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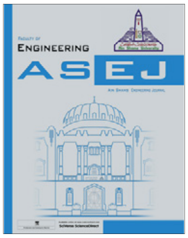

MECHANICAL ENGINEERING

An experimental study of freezing and melting of water inside spherical capsules used in thermal energy storage systems

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Abstract This paper reports the results of an experimental study on the heat transfer during freezing (charging) and melting (discharging) of water inside a spherical capsule of the type often found in the beds of thermal (ice) storage systems used for the building air conditioning systems. Spherical capsules of different diameters and materials are tested. The aqueous solution of 35-wt% ethylene glycol is used as the heat transfer fluid (HTF). The major studied parameters are the size and material of the spherical capsule, the volume flow rate and temperature of the heat transfer fluid (HTF). The effects of these parameters on the time for complete charging/discharging, the solidified/melted

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Abbreviations: Act, actual; CTES, cool thermal energy storage; ERR, energy recovery ratio; HTF, heat transfer fluid; PCM, phase change material; rot, rotameter; tc, thermocouple; TES, thermal energy storage

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mass fraction, the charging/discharging rate, the energy stored/regain, and the energy recovery ratio (ERR) are studied. The experimental results show that the energy recovery ratio is becoming better when using metallic capsules, increasing the capsule size and reducing the HTF volume flow rates.

Nomenclature

C_i	specific heat of ice, kJ/kg K
C_w	specific heat of water, kJ/kg K
d_{in}	inside diameter of test capsule, m
$\mathrm{F_O}$	Fourier number, $\mathrm{F_O} = \alpha_i \times t/r_{in}^2$
k_i	thermal conductivity of ice, kW/m K
$L.H.$	latent heat of fusion of water, kJ/kg
m_m	melted mass, kg
m_o	mass of PCM encapsulated inside the spherical capsule, kg
m_s	solidified mass, kg
m_m/m_o	melted mass fraction
m_s/m_o	solidified mass fraction
$\dot{Q}_{ch}$	charging rate, kW
$\dot{Q}_{dis}$	discharging rate, kW
Q_{reg}	accumulative energy regained, kJ
Q_{st}	accumulative energy stored, kJ
$Q_{st,max}$	maximum energy stored at the complete charging time, kJ
$Q_{reg,max}$	maximum energy regained at the complete charging time, kJ
$r_{avg_{h,v}}$	average radius of solid–liquid interface in test capsule, m
r_h	horizontal radius of solid–liquid interface in test capsule, m
r_{in}	inside radius of test capsule, m
r_v	vertical radius of solid–liquid interface in test capsule, m
T_{act}	actual temperature, °C
T_c	temperature of PCM at the center of capsule, °C
T_l	liquid phase temperature of PCM, °C
T_o	initial temperature of PCM (distilled water), °C
T_{pc}	phase change temperature, °C
T_s	solid phase temperature of PCM, °C
T_{tc}	thermocouple temperature reading, °C
T^*	dimensionless temperature, $T^* = T_c/T_{pc}$
t	time, s
$t_{comp.ch}$	complete charging time, s
$t_{comp.dis}$	complete discharging time, s
Δt	time difference, s
V_m	Melted volume, m^3
V_s	solidified volume, m^3
V_{shell}	spherical shell volume, m^3
$\dot{V}_{act}$	actual volume flow rate, Lpm
$\dot{V}_{rot}$	volume flow rate obtained from the rotameter reading, Lpm
V_o	volume of the PCM encapsulated inside the spherical capsule (equal to 80% of internal volume of the capsule), m^3

Greek symbols

ρ_w	water density, kg/m^3
ρ_i	ice density, kg/m^3
ρ_w/ρ_i	volume correction factor
α_i	thermal diffusivity of ice ($= k_i/\rho_i C_i$), m^2/s
τ	dimensionless time, ($\tau = F_o = \alpha_i \times /r_{in}^2$)
$\tau_{comp.ch}$	dimensionless complete charging time
$\tau_{comp.dis}$	dimensionless complete discharging time
α_i	thermal diffusivity of ice
ΔQ_{reg}	accumulative thermal energy regained difference, kJ
ΔQ_{st}	accumulative thermal energy stored difference, kJ
Δt	time difference, s

1. Introduction

Studying the thermal behavior during phase change in spherical capsules is extremely important for the design of efficient storage systems. Some experimental and theoretical studies investigations concerning the cool thermal energy storage (CTES) of encapsulated type are found in literature.

Eames and Adref [1] conducted an experimental study of the freezing and melting processes for water contained in spherical elements. They reported quantitative data on the movement of the solid–liquid interface position with time, the effect of HTF (coolant) temperature, and the effect of sphere size on the melting and freezing processes. They also reported the discharge and charge rates and the time required to melt and freeze a spherical ice storage element. Finally, their results were used to derive empirical equations describing charge and discharge for an ice storage element.

Yoon et al. [2] studied experimentally the freezing phenomenon of saturated water with the supercooled region in a horizontal circular cylinder. From the experiments, it was found that there were three types of freezing patterns. The first was the annular ice layer growing from the cylinder surface at a high cooling rate, the second was the asymmetric ice layer at an intermediate cooling rate, and the last was the instantaneous ice layer growing over the whole region at a low cooling rate.

Ismail et al. [3] presented the results of a numerical study on the heat transfer during the process of solidification of water inside a spherical capsule under convective boundary conditions. The numerical solution was based upon the finite