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A scale-bridging model for ice particles melting in air

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HIGHLIGHTS

- A new model has been developed for ice particles undergoing phase change due to convection.
- Validation against experimental data showed good agreement.
- The importance of the evaporation effects in the model was illustrated.
- The importance of thin water film around the melting ice particle is discussed.

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ABSTRACT

This work is devoted to the development of a zero-dimensional semi-empirical sub-grid model (or sub-model) which predicts the size and temperature of a solid particle undergoing a phase change inside a gaseous phase. Specifically, two sub-grid models are developed, one for a solid spherical particle and another for a solid cylindrical particle. The models can be implemented as a sub-grid model in Euler-Lagrange numerical models for particulate flows with solid particles undergoing phase changes. They can be used as scale-bridge relations to create a bridge between the scales in Euler-Lagrange models, to relate the heat transfer occurring at the interfacial scale to the macro heat transfer conservation equation written for the gaseous phase. The input parameters in our model are the particulate Reynolds number (*Re*), the Grashof number (*Gr*), the Stefan number (*Ste*) and the Prandtl number (*Pr*). The model has been validated against experimental results obtained by authors and existing experimental results produced by Janna and Jakubowski (1990). Good agreement is observed between our model predictions and both experimental results. The importance of a thin water film around the melting ice particle is discussed. The emissivity of the water film has been found to be influential in determining the melting rate of the ice particle.

1. Introduction

The process of ice melting or water freezing due to natural or forced convection in its surrounding air is common process in various natural and industrial processes. The problem of ice accretion, which is the formation of ice on the surface of solid objects in cold and humid ambient conditions containing tiny supercooled water droplets, affects various industrial and transport processes. Ice accretion has adverse effects on airplane wings, on ships, on electric power transmission lines, etc. Frost formation is another such process which can have unfavorable effects on various industrial processes. As an example, when humid air passes through a pipe with a cold surface, the resulting frost formation can lead to lowered heat transfer between the air and pipe and a greater pressure drop in the air flow. Recently, with increased demand for numerical modeling of these processes, the role of reliable mathematical models describing the melting or solidification of ice has also grown.

There have been many experimental efforts in the past to understand the melting/solidification of ice/water caused by natural or forced convection. It will be shown in this study that, when an ice particle starts melting, it develops a water film on its surface which is primarily responsible for the heat exchange with the air. The water film exchanges heat with the air in the form of convection, radiation and evaporative cooling. However, most past efforts to model this process have left out radiative or evaporative cooling of the water film itself.

Lopera-Valle and McDonald (2016) experimented with heating and melting ice in subzero ambient air temperatures. A coating of

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Nomenclature

C	concentration/drag coefficient
c	specific heat
D	diffusion coefficient
d	diameter
g	gas/acceleration due to gravity
h_c	heat transfer coefficient
h_{sf}	latent heat of fusion of ice
h_v	latent heat of vaporization
k	thermal conductivity
l	length
l_t	length corresponding to the average particle temperature
MW	molecular weight
m	mass
Nu	Nusselt number
n	normal to the surface
Pr	Prandtl number
q	rate of heat transfer
Ra	Rayleigh number
Re	Reynolds number
RH	Relative Humidity
r	radius
r_t	radius corresponding to the average particle temperature
T	temperature
t	time
u	velocity
V	Volume
y	mass fraction

Greek symbols

α	thermal diffusivity
α_{ab}	absorption coefficient
β	thermal expansion coefficient
δ	thickness
ϵ	emissivity
μ	dynamic viscosity
ν	kinematic viscosity
ρ	density
σ	Boltzmann constant
τ	Transmissivity of water layer

Subscripts

b	bottom surface of cylinder
bl	boundary layer
l	liquid
m	melting
p	particle
s	surface of spherical particle/side surface of cylindrical particle
t	top surface of cylinder
∞	air/ambient fluid

Superscripts

c	characteristic length
$''$	flux (per unit area)
$\bar{}$	average
$\dot{}$	rate (per unit time)

an alloy was deposited on a polymer composite and an ice layer was formed over the alloy coating. Electric current was supplied to the alloy to generate heat energy via resistive heating. It resulted in the ice heating and melting. The numerical model provided in the paper to predict the experimental results under-predicted the required heating time and melting time. The under-prediction can be attributed to the fact that the numerical model did not consider the radiative heat transfer between the air and ice. Its inclusion in the numerical model would result in a higher loss of heat from the ice-air interface, which would eventually result in a longer heating and melting time.

Lee et al. (1997) developed an analytical 1-D model to predict the frost formation when water vapor comes into contact with a cooled surface kept below 0 °C. They formulated a 1-D mass transfer equation for water vapor and a 1-D heat transfer equation for the frost layer. The heat transfer and mass transfer on the air side of the frost were calculated using existing auxiliary relations. However, they missed the radiative heat transfer between the air and the frost layer. The results were compared with experimental results in which humid air was passed over the cooled horizontal plate resulting in frost formation.

Lee et al. (2003) skipped the use of empirical correlations and solved a set of partial differential equations (PDEs) assuming that the frost layer was a porous medium. The heat transfer within the frost layer was defined using *'effective thermal conductivity'*. The model was in good agreement with experimental results, with an error of less than 10%, unlike previously existing models since this model did not use any empirical correlations. However, radiative heat transfer between the air and the frost layer was again ignored.

Wu et al. (2016) carried out the numerical modeling of an existing experiment from the literature, applied to the frost formation. In the experiment, a humid airflow was introduced above a cooling source through a thin rectangular channel such that the water vapor in the air directly started condensing into ice crystals as soon as the air entered the channel. A mass transfer model was developed in the numerical study to define the mass transfer rate between the phases in order to predict the frost layer growth. The calculated rate was used in the source terms in each conservation equation in ANSYS Fluent, implementing the Euler-Euler multiphase flow model. The obtained results were claimed to be in good agreement with experiments.

Battisti et al. (2006) provided a numerical model to study the effect of warm air flows inside the wind turbine blades, melting the ice forming over the blades. The radiative heat transfer and convective heat transfer were incorporated using a so-called overall heat transfer coefficient. The heat transfer due to the formation of new ice was skipped. When the Euler-Lagrange-based model of particulate flows with a phase change effect is applied to predict the heat and mass transfer between the particles and fluid, subgrid equations (submodels) are used. The main condition of submodels usage is a particle must be less smaller in size than the cell of a numerical grid used to calculate the conservation equation in Eulerian space. In order to overcome the problem of subgrid models, the so-called *resolved* discrete particle model (RDPM) or particle-resolved direct numerical modelling (PR-DNS) can be used (Deen et al., 2014, 2012) when the cell of a numerical grid is less smaller in size than the particle. However, applied to particulate flows where phase change phenomena plays a significant role, PR-DNSs are still computationally expensive tools used to understand the