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Water breakup phenomena in wave-impact sea spray on a vessel

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ABSTRACT

Breakup of water in wave-impact sea spray is examined in this paper. The formation of a spray cloud, caused by high energy striking of a sea wave on the bow or hull of a marine vessel, is dependent on the water breakup phenomena and droplet trajectories. The Weber and Reynolds numbers are key parameters defining the thresholds at which breakup begins. The model uses "stripping breakup" and "bag breakup" characteristics to demonstrate the breakup phenomena. A combined breakup model with droplet trajectories is developed in this paper to predict the extent of the breakup phenomena. The governing equations of breakup and trajectories of droplets are solved numerically. Stripping breakup occurs from the beginning of the breakup phenomenon and finishes in front of the vessel. Bag breakup completes the stripping breakup to create stable droplets with constant diameters. A sensitivity analysis evaluates the response of the model to various ranges of initial conditions. Numerical results have reasonable agreement with the size-velocity dependence characteristics at the tip of the bow. The extent of the spray as well as wet heights, obtained by the numerical solutions, are consistent with field observations reported for a Medium-sized Fishing Vessel (MFV).

1. Introduction

High energy striking of sea waves on a moving vessel creates wave-impact sea spray upstream and over the vessel (Bodaghkhani et al., 2016; Dehghani et al., 2016b; Zakrzewski, 1987; Zakrzewski et al., 1988). The resultant spray cloud travels over the vessel and carries droplets of various sizes and velocities (Ryerson, 1995). Droplet sizes and velocities determine the droplet paths and trajectories, and consequently the amount of incoming water to every point on the vessel (Dehghani et al., 2016a, 2016b; Zakrzewski et al., 1988). The incoming water flux is the most important key factor in estimating the accumulated ice on surfaces of vessels in cold regions (Horjen, 2013; Kulyakhtin and Tsarau, 2014).

Marine icing phenomena are strongly dependent on the extent of spray clouds over vessels (Borisenkov et al., 1975; Dehghani et al., 2016b; Lozowski et al., 2000; Zakrzewski, 1987; Zakrzewski et al., 1988). Size and velocity distributions of droplets are the most important characteristics of spray clouds and they are affected by water breakup phenomena and external forces exerted on droplets. The mass fraction of evaporation of droplets is usually negligible. The resultant droplets will have various sizes and velocities (Dehghani et al., 2016a, 2016b; Ryerson, 1995). Freezing of droplets on cold surfaces is strongly dependent on the droplet size and velocity (Dehghani-Sanij et al., 2017; Saha et al., 2016a). Limited information related to size and velocity distributions of droplets in spray clouds led past studies to use mono-size and mono-velocity models. Horjen (2013) used a size of 1.8 mm for the droplets. Shipilova et al. (2012) assumed 0.25 mm and 2 mm as the droplet sizes. Horjen (2015) considered the size of the droplets as 3.8 mm. Chung and Lozowski (1998) assumed the same size of droplets as Zakrzewski (1986), 1.75 mm. Kulyakhtin and Tsarau (2014) reported that droplet sizes are between 1 and 2 mm. They assumed that the spray cloud is dilute and droplets travel over the vessel individually. In addition, they assumed that the initial velocity of the droplets is equal to the wind velocity and one droplet is representative of droplets in the spray cloud.

The wave-impact sea spray phenomenon can be divided into several consequent processes: wave impact, sheet formation, sheet breakup, droplet breakup, and droplet trajectories (Bodaghkhani et al., 2016; Dehghani et al., 2016a, 2016b). The phenomenon is intermittent and dependent on time. There have been past studies on the duration of wave-impact sea spray (Ryerson, 1995; Zakrzewski, 1987). However, while the sizes of the droplets were reported, there was no record of the vertical distribution of size or velocity. The droplet velocities in a cloud of spray are variable and there have been few past studies about the order of droplet velocities (Dehghani et al., 2016a, 2016b).

Wave impact on a solid object has been an active field of research for many years. Past studies have estimated the force exerted on an object (Galiev and Flay, 2014). However, various limitations exist in past numerical methods (Clauss et al., 2009). Smoothed Particle Hydrodynamics (SPH), which is a Lagrangian method, is useful in

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Nomenclature

C_a	Added mass force coefficient (–)
C_d	Drag coefficient (–)
D_d	Droplet diameter (mm)
D_{max}	Maximum diameter of droplets (–)
D_n	Normalized diameter of droplets (–)
F_b	Freeboard of MFV (m)
g	Gravitational acceleration (m/s^2)
H_s	Significant wave height (m)
L	Vertical distance of the start of breakup to the tip of the bow (m)
m_d	Droplet mass (kg)
Re	Reynolds number (–)
r_b	Bag breakup radius (m)
r_d	Droplet radius (m)
r_s	Stripping breakup radius (m)
T_s	Water sheet thickness (m)
t	Time (s)
U	Relative velocity of wind to the vessel (m/s)
V_a	Air velocity (m/s)
V_d	Droplet velocity (m/s)
V_{max}	Maximum velocity of droplets (m/s)
V_n	Normalized velocity of droplets (m/s)
V_s	Water sheet velocity (m/s)
We	Weber number (–)
x	x-component of the position vector of droplets (m)
$\dot{x}$	x-component of the velocity vector of droplets (m/s)
$\ddot{x}$	x-component of the acceleration vector of droplets (m/s^2)
Z*	Criterion for stripping breakup (–)
z	z-component of the position vector of droplets (m)
$\dot{z}$	z-component of the velocity vector of droplets (m/s)
$\ddot{z}$	z-component of the acceleration vector of droplets (m/s^2)
$\forall_d$	Droplet volume (m^3)
γ	Liquid density to air density ratio (–)
μ_a	Dynamic viscosity of air (kg/m. s)
ρ_a	Air density (kg/m^3)
ρ_d	Sea water density (kg/m^3)
σ	Surface tension of sea water (N/m)
τ_b	Lifetime of bag breakup (s)
τ_s	Lifetime of stripping breakup (s)

modeling the wave impact phenomenon (Didier et al., 2014). In addition, water entry models include the velocity of the resultant water sheet (Gu et al., 2014). Water breakup phenomena and impact on a surface have also been examined in past studies (Galiev and Flay, 2014; Saha et al., 2016b; Yang et al., 2012).

Liquid sheet breakup has been widely investigated (Yang et al., 2012; Zhao et al., 2015). The wavelengths of instabilities in a sheet of liquid determine the characteristics of separated ligaments and droplets (Negeed et al., 2011). The splash of a droplet striking a solid surface is dependent on the Reynolds, Weber and Ohnesorge numbers. The non-dimensional average roughness of the surface and contact angles are also important in the creation of splash (Bussmann et al., 2000). The phenomenon of Kelvin-Helmholtz instability is a key consideration for increased instabilities in water sheets and consequently the occurrence of the breakup phenomenon (Lozano et al., 1998). A jet impinging onto a surface demonstrates three breakup modes: rim, hole and ligament. In this case, the dimensionless droplet sizes are dependent on the Weber number (Ren and Marshall, 2014). Disc impact on a liquid surface can also create water breakup, which is dependent on the Weber number (Peters et al., 2013). Spray breakup and penetration can be modeled using non-dimensional numbers related to breakup, droplet trajectories methods and evaporation rates (Apte and Moin, 2011; Reitz and Diwakar, 1987, 1986; Sazhin et al., 2003).

In this paper, the phenomena of water breakup and droplet trajectory are used to predict the penetration of an upward spray of sea water into the space in front of a vessel. In addition, droplet dispersion and movement over the vessel will be analyzed. An analysis will be performed to evaluate the sensitivity of the model to several variables. The analytical model and numerical results are discussed and compared with results reported in the literature.

2. Wave breakup model

Wave-impact sea spray occurs as a result of the high energy impact of a sea wave on the bow or hull of a vessel. The impact creates a sheet of water rising on the bow or hull surface. Sheet formation is the first step of the breakup phenomenon (Dehghani et al., 2016b). Fast movements of the sheet of water on a rough surface of the bow or hull, considering shear forces between the outer layer of the water sheet and ambient air, imply the creation and growth of instabilities in the water sheet. The sheet of water is split into some ligaments and strips. This stage can be named sheet breakup. The continuation of the growth of the instabilities causes the division of strips or ligaments into many droplets. This stage is named droplet breakup. The resultant droplets travel in the air with drag forces and gravitational forces. They also continue experiencing breakup phenomena to reach various stable states (Clanet and Villermaux, 2002; Jain et al., 2015; Mashayek and Ashgriz, 2011; Negeed et al., 2011). Fig. 1 shows a schematic of the steps of the breakup phenomena in wave-impact sea spray.

Breakup phenomena of wave-impact sea spray are significantly affected by the air stream. Instabilities of water sheets and ligaments are increased by air streams, which make them more unstable. Consequently, droplets split up before reaching a stable mode. There are several models for the mechanism of the breakup of liquid moving in an air stream. All models are developed based on the growth of the internal instabilities and shear forces on the surface of droplets or ligaments (Chryssakis et al., 2011; Dai and Faeth, 2001; Guildenbecher et al., 2011; Hsiang and Faeth, 1992; Krzeczkowski, 1980; Lee and Reitz, 2000; O'Rourke and Amsden, 1987; Reitz, 1987; Reitz and Diwakar, 1987). An analysis of two-phase media including the liquid phase, which splits up to smaller sizes, and the gas phase, which

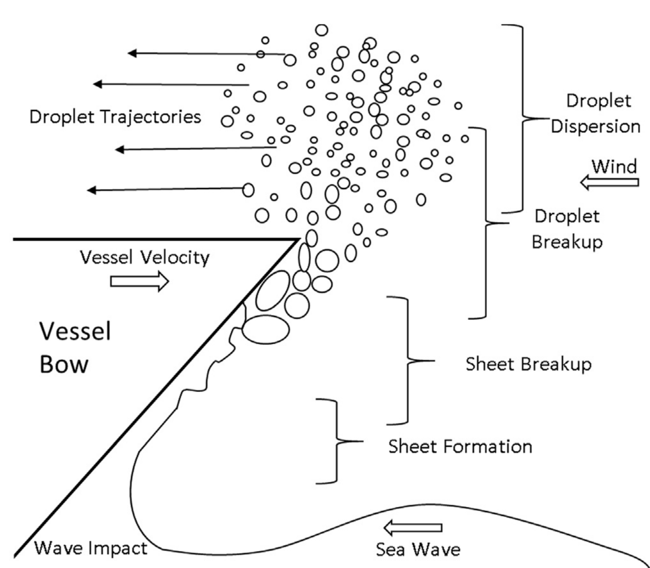

Fig. 1. Schematic of wave-impact sea spray formation and water breakup.