



Relationship between momentum of an impinging drop and intensities of vortex rings generated below free surface



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ABSTRACT

The characteristics of vortex rings induced below the free water surface due to the impingement of a falling single drop with small drop diameters and two impact angles were investigated by means of a three-dimensional direct numerical simulation (DNS) with a Level-Set method. The results show that the present DNS well captures the structures and transport processes of a crater vortex-ring (CV) and a water-column vortex-ring (WCV) due to the vertical impingement of a drop, and that the intensity of the WCV is larger than that of the CV. In the oblique impingement of a drop, a CV is similarly generated, but a vortex tube (VT) creeping along the free surface is also generated instead of the WCV, and the intensity of the VT is much smaller than that of the CV. The relationship between the momentum of a drop and the intensity of the dominant vortex ring is determined independently of diameter and impact angle and is also consistent with the previous measurements (Takagaki and Komori, 2014).

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1. Introduction

Turbulent scalar transfer across the air–water interface due to impingement of liquid drops is of great interest in both geophysics and engineering. Particularly, from the geophysical point of view, the estimate of the air–sea heat and mass (CO₂) transfer rate due to impingements of raindrops on the sea surface is expected to improve predictions of local carbon budget and cyclone development in the tropical region, since the impingements of raindrops break the air–sea interface and promote scalar transfer. Therefore, it is of great importance to investigate the air–water scalar transfer mechanism due to the impingement of a single liquid drop and to investigate the relationship between the mass transfer coefficient due to multiple impingements of drops and the drop concentration.

To investigate the effect of the impingements of multiple drops on the mass transfer across the air–water interface, Takagaki and Komori (2014) carried out a laboratory experiment for measuring the flow and CO₂ concentration fields below the surface after the impingement of a single liquid drop using particle imaging velocimetry (PIV) and planar laser-induced fluorescence (PLIF) techniques. They visualized velocity and CO₂ concentration fields after the impingement of a liquid drop and found that the impingement of a drop on the water surface generates several vortex rings

(e.g. Rodriguez and Mesler, 1988; Cresswell and Morton, 1995; Peck and Sigurdson, 1995; Dooley et al., 1997; Santini et al., 2013) and those vortex rings renew the water surface. In addition, they applied the surface-renewal concept (e.g. Higbie, 1935; Danckwerts, 1951; Fortescue and Pearson, 1967; Komori et al., 1982, 1989, 1993) to the air–water mass transfer phenomenon caused by the multiple impingements of drops on the air–water interface. By introducing the concept of spatial and temporal intermittencies into the mass transfer model, they obtained the following equation for the liquid-side mass transfer coefficient k_L :

$$k_L = 1.46\pi T_{VR} n_{VR} n \sqrt{2D_L r_{VR}^3 V_{VR}}, \quad (1)$$

where T_{VR} is the presence time of the surface renewal eddy, n_{VR} the number of eddies induced by a single drop's impingement, n the number of drops impinging on a unit area of the air–water interface per second, D_L the diffusion coefficient of gas in water, r_{VR} the radius of the vortex ring, and V_{VR} the center velocity of a vortex ring (see Fig. 1(a)). By employing values of k_L measured through a gas transfer experiments in an open channel under a multiple-drops generator (Takagaki and Komori, 2007), they stated that modeled values of k_L obtained from the surface renewal concept (Eq. (1)) were proportional to measurement values of k_L under the condition of thin drop concentration without interaction between multiple drops, and k_L was proportional to the mean vertical momentum flux of multiple drops (MF). Finally they concluded that the surface-renewal model shown as Eq. (1) was well acceptable for the real

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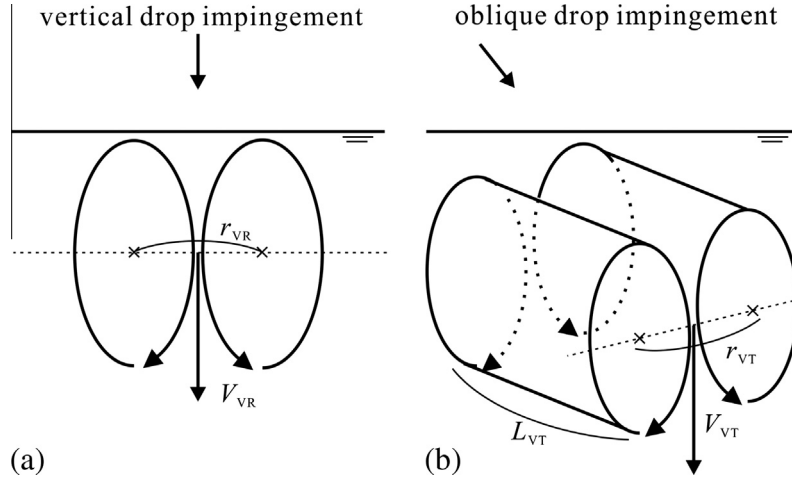


Fig. 1. Sketches of (a) vortex ring and (b) vortex tube. V_{VR} , center velocity; r_{VR} , radius of the vortex ring; V_{VT} , center velocity; r_{VT} , radius; L_{VT} , length of the vortex tube.

mass transfer phenomenon due to multiple impingements of drops. However, since the diameter of the impinged drop was limited to diameters larger than 2.2 mm because of the difficulty in the measurement, the investigation on drops with the diameter smaller than 2.2 mm has not been done yet. Impingements of such small drops rather exist in both engineering and geophysics. For example, it is estimated that the momentum flux of raindrops with diameters of $d_p < 2.2$ mm is almost 90% of the total momentum flux, when the rain has the rain rate of 1 mm h^{-1} and the raindrops distribute according to the distribution of Marshall and Palmer (1948). Moreover, the drops often impinge obliquely on the water surface and hence it is interesting to clarify the effect of the oblique impingement (e.g. Leneweit et al., 2005; Watanabe et al., 2008). However, it is much more difficult to conduct the laboratory experiment for the oblique impact.

Numerical simulation is useful for investigating the impingement of a single liquid drop with arbitrary drop diameter and impact angle. In fact, the splashing, bubble entrainment, underwater ambient noise and vortex rings generated by the impingement of a single drop have been the objects of many numerical investigations (e.g. Nystuen, 1986; Oguz and Prosperetti, 1990, 1991; Prosperetti and Oguz, 1993; Morton et al., 2000; Watanabe et al., 2008; Thoraval et al., 2012). However, there has been no study for investigating the liquid flow after the impingement of a single liquid drop and the relationship between the momentum of the drop and intensity of generated vortex rings.

The purpose of this study is therefore to investigate the relationship between the momentum of an impinging drop and intensities of vortex rings generated below the air–water interface by the impingement of a single drop on the surface against small drop diameters and two impact angles and to examine the validity of the model for air–water mass transfer due to multiple impingements of drops (Takagaki and Komori, 2014) by means of a three-dimensional direct numerical simulation (DNS) with a Level-Set method.

2. DNS

The movement of the air–water interface was captured using a Level-Set method (e.g. Sussman et al., 1994). The governing equations are conservation equations of mass (continuity), momentum (Navier–Stokes, NS), and Level-Set function ϕ , written as:

$$\frac{\partial u_j}{\partial x_j} = 0, \quad (2)$$

$$\frac{\partial u_i}{\partial t} + \frac{\partial u_i u_j}{\partial x_j} = -\frac{1}{\rho(\phi)} \frac{\partial p}{\partial x_i} + \frac{1}{\rho(\phi)} \frac{\partial \tau_{ij}}{\partial x_j} - \delta(\phi) \frac{\sigma \kappa(\phi)}{\rho(\phi)} \frac{\partial \phi}{\partial x_i} - g \delta_{2i}, \quad (3)$$

$$\frac{\partial \phi}{\partial t} + \frac{\partial u_i \phi}{\partial x_i} = 0, \quad (4)$$

where u_i is the i th component of the velocity vector ($i = 1$ and 2 denote the horizontal directions, and $i = 3$ denotes the vertical direction), ρ the density, p the pressure, τ the viscous stress tensor, Δ the smoothed Heaviside function, σ the coefficient of surface tension ($73 \times 10^{-3} \text{ N m}^{-1}$), κ the curvature of the surface, g the acceleration due to gravity, δ_{ij} the Kronecker delta. The surface tension was interpreted as a body force localized on the surface under the continuum surface-force (CSF) model proposed by Brackbill et al. (1992). The fluid density ρ and viscosity μ were estimated using the Heaviside function as a conventional Level-Set manner. The physical properties on each side are listed in Table 1.

The governing Eqs. (2)–(4) were discretized to construct a finite-difference formulation, and the simplified marker and cell (SMAC) method was used to solve the N–S equation. The discretizations of the advection terms in Eqs. (3) and (4) were derived from the second-order accurate fully-conservative scheme (Morinishi et al., 1998) and fifth-order accurate upwind-difference scheme (WENO scheme), respectively. The other spatial derivatives were approximated by a second-order accurate central difference scheme. The time integrations for the advection terms in Eqs. (3) and (4) were carried out by a third-order accurate Runge–Kutta method. The time integration for the diffusion term in Eq. (3) was carried out by the Crank–Nicolson method. The Level-Set function ϕ was reinitialized according to Yue et al. (2003). Slip boundary conditions were imposed on the velocity components on whole walls.

The computational domain and numerical grids for the computations of flows in the air and liquid are shown in Fig. 2. The sizes of the computational domain were 30.0 mm and 25.6 mm in the horizontal and vertical directions, respectively. The lower part of the computational domain was filled with quiescent liquid 16.0 mm deep. A single liquid drop was initially located over the quiescent

Table 1
Physical properties.

	Air	Water
ρ (kg m ⁻³)	1.205	998.0
μ (kg m ⁻¹ s ⁻¹)	1.8×10^{-5}	1.0×10^{-3}

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