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Numerical investigation on heat transfer and melting process of ice with different porosities

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ABSTRACT

The density of ice changes with icing conditions. The ice with different densities can be treated as a porous medium with different porosities. Porosity affects the ice melting process. A melting model based on the enthalpy-porosity method is applied to study the effects of porosity on the ice melting process and heat transfer. An electrothermal de-icing system is used to investigate the melting process of ice with different porosities. The transient process of ice melting is investigated, including the change of ice-water interface, the melted ice volume and the melted ice area on the surface. The effects of porosity on the temperature distribution of the ice-airfoil surface are analyzed. The effect of natural convection on ice melting process is also considered in this study. The results show that the porosity affects the temperature distribution of the ice melting zone, melting rate, melting ice area on the surface and melting ice volume significantly. The melting rate, melting ice area on the surface and melting ice volume in the ice melting process are all rise with the increase of porosity under the same heating condition. The investigation shows that the enthalpy-porosity method can describe the ice melting process more accurately.

1. Introduction

Icing is a serious problem that influences the efficiency and safety of some equipment such as wind turbines and aircrafts. It usually occurs in cold regions when supercooled droplets in clouds are intercepted by wind turbine blades, aircraft wings, engine inlet, or other aircraft components. For wind turbine, icing affects the wind assessment phase and the operation of wind farms [1], reduces the efficiency and even causes damage [2,3]. For aircraft, icing affects the aerodynamic performance such as increasing drag and reducing lift. Under some extreme climate conditions, icing even causes crash [4]. According to the survey, many accidents happened due to icing problems. So, icing is a safety problem need to be solved. Nowadays, anti-icing or de-icing systems are widely used to alleviate or avoid icing phenomenon [5]. anti-icing systems can avoid the formation and accretion of ice, while de-icing systems are designed to remove the accreted ice. As a kind of de-icing system, the electrothermal de-icing system uses electric heat source to melt the ice accreted on the outer surface of icing components. The ice melts after the electrothermal de-icing system working for a period of time. The melting efficiency depends on two factors: one is the electric heat power and the other is the thermal physical property of ice. Investigate the effects of thermal physical properties on the ice melting process is helpful to design more suitable de-icing system. There are three different types of ice will formed on the icing components. They are defined as glaze ice, rime ice and mixed ice, respectively. The main difference of these three kinds of ice is their densities because of different porosity filled with air. Porosity affects the ice melting process under the same electric heating condition. The ice melting process involves many issues, such as melting zone temperature distribution, melting rate, melting ice area, melting ice volume.

At present, some researches have been devoted to the area of the heat transfer and melting process of ice. For heat transfer and melting process of ice, such as the temperature distribution and the motion of the interface was analyzed by means of a finite-difference method [6]. The melting process in a rectangular enclosure, driven by the coupling of heat conduction in the solid phase and natural convection in the phase-change material (PCM), was studied [7]. Three-dimensional melting of ice around a liquid-carrying tube placed in an adiabatic rectangular cavity is investigated by numerical analysis [8]. Heat transfer and melting process of ice in a spherical enclosure [9], in a rectangular enclosure [10,11] and in a rectangular enclosures with horizontal partial fins [12] were studied. The characteristics of ice melting heat transfer in a horizontal elliptical tube immersed in water [13] and heat transfer characteristics of lauric acid in a rectangular thermal storage unit

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Nomenclature

Symbol	Quantity (SI unit)
C	specific heat (J/(kg·K))
D	diameter (cm)
H	total enthalpy (J)
ΔH	latent heat (J/kg)
h	sensible enthalpy (J)
k	thermal conductivity (W/(m·K))
L	latent heat of a material (J/kg)
LWC	liquid water content (g/m^3)
MVD	mean volume diameter of water droplets (μm)
m	mass (kg)
PCM	phase-change material
Q	heat source (J)
S	environment function
T	temperature (°C)
V	volume (m^3)
v	velocity (m/s)
ρ	density (kg/m^3)
α	thermal diffusivity (m^2/s)
β	liquid fraction
$\varnothing$	porosity

Subscripts, superscripts

ambient	ambient environment
eff	effective
f	fluid
fusion	fusion
ice	ice
inner	inner face
j	grid point in y-direction
l	liquid
liquidus	liquidus
lm	liquid at the melting point temperature
max	max
melt	melt
p	constant pressure
pore	pore
ref	reference
s	solid
sm	solid at the melting point temperature
solidus	solidus
total	total
wall	wall
x	space coordinate in the x direction
y	space coordinate in the y direction
z	space coordinate in the z direction

[14] were studied. The freezing and melting process of a small water droplet was investigated [15,16]. The turbulent convection beneath a horizontal ice-water interface was investigated by direct numerical simulation and laboratory experiments [17]. An experimental determination was made of the velocity profiles which result from the free convective melting of a vertical ice sheet into fresh water with temperature range from 2.0 °C to 7.0 °C [18]. The fluid flow under solid-liquid phase change conditions was studied numerically [19], experimental and theoretical study has been performed on the melting of spherical ice particles [20–23]. The effect of buoyancy-driven flow of cold water on the melting of a flat ice surface inside a porous matrix [24] and effect of thermal and mass diffusion in a cavity with differentially heated side walls [25] were studied. The melting driven convection at the ice-seawater interface was investigated by direct numerical simulation [26]. A natural convection model for melting phase change in porous media was established [27]. The melting process with natural convection in an inclined cavity has been studied using the enthalpy-based lattice Boltzmann method [28]. Previous research mentioned above, the ice melting process was studied when ice was treated as a constant density material rather than porous medium.

Although some research have been focused on the area of the heat transfer, melting process and density change of ice, little research focus on the effect of porosity on heat transfer and melting process of ice. The investigation is useful for improving the efficiency of de-icing system. In order to study the effect of porosity on heat transfer and melting process of ice, a numerical investigation is implemented in this paper.

This paper proposed a numerical method to analyze the melting process of ice with different porosity. The pore filled with air in the ice. The volume ratio of the pore and the ice is porosity. The buoyancy-driven flow in the melted zone as well as the natural convection heat transfer in the melted zone is also considered. The melting model with considering the ice density is used to simulate the ice melting process. The streamlines of natural convection in the melted zone were analyzed.

2. Theoretical model

2.1. Enthalpy method

When ice melts to water, two phases exist. The ice and the water are separated by the moving interface. The difficulty in simulating a phase change process is the presence of a moving boundary or region on which heat and mass balance conditions have to be met. The general method to solve the moving boundary problem is enthalpy method. The enthalpy method treats the enthalpy as a dependent variable and hence can write a single energy equation for the whole domain [29,30]. In the process of solving the energy equation, determination the interface position is not necessary in the enthalpy method. In ice melting model, the enthalpy is assumed to be a function of temperature. The enthalpy-temperature relationship curve is shown in Fig. 1. Where T_{melt} is the melting point of ice, H_{sm} and H_{lm} represent the enthalpy associated with the ice and water at the melting point, respectively.

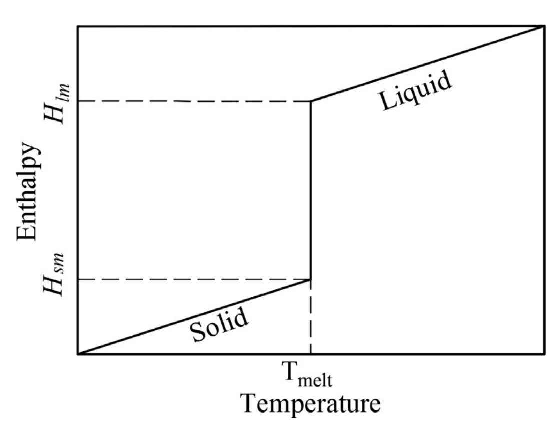

Fig. 1. Enthalpy-Temperature relationship graph.