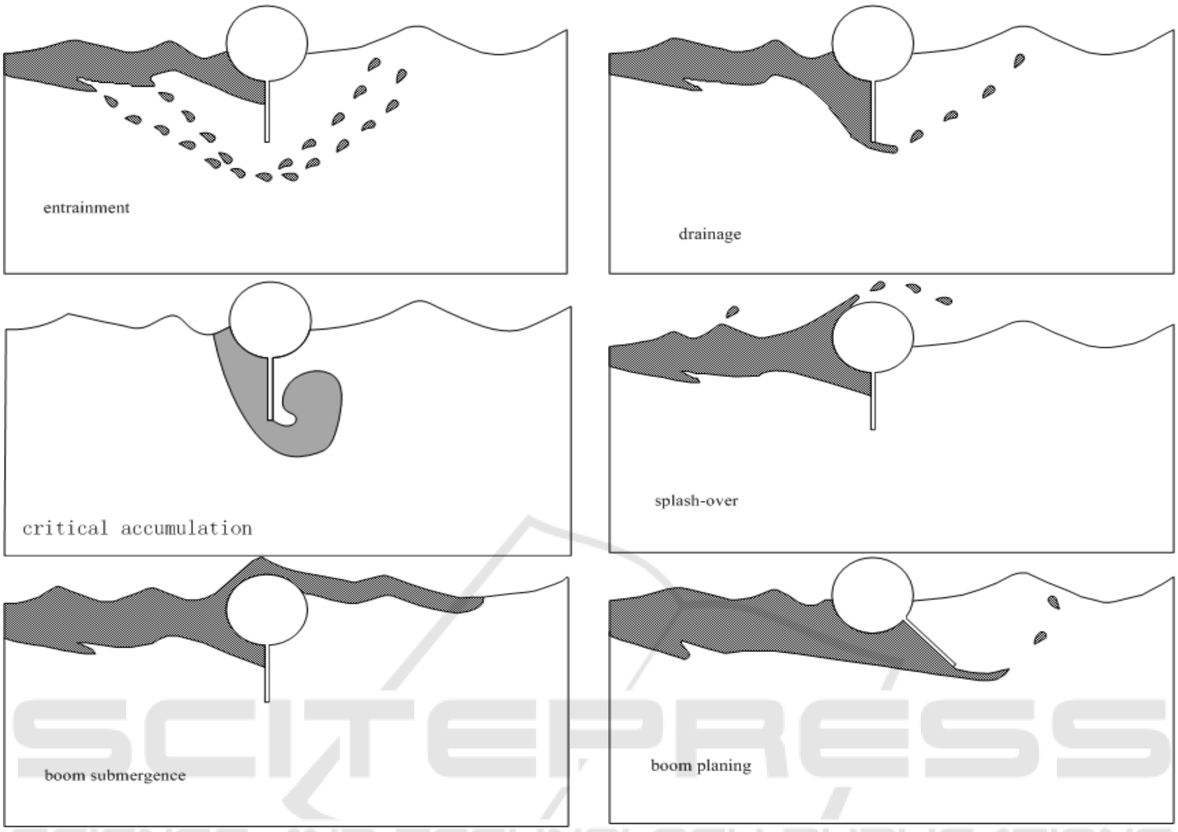

Figure 1. Six different modes of oil containment failure.

Although oil boom is widely studied, it is far from being fully investigated. For most of the numerical study of the oil boom performance, the oil boom is usually considered to be rigid. As of today, the PVC material is usually used as the skirt of the oil boom, which is flexible under the current action. In this paper, the ANSYS14.5 software has been used to simulate the oil water flow around a flexible boom used in inland waters. The details of the flow field before the flexible boom skirt and the deformation process of the boom skirt are studied and the impact of boom deformation on flow field is investigated in detail.

2. Governing equations

For the flows of incompressible fluid with the free surface, the governing equations are the continuity equation and the Reynolds-averaged Navier-Stokes equations:

Continuity equation:

$$\frac{\partial \rho}{\partial t} + \frac{\partial(\rho u)}{\partial x} + \frac{\partial(\rho v)}{\partial y} = 0 \tag{1}$$

The incompressible RANS momentum equation solved in the software can be written as:

$$\frac{\partial(\rho u)}{\partial t} + u\frac{\partial(\rho u)}{\partial x} + v\frac{\partial(\rho u)}{\partial y} = 2\frac{\partial}{\partial x}\left[\left(\mu + \mu_t\right)\left(\frac{\partial u}{\partial x}\right)\right] + \frac{\partial}{\partial y}\left[\left(\mu + \mu_t\right)\left(\frac{\partial u}{\partial x} + \frac{\partial u}{\partial y}\right)\right] - \frac{\partial p}{\partial x} \tag{2}$$

$$\frac{\partial(\rho v)}{\partial t} + u\frac{\partial(\rho v)}{\partial x} + v\frac{\partial(\rho v)}{\partial y} = \frac{\partial}{\partial x}\left[(\mu + \mu_t)\left(\frac{\partial v}{\partial x} + \frac{\partial u}{\partial y}\right)\right] + 2\frac{\partial}{\partial y}\left[(\mu + \mu_t)\frac{\partial v}{\partial y}\right] - \frac{\partial p}{\partial y} - \rho g \tag{3}$$

In which t is time and ρ is the density, x, y denotes the Cartesian coordinates, u, v is an ensemble mean velocity component, p is the fluid pressure, μ is the dynamic viscosity, and g is the gravitational acceleration. The standard $k-\varepsilon$ model is adopted to compute the Reynolds stress and the free surface is computed by the VOF method.

For computing the deformation of oil boom skirt, the conserving equations can be derived from the Newton Second Law as shown in following:

$$\rho_s \ddot{d}_s = \nabla \cdot \sigma_s + f_s \tag{4}$$

In which ρ_s is the density of the oil boom skirt， σ_s is Cauchy stress tensor, f_s is Volume force vector, $\ddot{d}_s$ is the acceleration vector. The deformation of the structure caused by the fluid can be calculated by:

$$M_s \frac{d^2 r}{dt^2} + C_s \frac{dr}{dt} + K_s r + \tau_s = 0 \tag{5}$$

In which M_s is the mass matrix,C_s is damping matrix,K_s is the element stiffness matrix； r is the deformation and τ_s is the stress.

For coupling the fluid equations and the structure equations, the following rules should be satisfied:

$$n \cdot \tau_f = n \cdot \tau_s \tag{6}$$

$$r_f = r_s \tag{7}$$

3. Numerical simulations and analysis of the numerical results

3.1. Numerical model set-up

The computational domain is 20.04 m long, 5 m deep and 0.4m wide (see Figure 2). The oil boom is placed near the surface and in the middle of the computational domain in length direction. The boom draft D is chosen as 0.6 m. The current velocity U range is chosen of 0.2 - 0.7 m/s at interval of 0.1 m/s. The computational zones are discrete by the structured grids using MESHING, and the mesh length is 0.04m, and the mesh height is 0.04m.

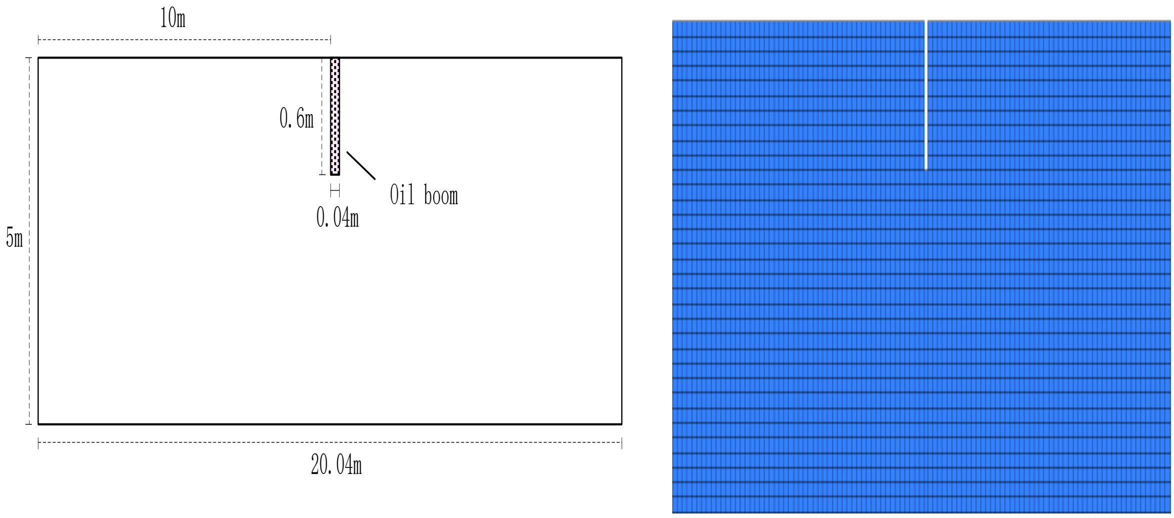

Figure 2. The schematic drawing and mesh of the computational domain.

3.2. The impact of the boom deformation on the flow field

As is known, the boom deformation has huge impact on the flow field near the oil boom which will accordingly influence the performance of the oil boom. Here, the current velocity is chosen as 0.5m/s and both rigid and flexible boom are considered. As shown in Figure 3, the effective boom draft of the flexible boom is less than that of rigid boom with the same size due to the boom deformation. The streaming location under the boom bottom for the flexible boom is risen up due to the boom deformation, which making the streaming before boom easier. As compared with the rigid boom, the whirlpool after the flexible boom is flat and long.

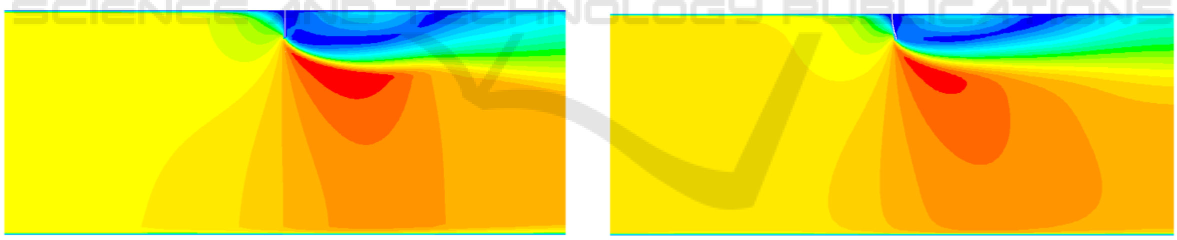

Figure 3. The contour plots of fluid velocity.

3.3. Numerical simulation of the oil containment process

Then, the oil containment process of the flexible boom is simulated. Here, the oil with density ρ=860kg/m^3 and viscosity μ=0.06kg/m-s is chosen as the experimental material, and the initial oil volume Q is chosen as 1.516m^3. The oil boom with modulus of elasticity E=1.2e^{6}Pa and Poisson ratio σ =0.49 is used. As shown in the initial contour map of the oil volume fraction(Figure 4), the red region indicate that the oil fraction equals 1 and the blue region indicate that the oil fraction equals 0, and there is no boom deformation at initial moment.

Figure 4. The contour plot of oil volume fraction at initial moment.

Figure 5 shows the variations of oil shape and the oil containment and the boom deformation process. As is shown, the oil floating on the water will expand and move towards the oil boom under the current, and the flexible boom skirt will deform. As the oil slick approaching the boom, it will accumulate before the boom with the length of the oil slick decreased and the thickness increased. At time t=2.4s, the oil slick will escape under the bottom of the boom and then the drainage failure happens. After escaping from the bottom of the boom, part of the oil slick will flow with the current and part of the oil will be retained after the boom under the action of buoyancy. The total simulation time is 120 seconds and after that the oil slick shape will maintain unchanged shown in the last picture in Figure 5.

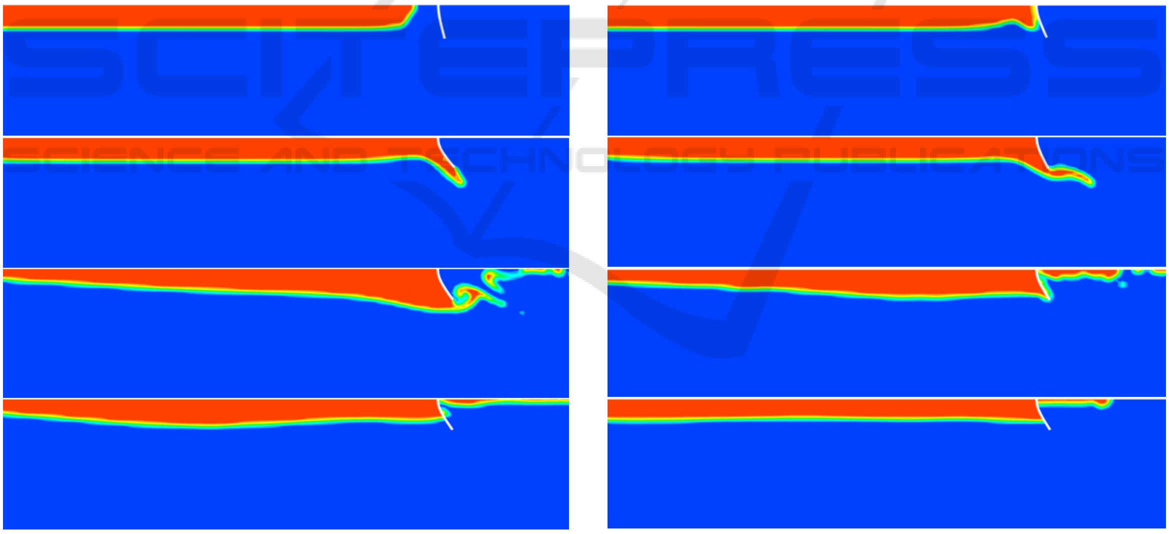

Figure 5. Variations of oil shape outlined by the oil volume fraction contour plot.

at t=0.8s, 1.6s ,2.4s, 3.2s, 6.4s, 12.8s, 21.6s and 120s

4. Conclusions

Based on the analysis of Fluid-Structure Interaction, the deformation of oil boom under pure current condition is numerically simulated. Then, the simulations of flow passing a rigid boom and a flexible boom are carried out, which provides the possibility to compare velocity fields for different booms. When the body of boom deformed, the fluid field in the vicinity of the boom changed, and oil containment is affected. The process of spilled oil interception by oil boom is simulated through employing the VOF (volume of fluids) method to tracing the oil-water two phase flows and the variation of oil slick shape is investigated. Compared with the rigid boom, the whirlpool after the flexible boom is flat and long. During the oil containment process, the oil floating on the water will expand and move towards the oil boom under the current, and the flexible boom skirt will deform.

Acknowledgement
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