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Modeling transport phenomena of ice slurry in an ice forming unit

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In this article, multiphase convective and solidification transport phenomena of ice slurry is investigated by developing a one-domain macroscopic model to simulate its formation in a rectangular ice forming unit. Convection, sedimentation, interfacial drag, permeability, remelting and viscosity variations are incorporated into this model through the appropriate governing multiphase transport equations. Validation studies with literature data are performed to determine the most suitable drag law by comparing the position of the interface between the coherent and non-coherent zones. After establishing modified Stokes' Law as the best-suited drag model, solidification study of an aqueous ammonium chloride solution is performed. The results for the evolution of ice fraction, species distribution, temperature profile and multiphase velocity field are presented. Solid fraction gradient, due to the generation of ice particles, has a major influence on the density gradient leading to a counterclockwise flow current resulting in the homogenization of temperature and species in the generated ice slurry.

Modélisation du phénomène de transport de coulis de glace dans un dispositif de formation de glace

Mots clés : Coulis de glace ; Phénomène de transport ; Solidification ; Stockage d'énergie thermique froide

1. Introduction

Energy is the lifeline of all human activities. The world energy consumption increased by 29% between 2001 and 2010 and it has been estimated that it will grow by 57% by 2040 (U.S. Energy Information Administration). Today, approximately 80% of the primary sources of world energy supply are crude oil, coal and gas, and these non-renewable resources are depleting rapidly (Desideri et al., 2009; Ma et al., 2006). As a result, energy security is emerging as one of the driving forces for the development of research on reducing energy consumption in a nation (Fumo, 2014). It has been estimated that building energy usage forms a major portion of the energy demand in a country, with heating, ventilation, air conditioning and refrigeration (HVAC&R) systems as the largest consumers of energy in

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Nomenclature

C	concentration [wt. fraction]
c_p	specific heat [J kg^{-1} K^{-1}]
C_D	drag coefficient
D	diffusion coefficient [m^2 s^{-1}]
d_{coh}	representative equivalent diameter of dendrites in the immobile equiaxed zone [m]
d_{char}	characteristic diameter of the moving ice particles [m]
f	mass fraction
g	volume fraction
g_r	gravity [m s^{-2}]
H	enthalpy [J kg^{-1}]
ΔH	latent enthalpy of a cell [J kg^{-1}]
k	thermal conductivity [W m^{-1} K^{-1}]
K	permeability [m^2]
k_p	partition coefficient
L	latent heat of fusion [J kg^{-1}]
m	mass [kg]
p	dynamic pressure [Pa]
P	constant involved in calculating permeability [m^{-2}]
Re_g	Reynolds number based on grain size
S	source term
t	time [s]
T	temperature [K]
$\vec{u}$	velocity [m s^{-1}]
X, Y	coordinate axes [m]

Greek symbols

ρ	density [kg m^{-3}]
μ	viscosity [kg m^{-1} s^{-1}]
β_T	thermal expansion coefficient [K^{-1}]
β_C	solutal expansion coefficient [(wt fr.)$^{-1}$]
φ	transport variable
Γ	diffusion coefficient

Subscripts

cold	cold temperature
eff	effective
l	liquid
liq	liquidus
i	initial
ref	reference
s	solid
sol	solidus
x, y	coordinate axes

Abbreviations

TES	thermal energy storage
HVAC&R	heating, ventilation, air conditioning and refrigeration
CTES	cold thermal energy storage

buildings (Vakiloroaya et al., 2014). They constitute over 32% and 50% of electricity consumed in a building in India and US, respectively, whereas in Australia they consume nearly 70% of power in non-residential buildings (Vakiloroaya et al., 2014). In the Middle East, the energy consumption of building cooling systems is more than 70% (Vakiloroaya et al., 2014). Enhancing the performance of these systems can create an exciting opportunity to reduce the energy consumption significantly, which will have a huge impact on lowering the energy demand. Various technologies and approaches have been uncovered to improve the performance of HVAC systems in order to reduce the energy consumption (Vakiloroaya et al., 2014). One such attractive energy saving strategy is the use of ice slurry based Cold Thermal Energy Storage System (CTES) in water-cooled systems (Saito, 2002; Vakiloroaya et al., 2014).

Ice slurry is a suspension of millions micro-crystals of ice (typically 0.01 mm to 0.1 mm in diameter (Meewisse and Ferreira, 2001)) formed and suspended in water or an aqueous solution of a freezing point depressant (e.g., some salt). The growing interest toward ice slurry in the past two decades has garnered the attention of many researchers who started working in the field of ice slurry generation, rheology, flow and heat transfer. The phasing out of CFCs and HFCs has made the search for alternative refrigerants difficult and it has also envisaged the development of ice slurry technology as a potential new secondary refrigerant (Fernández-Seara and Diz, 2014; Kalaiselvam et al., 2009; Pronk et al., 2005; Zhang and Ma, 2012) as using ice slurry in HVAC&R systems has various potential benefits (Kalaiselvam et al., 2009). According to many researchers, ice slurry is a promising technology that has numerous advantages, in particular, energy saving and environmental benefits (Davies, 2005; Egolf and Kauffeld, 2005; Haruki and Horibe, 2013; Illán and Viedma, 2012). Ice slurry flows like conventional chilled water and provides 4–5 times more cooling when it contains an ice concentration of 20% (Netherlands Agency for Energy and the Environment, 1993). Ice slurry based CTES has a significant advantage over static ice storage systems as the ice slurry formed can be pumped directly from the storage tank to the cooling coils without any requirement of a secondary heat exchanger, leading to an increase in the efficiency and a reduction of the overall cost of the system (Tassou et al.). The ability to use ice slurry at temperatures below 0 °C, as per the requirement of the various applications, gives it an added advantage over chilled water storage and distribution systems (Tassou et al.). It also provides a higher heat storage density due to the latent heat of fusion of ice, which is 80 times the heat capacity of an equal weight of water undergoing a unit change in temperature (Mohlman, 1966). Thus, a small volume of ice slurry provides the same amount of cooling as a much larger volume of cold water (Mohlman, 1966). Because of the presence of many small ice particles the effective heat transfer area increases which provides higher heat transfer density (Kauffeld et al., 2010). This leads to a requirement of lower flow rates and pumping power compared to conventional chilled water or other single-phase secondary heat transfer fluid distribution systems (Kauffeld et al., 2010). Phase change slurries