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Numerical modeling of two-dimensional sea spray icing on vessel-mounted cylinders

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ABSTRACT

This report presents an important extension of the first Norwegian marine icing model: ICEMOD. That model was one-dimensional in the sense that the brine film covering the accreted ice moved only in one coordinate direction. The improved model, ICEMOD2, presented in this article is two-dimensional. After a thorough presentation of the mathematical model and an outline of the numerical method used the model is applied to cylinders with various diameters. The brine film is acted upon by both wind and spray stress forces and the gravity force. Model results are compared with real icing observations on vertical cylinders placed on the observation vessel "Endre Dyrøy" (former trawler) and satisfactory agreements are obtained. A mean spray mass flux formula based on spray measurements on the same vessel was used. A simple theoretical formula is used to calculate single spray duration. Perhaps somewhat surprisingly it turns out that maximum ice thickness often occurs at some angle away from the stagnation line. But this form of the ice profile has actually been observed by others. Finally, sensitivity tests were done to examine the possible effect of the vessel speed, spray salinity, cylinder heeling angle and relative wind heading. It turns out that variations of the relative wind direction have the most significant effect upon vessel icing. The model tests show that more ice accumulates when the heading increases, the vessel speed increases or the spray salinity decreases. If the cylinder is not vertical ice accumulates slightly asymmetrical around the stagnation line, provided a sufficient wet icing mode is present.

Sea spray icing on a ship. From http://upload.wikimedia.org.

PART 1: PRESENTATION OF THE MODEL

1. Introduction

In the 1980s a numerical marine icing package called "ICEMOD" (Horjen and Vefsnmo, 1987) was developed at the Norwegian Hydrotechnical Laboratory (NHL). The work was going on for about ten years. At that time there was great interest in searching for oil in northern Norwegian waters, and the oil companies wanted to know the risk of icing on oil rigs and supply vessels. The author of this report was responsible for developing a mathematical icing model. The accompanying numerical model turned out to give satisfactory results compared to field and laboratory experiments. But the model was restricted to analyzing problems in one space dimension along the icing surface. For example, for icing on a non-horizontal cylinder only icing at the stagnation line was calculated. For calculating ice load on the whole cylinder we then had to assume a specified ice profile. The horizontal cylinder problem is however one-dimensional, and ICEMOD also contained a module for calculating icing along the circumference in this case. These results agreed quite well with controlled laboratory tests in the NHL outdoor icing wind tunnel (Horjen, 1990).

ICEMOD became probably the first real time-dependent sea spray icing model ever developed. Several stationary models were developed during the same pioneer time period. One of the most well-known stationary models was the Canadian model RIGICE (Roebber and Mitten, 1987), especially applicable to offshore drilling platforms. RIGICE is based on the segmentation approach which in fact also was used in the very first version of ICEMOD. The first comprehensive Canadian icing model for vessel icing was the "Midgett" model, developed at the University of Alberta (Lozowski and Zakrzewski, 1993). (USCGC *MIDGETT* is a US coast guard patrol vessel.) The model is categorized

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Nomenclature

R	instantaneous local icing intensity (kg/(m^2/s))
R_w	instantaneous local water catch rate (kg/(m^2/s))
Q	unit heat flux (W/m^2)
$\dot{M}$	time-average spray mass flux far from the icing object (kg/(m^2/s))
U	wind speed (m/s)
T	wave period (s)
S	salinity (‰)
D	initial cylinder diameter (m)
C	specific heat capacity at constant pressure (J/(kg °C)) or wave speed (m/s)
W	vessel speed (m/s or knot)
V_1	free horizontal spray velocity (m/s)
f	humidity or spray frequency (1/s)
θ	temperature (°C)
γ	local collection efficiency
ρ	density (kg/m^3)
δ	brine film thickness (m)
μ	dynamic viscosity (kg/ms)
ν	kinematic viscosity $= \mu / \rho$ (m^2/s)
λ	wave length (m)
τ	volume fraction
σ	interfacial distribution coefficient
l_0	specific latent heat of fusion of pure ice (J/kg)
$l_f = (1-\sigma)l_0$	specific latent heat of fusion of saline ice (J/kg)
l_v	specific latent heat of evaporation
$\dot{m}_v$	mass flux of vapor from the water film on the ice surface (kg/(m^2 s))

Subscripts

C	collision-generated
W	wind-generated
r	relative
i	ice
b	brine film
a	air
w	sea surface
s	significant
sp	spray

as a time-dependent spray icing model due to a combination of a slow and a fast time dependence. The slow variation is the hourly changes in the environmental conditions and the fast variation is the change in the spray mass flux during one spray period. But the model seems to be somewhat incomplete concerning the transient transport of liquid along the icing surface. Based on empirical Russian results (Panov, 1976) the *effective* distribution coefficient used in the Midgett model is assumed to be constant (0.75), in contrast to the results of Makkonen (1987), indicating that the effective distribution coefficient increases with increasing freezing fraction. In ICEMOD, on the other hand, the *interfacial* distribution coefficient is assumed to be constant (0.34). This approximation is also based on several empirical results to be discussed in Section 2.3 of this article.

The new spray icing model, let us name it ICEMOD2, presented in this article may be used to calculate ice accretion due to impact- and wind-generated sea spray on the *whole* windward side of a non-horizontal cylinder placed on an offshore oil rig or a vessel. This article is however limited to analyzing vessel icing. The main intention is to give a first thorough presentation of the mathematical foundation of a time-dependent icing model with two space variables, i.e. the set of differential equations necessary to find the most important parameter controlling sea spray ice accretion: the brine film salinity.

2. The icing equations

We now consider a cylinder making an angle υ with the horizontal plane (Fig. 1). We assume that the wind is blowing normal to the cylinder axis. A curvilinear coordinate system (s,ζ) is introduced with s along the cylinder circumference (including accreted ice) and the ζ-axis pointing upward and parallel to the cylinder axis. We will consider ice accretion only on the upwind side of the cylinder between the points S_1 and S_2. Origin of this system is the lower point S_1 and s is positive in the clockwise direction. Unless we have the special case of dry icing (to be discussed later) the ice surface is covered by a thin liquid layer. Using the boundary layer approximation of Schlichting (1979) and assuming uniform temperature and salt mixing over the liquid film layer the integrated continuity, enthalpy and salt diffusion equation becomes:

$$\frac{\partial}{\partial t}(\rho_b\delta) + \frac{\partial}{\partial s}(\rho_b\delta u_b) + \frac{\partial}{\partial \zeta}(\rho_b\delta w_b) = R_w + \dot{m}_v - R \tag{1}$$

$$\rho_b C_b \delta \frac{D\theta_b}{dt} = Q_s + l_f R + Q_i \tag{2}$$

$$\rho_b \delta \frac{DS_b}{dt} = R(S_b - S_i) - R_w(S_b - S_w) - S_b \dot{m}_v \tag{3}$$

where $\frac{D}{dt}$ is the *total* derivative:

$$\frac{D}{dt} = \frac{\partial}{\partial t} + u_b\frac{\partial}{\partial s} + w_b\frac{\partial}{\partial \zeta}.$$

Q_s is the net heat flux to the liquid film at the air/brine film interface and $Q_i \le 0$ is the heat flux to the ice at the brine film/ice interface. The mass flux of vapor $\dot{m}_v$ is normally due to evaporation from the icing surface, but may in some special cases also be due to condensation of vapor in the air. The net heat flux is a combination of several terms:

$$Q_s = Q_c + Q_e + Q_w + Q_r + Q_v \tag{4}$$

where

Q_c	sensible heat flux (convective transport outside the air boundary layer)
$Q_e = l_e \cdot \dot{m}_v$	heat flux due to vapor transport
Q_w	heat transfer between impinging spray and liquid film
Q_r	heat transfer by radiation
Q_v	heating due to adiabatic compression of the air and viscous work in the air boundary layer.

Cooling of the collision-generated droplets during flight is taken care of by the heat flux term Q_w. Due to the sponginess of accreted saline ice the heat transport at the brine film/ice interface is assumed to be rather small and has been neglected in this study. The heat loss to the underlying structure may however be important in the very beginning of an icing process.

The velocity components of the brine film movement are u_b and w_b in the s and ζ-direction respectively and ρ_b, δ and S_b are the local density, thickness and salinity of the brine film. A thorough derivation of the above equations is given in Horjen (1990).

We now introduce two new dependant variables X and Y defined by:

$$X = \rho_b\delta \quad Y = \rho_b\delta\, S_b. \tag{5}$$