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Transport processes in a wet granular ice layer: Model for ice accretion and shedding

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ABSTRACT

Aircraft icing due to ice crystal impact occurs in the relatively hot areas near the engines, where the ice particles partially melt. Ice crystal accretion in the presence of a liquid water fraction leads to the creation of a wet granular ice layer. The present study addresses the transport processes in this granular ice layer in order to describe theoretically the ice accretion phenomenon and to predict the instant of ice layer shedding. Among these transport phenomena are heat transport in the granular solid ice region, water region and gas area, ice granule melting and solidification, and liquid water imbibition. Within the scope of this work, a theoretical model describing these transport phenomena in a granular media is developed. The equations for the effective transport are formulated and solved numerically using a computational code based on a Finite-Volume method. The model is applied to the description of ice crystal accretion on warm aircraft components and the results are compared with available experimental data. The theoretical predictions agree well with the experimentally observed icing and shedding behavior by describing the composition and heat and mass transport within the ice layer.

1. Introduction

Melting of porous structures or melting of material bound by a solid matrix occurs in a multitude of processes in nature and industrial applications. Fallen snow usually consists of ice crystals, entrapped air and, depending on the weather conditions, more or less liquid water. Natural melting of the snow influences its liquid water content, which affects the snow's behavior significantly, in particular with regard to avalanches [1]. Often fallen snow is melted as a means to clear roads, airport runways or helipads to increase transportation safety [2,3]. Atmospheric ice crystals which are ingested into aero-engines start to melt as they are exposed to the warm environment of the engine. At a certain melt ratio, they accumulate on stator blades forming a granular (or porous) ice/water accretion, which reduces the engine's power, reliability and efficiency [4–6]. The melting behavior of such ice-pack accretion determines its adhesion to the surface, moment of shedding [7] and therefore the icing severity.

Ice slurries, comprising ice particles suspended in liquid water, are an alternative solution for secondary refrigerants [8], exhibiting many advantages over single-phase fluids. Yet, their handling is more complicated, especially since describing the flow behavior [9] and the heat transfer characteristics [10] are very challenging tasks. Since the ice crystals are usually irregular, even prediction of the melting behavior of a single particle is a challenging problem [11].

Food has been conserved by freezing for thousands of years [12], which often leads to porous structures due to the morphology of the food stuff or by outgassing of air whilst solidifying. The freezing and thawing process of the food significantly influences its quality. Air entrapment in melting solids also affect the melting behavior of ice cream [13], the welding of sintered materials [14–16] or the selective laser sintering process [17]. Further applications are magma liquefying porous rock beds [18,19] or a nuclear meltdown, where the porous rubble of the fuel rods melts [20].

Phase change materials are often used for thermal control of electronics, spacecraft or buildings. They are capable of storing energy by absorbing or releasing the latent heat of fusion. Usually, the phase changing material is contained in a porous structure of a solid, whereby the non-melting material provides structural stability at the operating temperatures [21–23]. During the thawing of frozen ground, soil poses a porous structure in which the liquid and air is contained [24,25].

Melting or solidifying is most commonly computed using the classical Stefan problem [26] in which the liquid and the solid phase are separated by an interface of zero thickness. Material

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Nomenclature

Latin Symbols

a	moisture transfer coefficient, $m^2\,s^{-1}$
AOA	angle of attack, °
C	shedding criterion
c_p	specific heat, $J\,kg^{-1}\,K^{-1}$
D	diffusivity, $m^2\,s^{-1}$
h	ice thickness, m
IWC	ice water content, kg/m^3
k	thermal conductivity, $W\,m^{-1}\,K^{-1}$
L	latent heat, J/kg
l	length, m
Le	Lewis number
LWC	liquid water content, kg/m^3
m	mass, kg
Ma	Mach number
n	amount
$\vec{n}$	unit normal vector
P	probability
p	pressure, Pa
$\dot{q}$	specific heat flux, W/m^2
R	gas constant, $J\,kg^{-1}\,K^{-1}$
r	radius, m
S	source, $J\,s^{-1}\,m^{-3}$
T	temperature, K
t	time, s
TWC	total water content, kg/m^3
$\vec{u}$	velocity, m/s
$\vec{v}$	velocity, m/s
x	position, m
y^+	dimensionless wall distance

Greek symbols

α	volume fraction
γ	model constant
Γ	heat transfer coefficient, $W\,m^{-2}\,K^{-1}$
Γ_E	mass transfer coefficient, m/s
ε	porosity
ζ	moisture content
η	extinction function
λ	cumulative volume with regard to entire volume
ν	kinematic viscosity, $m^2\,s^{-1}$
$\tilde{\nu}$	working variable of turbulence model, $m^2\,s^{-1}$
ρ	density, kg/m^3
ϑ	temperature, °C

Indices

0	initial values
∞	ambient values
a	air
C	convection
ch	chord
con	converging
Cond	conduction
div	diverging
E	evaporation
f	reference
H2O	water
i	imbibition
in	input
inl	inlet values
l	liquid
m	melting
oc	occupied
p	particle
s	solid
t	total values
wb	wet-bulb
WT	wind tunnel
λ	decay

properties, such as the specific heat c_p, thermal conductivity k and density ρ are assumed phase-wise constant. The latent heat of fusion L_m, which is also presumed constant, is released or absorbed at the interface during freezing or melting, respectively. It equals the net amount of heat conducted to the interface which is at the melting temperature, other heat fluxes are neglected. An energy balance for a control volume of infinitesimal thickness containing the moving interface reads

$$[\rho L_m \vec{v}] \cdot \vec{n} = [k_s(\nabla T)_s - k_l(\nabla T)_l] \cdot \vec{n}, \tag{1}$$

where the indices correspond to the solid (s) and liquid (l) phase, respectively, $\vec{v}$ is the velocity at which the melting/freezing front propagates and $\vec{n}$ is the normal vector on the interface. The classical Stefan problem describes phase changes of non-porous materials rather well [26] as the underlying assumptions are very reasonable for most cases.

Anyhow, some of them do not apply for the melting of a porous material. The goal of this work is to overcome these limitations for heterogeneous multiphase materials by theoretically modeling the transport phenomena in granular, multiphase materials. These phenomena include heat transfer, melting and liquid phase imbibition. When heat is applied to a porous structure in which one of the phases melts, heat is conducted in the non-melting phase while it is absorbed by the melting phase. The Stefan boundary condition at the interface of melting grains is replaced by a distribution of heat sinks. Hence, the heat flux decays over a certain distance due to the energy expended on melting at the grains' boundaries. Information about thermodynamic conditions at the wall does not propagate beyond this thermal boundary layer. As a result, the interface at which the phase change takes place is not sharp as assumed in the Stefan problem, but smeared over a certain thickness. Moreover, the transport of the liquid by capillary suction into the pores of the solid material is taken into account as well as the convective heat transport associated with it. Such modeling is important for the accurate prediction of the phase change process in porous media as in the examples set out earlier in this chapter.

In this study the heat transfer equations are coupled with generation and imbibition equations for the liquid phase. The model is implemented in the framework of a Finite-Volume code and applied to compute the composition of ice accumulation on airfoils observed in wind tunnel experiments. The composition of the ice layer at the wall provides an estimate of how well the ice is connected to it, thus, modeling the shedding. Finally, the predicted evolution of the thickness of the ice layer and of the instant of the ice shedding are compared with the accretion behavior observed in available experiments. The agreement is rather good.

2. Transport phenomena in a melting porous/granular two-phase ice layer: model development

By means of 3D numerical simulations of the melting of porous materials, it is shown that it can be described by an extinction