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Role of metallic foam in heat storage in the presence of nanofluid and microencapsulated phase change material

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ABSTRACT

The focus of this paper is the use of a ternary fluid containing Al_2O_3 nanoparticles and the microencapsulated phase change material MEPCM. Different heat flux intensities were applied in the outside wall of a porous pipe with fluid entering at different flow rates. The results revealed that the addition of metallic foam improves the heat transfer between the wall of the pipe and the fluid. ERG aluminum foam was the metal foam used in this analysis with a permeability ranging from 10 ppi to 40 ppi. This heat enhancement further improved by adding nanoparticles to the fluid. The heat storage capability of the proposed fluid also increased with the addition of microencapsulated phase change material (MEPCM) particles. The results revealed that 20% MEPCM and 3% nanoparticles in water is an ideal balance for heat storage and enhancement, with a 6.7% improvement in the case of water flowing in a porous pipe.

1. Introduction

Due to the high demand for energy worldwide, it is necessary to find efficient alternative energy sources such as renewable energy in order to reduce energy consumption and greenhouse emissions. One of the important questions regarding these energy sources is how this energy can be stored and reused when it is in demand.

Nanofluids (NF) have been proposed and investigated for heat enhancement purposes [1–9]. The high thermal conductivity of nanofluids make them great for heat extraction. Heat enhancements have been reported in previous research [6,9].

Thermal energy storage (TES) in general, and phase change materials in particular, have been a popular topic in research and industry for the last 20 years. Phase change materials (PCMs) can absorb, store and release large amounts of latent heat over a defined narrow temperature range while the material changes phase or state and have been used for the storage of heat energy due to their high latent heat of transition, high energy densities and low cost. Phase change materials (PCMs) have been recognized as a sustainable and environmentally friendly technology. That being said, there is lack of experimental data that aims to measure the physical properties of PCMs in water. In this study, PCM is referred to as microencapsulated particles or MEPCM.

Ho et al. [10] managed to experimentally measure the physical properties of microencapsulated phase change materials in water. With a variable heat capacity, the thermophysical properties were measured for different MEPCM concentrations and temperatures. In order to further improve heat conductivity, different nanofluid concentrations were added to the mixture. Saghir et al [7–9] used these physical properties and conducted detailed numerical modelling of the flow in a horizontal pipe. Saghir demonstrated that a mixture of nanofluid and PCM in water increased the heat storage capacity, and that a mixture of water and nanofluid increased the heat enhancement.

In order to further enhance heat extraction, phase change materials embedded in metal foams such as Al_2O_3, copper or Nickel have been proposed by many researchers. Chen et al. [11] conducted a detailed literature review focusing on phase change materials in metal foams. Because PCMs have low thermal conductivity which decreases heat transfer, metal foam is proposed as a solution to improve heat conductivity. A combination of PCM in metal foam has also been found to be effective for heat storage. The high conductivity, porosity and surface area to volume ratio of metal foams make them suitable to increase the overall heat transfer in a system. Different metal foam materials such as Al_2O_3, Copper and Nickel have been suggested. Martinelli et al. [12] conducted an experimental study using a phase change material and copper foam. Their objective was to investigate the use of metal foams as a thermal conductivity enhancement technique for latent heat storage applications. The copper foam is inserted in a shell and tube heat exchanger. The researchers used both a horizontal and vertical tube orientation in order to study the orientation effect in heat storage. Paraffin was selected as the phase change material. The results revealed that the combination of a copper metal foam and phase change material improved the heat transfer, thereby enabling the PCM to fully solidify

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Nomenclature

cp	Specific heat (J/kg. K)
Gr	Grashof number
l	Characteristic length (m)
P	Non-dimensional pressure
Re	Reynolds number
T	Temperature (K)
U_o	Characteristic Velocity [m/s]
R,Z,φ	Non-dimensional coordinates
L	Pipe length [cm]
MEPCM	Microencapsulation phase change material
g	Gravitational acceleration (m/s^2)
k	Thermal conductivity (W/m. K)
$\overline{Nu}$	Average Nusselt number
Pr	Prandtl number
St	Stefan number
U, V, W	Non-dimensional velocities
u_r, u_z, u_φ	Dimensional velocities [m/s]
e	Pipe thickness [cm]
$Da = K/l^2$	Darcy number
PCM	Phase change material

Greek symbols

α	Thermal diffusivity (m^2/s)
β	Thermal expansion coefficient (1/K)
μ	Dynamic viscosity (N/kg. s)
κ	Permeability
ν	Kinematic viscosity (m^2/s)
ρ	Density (kg/m^3)
θ	Non-dimensional temperature

Subscript

c	Cold temperature
h	Hot temperature
m	Mixture
f	Clear water
in	inlet
m_2	Mixture in clear fluid

and melt ten times faster than a single stainless-steel tube.

Chen et al. [13] conducted an experimental study of the melting behaviour of phase change materials in metal foam at pore scale. The aluminum metal foam is embedded with paraffin in order to enhance the heat transfer and storage capacity. A detailed measurement of the temperature profile was obtained using an infrared camera. The results revealed that metal foam enhanced the heat transfer, mainly due to the thermal conduction in the metal matrix. Further corroboration was provided using numerical modelling based on the Lattice Boltzmann method. In addition, the authors demonstrated that the metal foam structure has a direct effect on the heat transfer during the melting process.

Fleming et al. [14] investigated the heat transfer enhancement of a shell-tube latent heat storage unit using water as the phase change material. Contrary to other researchers who used a high thermal conductivity phase change material, they sought to demonstrate the effect of metal foam in improving thermal conductivity in water. The experimental results indicated that the metal foam significantly increased the heat transfer during both solidification and melting, as characterized by the overall heat transfer coefficient. The researchers noted that the natural convection during melting was suppressed by the presence of metal foam in the tube. The effective thermal conductivity model during melting and solidification were obtained both analytically and experimentally. The discrepancies between the effective thermal conductivity reported in the numerical and experimental approaches was attributed to local thermal non-equilibrium which is more important during melting than solidification.

Feng et al. [15] experimentally investigated the importance of metal foam using water as a phase change material. The contact between the metal foam and the cold wall was observed for three different conditions: mainly natural contact, applied pressure, and with bonding with high thermal conductivity adhesive. The freezing rate was found to be identical for the three conditions. Copper metal foam was used in this analysis. The local thermal equilibrium between the metal foam and the water was measured experimentally.

Atal et al. [16] continued the work of Fleming by investigating the effect of porosity in aluminum metal foam. The phase change material used in this study was paraffin. Experimental and numerical temperature measurements were obtained during solidification and melting in a shell-tube configuration. It was demonstrated that similar pattern of the melting evolution was obtained with paraffin (as the phase change material) and not a direct agreement for the temperature between the two techniques was achieved. The results revealed that the metal foam with less porosity created a faster charging/discharging cycle due to a higher overall thermal conductivity.

Lafdi et al. [17] conducted an experimental investigation of the heat transfer phenomena and solid/liquid PCM interface shape inside an aluminum metal foam. The temperature was measured for a high porosity material where the steady state condition was reached more rapidly. Zhu et al. [18] conducted a numerical investigation of the thermal performance of an aluminum metal foam with 90% porosity and paraffin as the phase change material. The non-equilibrium equation was applied to study the melting process of the paraffin embedded in the aluminum foam. The results revealed that the permeability of the metal foam plays a role in the interface shape and growth. An optimization method was proposed to improve the efficiency of the latent heat storage up to 83.25% when compared to pure paraffin. Thus, one can conclude that the use of metal foam enhances the heat storage performance.

Abadi et al. [19] studied the importance of heat transfer in a heat exchanger. The channels in the heat exchanger were filled with copper foam metal. The effect of permeability, working pressure and different metal foam arrangements were investigated. The results revealed that the use of metal foam increases the pressure drop and enhances heat removal. In addition, the overall heat transfer coefficient of the heat exchanger increased by up to 2.3 times.

Cui et al. [20] conducted an experiment that aimed at investigating the thermal energy storage time. Paraffin was used as a phase change material in a copper metal foam. Temperature measurements indicated that the presence of metal foam shortens the charging time and provides a uniform temperature distribution within the thermal storage unit. Baby et al. [21] conducted an experimental investigation of the effect of heat transfer performance of a phase change material based plate using n-eicosane. The melting temperature was approximately 36.5 °C. The metal foam used in this experiment was aluminum. The importance of applied heat flux to the thermal performance was investigated. The results revealed that metal foam with PCM provided noticeable heat enhancement.

Chintakrinda et al. [22] used paraffin and three different mediums (graphite foam, aluminum foam, and graphite nanofibers) in order to investigate thermal performance and energy storage. The applied heat fluxes varied between 1.93 W/cm^2 and 19.3 W/cm^2. The results revealed that the presence of a foam material caused a noticeable improvement in the heat sink performance, although the graphite