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Numerical analysis of a lock-release oil slick

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ABSTRACT

Presented in this paper for the spread of a lock-release oil slick is a numerical analysis based on the renormalization group (RNG) k-ε model for turbulence closure, the volume of fluid (VOF) method for tracking the oil–water interface, and a rigid-cover approximation for the open surface. In agreement with theoretical analyses and experimental observations, numerical results show that the spread of the oil slick passes through three phases: the initial inertial slumping phase in which the inertial force and the horizontal buoyancy are dominant and the front speed is constant, the transitional phase in which the viscous force begins to play an important role instead of the inertial force and the front speed declines, and the viscous self-similar phase in which the viscous force and the horizontal buoyancy are dominant and the front speed declines as $t^{-5/8}$. Typical flow and pressure distributions are illustrated.

1. Introduction

With increasing global oil demands, a large quantity of crude oil and refined petroleum products are transported by ocean vessels. Unluckily, an oil slick caused by the accident of collision, grounding or capsizing frequently occurs, resulting in permanent and widespread damage to marine and coastal ecological system by killing algae, sea birds, fish, whale, etc. [1]. Although many advanced technologies for hull design and navigation system have been used to ensure shipping security, severe accidents still continue to happen. To assess the environmental impacts caused by the oil slick and to take proper cleanup measures to minimize its damage, corresponding numerical simulation technique for understanding its evolution mechanism has received considerable attention [2–9].

An oil slick in a laboratory is frequently obtained by the sudden removal of a lock gate separating oil from water in a rectangular channel [10,6]. After the removal, the lighter oil will advance along the water surface driven by the heavier water, thus generating a so-called lock-release oil slick as a typical two-phase gravity current, as shown in Fig. 1 [6].

With regard to the evolution mechanism of the lock-release oil slick, there have been some efforts, with focus on the spreading law of slick front. Based on the magnitude analysis of buoyancy, inertial force, viscous force and surface tension, Fay indicated that the motion of the oil slick would undergo three phases, i.e. an inertial phase, a viscous phase and a surface tension phase [11]. However, the surface tension phase scarcely appears for the oil slick produced in the laboratory, due to the limit of channel length. The specific spreading law for the first two phases is obtained based on the depth-averaged shallow-water

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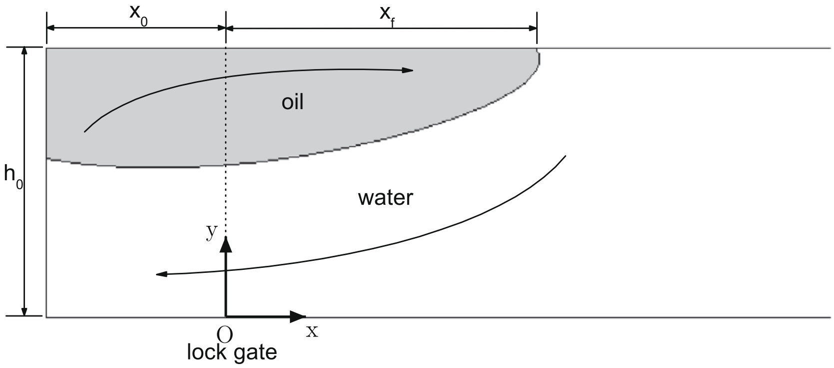

Fig. 1. Sketch map of a lock-release oil slick.

equations [12,13]. For the two-dimensional case concerned in this paper, it can be expressed as $x_f = 1.6(h_0 x_0 g')^{1/3} t^{2/3}$ and $x_f = 1.5(h_0 x_0)^{1/2} \nu_w^{-1/8} t^{3/8} g'^{1/4}$, where x_f is the length of the oil slick, h_0 is the initial depth of oil and water, x_0 is the length of the lock, t is the time measured from the removal of the lock gate, ν_w is the kinetic viscosity of water, and $g' = g(\rho_w - \rho_{oil})/\rho_w$ is the reduced gravitational acceleration, with g standing for the gravitational acceleration, ρ_w standing for the density of water, and ρ_{oil} standing for the density of oil [12,13].

Further experimental studies and field investigations at different scales show that a gravity current firstly moves at a constant front speed rather than the speed declining as $t^{-1/3}$ [14–17]. A so-called box model may be used to interpret this phenomenon to some extent [18]. According to Rottman and Simpson's summarization [19], the spread of the gravity current comprises four phases: the inertial slumping phase with a constant front speed, the inviscid self-similar phase with a front speed decreasing as $t^{-1/3}$, the viscous self-similar phase with a front speed decreasing as $t^{-5/8}$, and the surface tension phase. As the front of gravity is caught up by a strong disturbance produced by a water hit on the wall, transition from the inertial slumping phase to the inviscid self-similar phase happens [19].

Owing to the complexity of momentum transport in the lock-release oil slick, only partial characteristics are verified via numerical simulation [6,20]. Even for a single phase gravity current, spreading process is recently reproduced as a whole with various phases [18,21–25]. For the case of the lock-release oil slick as a two-phase gravity current, although Chen et al. succeeded in simulating the spreading process, their endeavors were still confined to the inviscid self-similar phase and the viscous self-similar phase [6]. Lin simulated the global energy balance associated with averaged kinetic energy, turbulent kinetic energy, potential energy, turbulent dissipation and viscous dissipation [20]. The integrated force balance of the lock-release oil slick is still not revealed via numerical simulation.

Presented in this paper is a numerical study on the spreading law and integrated force balance of the lock-release oil slick, as a continuation of pioneering work made by Chen et al. [6]. The specific objectives are: (I) to reproduce the spread of the oil slick as a whole with the inertial slumping phase, transitional phase and viscous self-similar phase, and (II) to reveal numerically the integrated force balance among the global horizontal buoyancy, inertial force, and viscous force.

2. Formulation

Following work [6], the volume of fluid (VOF) method [26] is employed to track the oil–water interface. For a grid cell, the volume fraction of oil θ_{oil} and the volume fraction of water θ_w satisfy

$$\frac{\partial \theta_{oil}}{\partial t} + \nabla \cdot (\mathbf{u}\theta_{oil}) = 0, \tag{1}$$

$$\theta_{oil} + \theta_w = 1, \tag{2}$$

where t is time, and $\mathbf{u}$ is velocity, with components in the horizontal (x) and vertical (y) directions denoted as u_x and u_y, respectively. As the cell is full of oil, $\theta_{oil} = 1$, and as the cell is full of water, $\theta_{oil} = 0$. The density and dynamic viscosity of the cell are, respectively, defined as $\rho \equiv \theta_{oil}\rho_{oil} + \theta_w \rho_w$ and $\mu \equiv \theta_{oil}\mu_{oil} + \theta_w \mu_w$, where μ_{oil} and μ_w are the dynamic viscosity of oil and water, respectively.

The Reynolds-averaged global equations for mass conservation and momentum transport in an inertial reference are given by

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0, \tag{3}$$

$$\frac{\partial (\rho \mathbf{u})}{\partial t} + \nabla \cdot (\rho \mathbf{u}\mathbf{u}) = -\nabla p + \nabla \cdot \boldsymbol{\tau} + \rho \mathbf{g} + \mathbf{F}, \tag{4}$$