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Droplet size and velocity distributions of wave-impact sea spray over a marine vessel

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ABSTRACT

The spatial distribution of droplets in a spray cloud created by wave-impact sea spray and the distribution of their sizes and velocities over a vessel deck are investigated. Existing mono-size and mono-velocity models of sea spray are not accurate enough for modelling marine icing phenomena. Wave-impact sea spray creates numerous droplets in front of and around a vessel. Droplets are the result of sheet and droplet breakup of sea water. The velocity-size dependence of the resultant droplets causes the creation of various sizes and velocities of droplets. A droplet trajectory method employs the velocity-size dependence of the droplets to find their spatial distributions in the cloud of spray over the vessel deck. Drag and body forces overcome the initial velocities of the droplets, and consequently, they follow the wind and gravitational directions. The motion of the droplets affects the shape and extent of the spray cloud over the vessel. A numerical scheme is used to find the distribution of sizes and velocities of the droplets over a vessel. Results show that neither the smallest nor the largest droplets reach the maximum height. The medium-sized droplets can reach the maximum height of the spray cloud. As the spray cloud travels over the deck, the droplet velocities become almost the same. Comparing the numerical results with field observations shows that the predicted results are consistent and have reasonable agreement with the field measurements.

1. Introduction

Wave-impact sea spray, which results from high energy striking of sea waves on vessel bows or hulls, is the main cause of marine icing in cold regions (Bodaghkhani et al., 2016; Lozowski et al., 2000; Panov, 1978; Zakrzewski, 1987). Every spray cloud carries numerous droplets towards the vessel platform (Zakrzewski, 1986; Zakrzewski et al., 1988). The nature of the spray cloud and droplets affects the process of ice accretion on a marine vessel (Borisenkov et al., 1975; Ryerson, 1995). A spray cloud can be defined based on time-dependent spatial distributions of sizes and velocities of the droplets. Using the spatial distribution of size and velocity of droplets, the concentration of droplets in a spray cloud, which means droplet numbers per unit volume of the spray cloud, is achievable (Dehghani et al., 2016; Zakrzewski et al., 1988).

Among with the ambient temperature, relative humidity and wind velocity, the incoming water flux to a vessel deck is important for calculating the amount of accumulated ice on the vessel (Horjen, 2013; Kulyakhtin and Tsarau, 2014). The accumulated ice is brine-spongy ice. The water flux varies with position and time. Size and velocity distributions of the droplets in a spray cloud determine the local concentration of droplets and the spray flux at every point of a vessel. Distributions of size and velocity will yield the water flux, which will also be a function of time and space (Dehghani et al., 2016).

Past studies reported mono-size models for which there is no distribution of size and velocity for a cloud of spray or models without using any droplet size. Horjen (2013) used a size of 1.8 mm for 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) used the same size of droplets as Zakrzewski (1986), 1.75 mm. Kulyakhtin and Tsarau (2014) mentioned that droplet sizes are between 1 and 2 mm. Dehghani-sanij et al. (2015) modeled a case of marine icing without using any droplet size. These past studies assumed the initial velocity of the droplets as equal to the wind velocity. A lack of recording the distribution of size and velocity in a spray cloud led the researchers to use mono-size and mono-velocity models.

Droplet trajectory models can predict the droplet paths and consequently their positions (Dehghani et al., 2009). When a spray cloud moves, droplets start their movements at their initial positions and finish by impinging on vessel surfaces (Zakrzewski et al., 1988). The droplet trajectory method, which needs the initial size and velocity distributions, will determine the distribution of the size and velocity of

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Nomenclature

C_a	Added mass force coefficient (−)
C_D	Drag force coefficient (−)
D	Droplet diameter (mm)
$\frac{\mathcal{D}(\ )}{\mathcal{D}t}$	Material derivative (( )/s)
F_D	Drag force (mN)
F_{Dx}	x-component of drag force (mN)
F_{Dz}	z-component of drag force (mN)
F_G	Gravitational force (mN)
g	Gravitational acceleration (m/s^2)
m_d	Droplet mass (kg)
Re	Reynolds number (−)
t	Time (s)
U	Relative velocity of the wind to the vessel (m/s)
V	Droplet velocity with respect to the vessel (m/s)
V_a	Air velocity with respect to the ground (m/s)
V_d	Droplet velocity with respect to the ground (m/s)
V_x	x-component of droplet velocity with respect to the vessel (m/s)
V_z	z-component of droplet velocity with respect to the vessel (m/s)
w	Liquid water content (g/m^3)
x	x-component of the position vector of droplets with respect to the vessel (m)
$\dot{x}$	x-component of the velocity vector of droplets with respect to the vessel (m/s)
$\ddot{x}$	x-component of the acceleration vector of droplets with respect to the vessel (m/s^2)
z	z-component of the position vector of droplets (m)
$\dot{z}$	z-component of the velocity vector of droplets with respect to the vessel (m/s)
$\ddot{z}$	z-component of the acceleration vector of droplets with respect to the vessel (m/s^2)
$\forall_d$	Droplet volume (m^3)
γ	Sea water density to air density ratio (−)
ρ_a	Air density (kg/m^3)
ρ_d	Sea water density (kg/m^3)
θ	Travel angle of droplets (°)

the droplets at every section of the spray cloud, and consequently, the final distribution of the spray flux over the vessel surfaces (Dehghani et al., 2016, 2013).

The liquid water content (LWC) of a spray cloud over a vessel deck is affected by the distributions of size and velocity of droplets over a vessel platform (Dehghani et al., 2016; Ryerson, 1995). The collision efficiency, which is a key parameter in calculating the fraction of impingement of the droplets on a specific surface, is also a function of the size and velocity of the droplets close to the surface (Zakrzewski, 1986). The freezing rate can be affected by the incoming flux of water and the collision efficiency. Both are also dependent on the distribution of size and velocity of droplets (Chung and Lozowski, 1998; Chung et al., 1998; Sharapov, 1971; Shipilova et al., 2012).

Therefore, determination of the distributions of size and velocity of the droplets and their variations over marine vessels during the motion of a spray cloud are essential for accurate modelling of marine icing phenomena (Zakrzewski et al., 1988). The assumptions of constant droplet sizes and velocities used in previous models of marine icing are not satisfactory. These assumptions do not yield a sufficiently accurate estimation of ice accretion over a marine vessel. A vertically uniform size and velocity are the most common assumptions in past studies (Horjen, 2015, 2013; Kulyakhtin and Tsarau, 2014; Lozowski et al., 2000; Shipilova et al., 2012).

This paper focuses on a new model for the distributions of size and velocity of droplets in a spray cloud over a marine vessel, using a droplet trajectory method and droplet-size-dependent characteristics after water breakup in front of a vessel. New patterns of distributions of size and velocity are presented. The distribution of size and velocity can determine the extent of the spray cloud over a vessel. Although the model is examined using an available case of wave-impact sea spray, the model can be used for every different case to find the distribution of size and velocity of droplets in a cloud of spray. The model will be compared with available data from field observations.

2. Spray cloud processes

Wave-impact sea spray is created by high energy collisions between vessels and waves (Dehghani et al., 2016; Zakrzewski, 1986). The process of creating a spray cloud and its development and motion can be divided into several stages: wave impact, sheet breakup, droplet breakup, spray cloud formation, spray cloud acceleration and deceleration and spray cloud fall and impingement. These stages have not been well understood (Dehghani et al., 2016; Ryerson, 1995). The mechanisms of sheet creation, sheet breakup and droplet breakup have been examined in a few past studies but need more investigation (Bullock et al., 2007; Dehghani et al., 2016; Galiev and Flay, 2014; Greco et al., 2013; Gu et al., 2014; Ren and Marshall, 2014).

After the stage of droplet breakup, there are numerous droplets with various sizes and velocities in the spray cloud. At the front edge of the vessel, the droplets are moving upward and also in the same direction as the vessel. The stage of spray cloud formation begins with decelerating and accelerating droplets. Upward movement of the droplets is decelerated by drag forces and body forces. Drag forces are created as a result of the relative velocity of the droplets and wind. Body forces occur with the gravity force exerted on the droplets. Due to the drag force and body force, the vertical component of droplet velocities decreases to reach zero. At this point, droplets reach their maximum height. The horizontal component of the droplet velocities experiences the same trend. The start of the horizontal movement of the droplets is usually in the opposite direction to the wind velocity. The wind slows down the droplets. After a short time, in the decelerating period, the horizontal velocities of the droplets become zero. This point is the maximum horizontal development of a spray cloud in the opposite direction of the wind.

Droplets with a vertical velocity of zero, which are at their maximum heights, start a downward movement because of gravity. This accelerates the droplets to reach their terminal velocities. The droplets with zero horizontal velocities are affected by the wind velocity and increase their velocities. The wind accelerates these droplets and increases their velocities to the wind velocity. Acceleration of the droplets continues until the droplets strike the vessel surfaces.

The spray cloud fall and droplet impingement are the last stages of motion of a spray cloud over a marine vessel. The various droplets with various sizes and velocities take different paths and reach different positions. The drag force, wind velocity, droplet size, gravity and initial velocity of droplets determine the trajectory of the droplets. Fig. 1 illustrates these stages of a spray cloud development related to wave-impact sea spray over a marine vessel. The information of the figure is from a medium-size fishing vessel (MFV) (Borisenkov et al., 1975; Sharapov, 1971; Zakrzewski, 1986). The important components of the MFV are illustrated in the figure. The overall length of the vessel is about 39.5 m. The foremast is located at 11.0 m from the ship bow. The front side of the superstructure is located at a distance of 19.2 m from the ship bow. The height of the superstructure above the deck is 4.5 m. The lifeboat is located 29.0 to 34.1 m from the ship bow (Zakrzewski et al., 1988). In Fig. 1, a coordinate system of x-z is attached at the tip of the bow. The z-axis represents the vertical distance from the tip of the bow and the x-axis represents the horizontal component from the tip