CFD modeling of pneumatic oil barrier

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Abstract

ID: 300087 Pneumatic oil barriers (so called "bubble oil boom (BOB)") are based on the rise of air bubbles which are injected from the submerged parallel line spargers (McClimans et al., 2012). Local outward flows are formed when the bubbles and entrained water reach the sea surface, and thereby could counterbalance the opposing sea current to retain the spilled oil. It could function alone or work together with a traditional oil boom to improve the recovery effectiveness. A multiphase Computational Fluid Dynamic model, which couples volume of fluid (VOF) and discrete phase model (DPM) approach together with an enhanced k-epsilon model, is developed. Trajectories of bubbles are computed in the Lagrangian frame of reference, exchanging momentum and turbulent energy with water and oil slick, represented in the Eulerian frame of reference. The interface between atmosphere, water and oil slick is captured by the VOF model. The model is applied to meso-scale experiments in McClimans et al. (2012) for validation. The validated numerical model can provide improved basis for the further design of BOB system.

Introduction and Methods

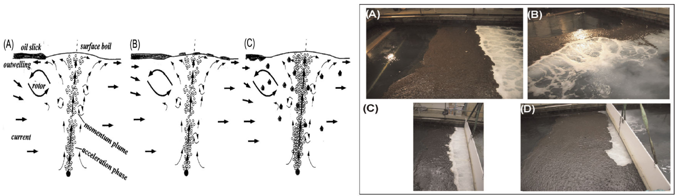

Fig 1. Left are sketches of the flow induced by a BOB.; Right are Images showing the BOB operation in meso-scale test in McClimans et al. (2012).

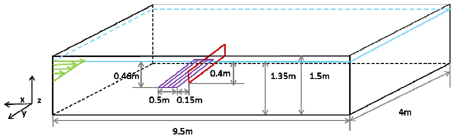

Fig 2: Schematic of the BOB system in meso-scale test in McClimans et al. (2012). Green arrows represent the currents. The purple parallel lines represent the spargers at a depth of 0.46 m. And the red box represents the boom skirt installed at 0.4 m. The horizontal blue plane is the initial free surface of 1.35 m.

Table 1. Model description

Fluid representation (continuous air and water): VOF

The VOF model solves mass conservation equations for atmosphere (k=g), oil slick (k=o), and water (k=f), together with a single set of Reynolds averaged Navier-stokes equation .

$$\frac{\partial}{\partial t}\alpha_k + \bar{u}_j \cdot \frac{\partial \alpha_k}{\partial x_j} = 0$$

$$\frac{\partial}{\partial t}(\rho \bar{u}_i) + \frac{\partial}{\partial x_j}(\rho \bar{u}_i \bar{u}_j) = -\frac{\partial \bar{p}}{\partial x_i} + \frac{\partial}{\partial x_j}\left[\mu\left(\frac{\partial \bar{u}_i}{\partial x_j} + \frac{\partial \bar{u}_j}{\partial x_i}\right)\right] - \frac{\partial}{\partial x_j}\left(\rho \overline{u_i' u_j'}\right) + \rho g_i + \bar{F}_i^c + S_{current}$$

α is volume fraction; u is shared velocity; ρ is mixture density; μ is mixture viscosity; F^c is the coupling force from bubbles; $S_{current}$ is the opposing current against to bubble plume. $u_{current,x} = \frac{0.315\times(1.35-z)}{0.35} - 0.315$

Bubble representation: DPM $\frac{d\mathbf{x}_b}{dt} = \mathbf{v}_b, \frac{d\mathbf{v}_b}{dt} = \frac{\mathbf{F}}{m_b}$

$\mathbf{X}_b$ $\mathbf{V}_b$ $\mathbf{m}_b$ are bubble position, velocity and mass. **F** is the force on a single bubble, there are contributions from buoyancy, drag, lift,virtual mass and turbulent dispersion force. See Pan et al. (2013) for detailed information

Enhanced k-epsilon turbulence model:

$$\rho\frac{\partial k}{\partial t} + \rho \bar{u}_j \frac{\partial k}{\partial x_j} = \mu_t\left(\frac{\partial \bar{u}_i}{\partial x_j} + \frac{\partial \bar{u}_j}{\partial x_i}\right)\frac{\partial \bar{u}_i}{\partial x_j} + \frac{\partial}{\partial x_j}\left(\mu + \frac{\mu_t}{\sigma_k}\frac{\partial k}{\partial x_j}\right) - \rho\varepsilon + G_B$$

$$\rho\frac{\partial \varepsilon}{\partial t} + \rho \bar{u}_j \frac{\partial \varepsilon}{\partial x_j} = C_{1\varepsilon}\frac{\varepsilon}{k}\left[\mu_t\left(\frac{\partial \bar{u}_i}{\partial x_j} + \frac{\partial \bar{u}_j}{\partial x_i}\right)\frac{\partial \bar{u}_i}{\partial x_j}\right] + \frac{\partial}{\partial x_j}\left(\mu + \frac{\mu_t}{\sigma_\varepsilon}\frac{\partial \varepsilon}{\partial x_j}\right) - \rho C_{2\varepsilon}\frac{\varepsilon^2}{k}$$

$$+S_{damping} + C_{\varepsilon\_buo} \cdot \frac{\varepsilon}{\kappa} \cdot G_B$$

The enhanced turbulence model account for: the free surface damping effects which introduce the added turbulence dissipation in the proximity of a free surface, and the buoyancy modified turbulence which introduce the turbulence modulation due to bubble induced stratification. The rightmost terms G_B and $S_{damping}$ are the corresponding source terms.See Pan et al. (2013) for detained information. Other parameters are the standard k-epsilon model as Launder and Spalding (1974).

Coupling: Force coupling (momentum) and coupled to turbulence of Eulerian phase.

Results

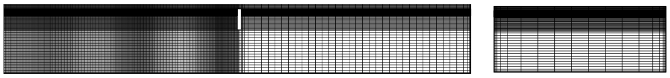

Fig 3. The simulations were performed on 633821 hexahedral cells with skirt. Left is Side view (-4.75 m < x < 4.75 m, 0 m < z < 1.5 m) and right is plane view of grids (-2 m < y < 2 m, 0 m < z < 1.5 m). Spargers are located at x_0 = 0.15 4m, x_1= 0.23 m, x_2 = 0.31 m, x_3 = 0.39 m, x4 = 0.47 m, and the skirt is located at -0.08 m < x < 0 m, 0.95 m < z < 1.45 m. The boundary conditions are set as: wall for the tank and boom skirt, pressure outlet for the upper limit of the gas phase.

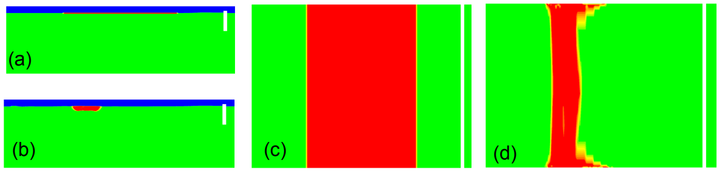

Fig 4. Representation of three phases under : air (blue), water (green) and oil (red).(a) and (c) are taken from half of the y middle plane y = 0 m; (b) and (d) are from half of a horizontal plane z = 1.34 m. (a) and (c) are at start of simulation. Sea water of 34 ppt salinity, 1070 kg/m³ density, 1.6674 × 10⁻³ Pa•s viscosity was patched at x = -4.75 - 4.75 m, z = 0 - 1.35 m. 150 l emulsified oil with 987 kg/m³ density, 6.405 Pa•s viscosity was patched at x = 1.0 - 3.5 m, z = 1.335 - 1.35 m with 1.5 cm thickness. Air is of 1.2736 kg/m³ and 1.7566 × 10⁻⁵ Pa•s viscosity. Gas bubbles of 1.2736 kg/m³ density are injected at a flow rate of 0.0167 m³/s (1000 l/min) from spargers. (b) and (d) are the accumulated oil at the steady state, located at x = 2.7 - 3.3 m, z = 1.288 - 1.35 m with 6.25 cm thickness, where the bubble plume counterbalances the current.

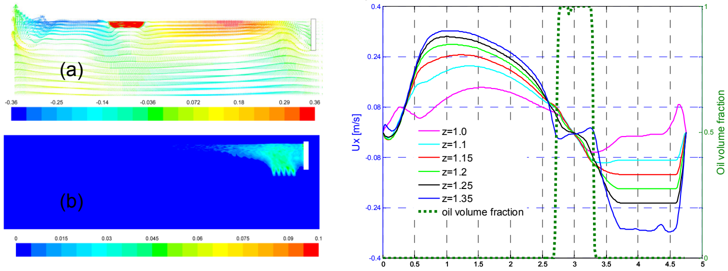

Fig 5. (a) is the predicted velocity vectors around the oil slick at half of the y middle plane, coloured by the x velocity. (b) is the predicted volume fraction of gas. In (c), the primary vertical axis with solid lines is the x velocity along the x direction at different height.(z =1.0, 1.1, 1.15, 1.2, 1.25 and 1.35 m.. x = 0 m is at the skirt, x= 4.75 m is at the tank wall. The positive outward flow is generated by the bubble plume, and the negative flow is the opposing current. The secondary vertical axis with the dotted line is the oil volume fraction at z = 1.3 m, oil accumulates where bubble plume and opposing current converge at around x = 3 m.

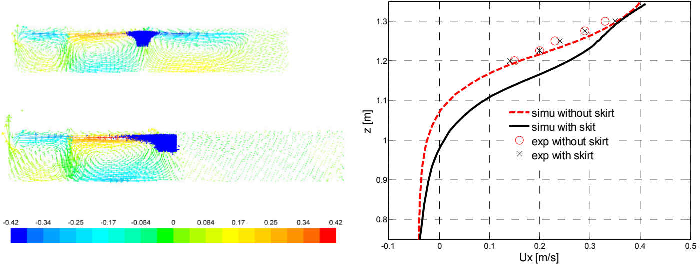

Fig 6. Left presents two set-ups: stand-alone bubble plume and bubble plume together with boom skirt at x = 0.67 m. The velocity vector plots are coloured by the x velocity at the y middle plane together with the bubble plume. Right is the x velocity along vertical direction at x= 0.67 m. "simu" means simulation. "exp" means experimental data from McClimans et al. (2012).

Conclusion

The current numerical model provides realistic prediction of the bubble oil boom system. The prediction of entrainment of oil droplets is a limitation of the current model. To consider the oil slick as a packing of oil droplets could solve the problem.

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