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Cooling of air using heptadecane phase change material in shell and tube arrangement: Analytical and experimental study

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ABSTRACT

A shell and tube latent heat storage (LHS) system using heptadecane with melting point 22.33 °C for active cooling of air has been analyzed analytically and experimentally in this paper. A theoretical model of laminar forced convection with varying wall temperature due to phase change material (PCM) outside a double wall circular tube and air as heat transfer fluid (HTF) inside a tube was employed to analyze active cooling of air. The analytical prediction in terms of outlet temperature was validated with experimental data. Furthermore, influences of some important design parameters (e.g. inner radius and thickness of the tube) on cooling effect were investigated. It was found that an optimum inner radius and thickness of the tube should be considered to design an LHS system. Better co-efficient of performance (COP) was observed for higher inlet air temperature while the outlet air temperature was almost identical. In this study, the COP of cooling was found 4.16 for 34.5 °C inlet air temperature using tube with 5.35 mm inner radius and 1 mm thickness. Some important thermophysical properties of heptadecane e.g. specific heat, thermal conductivity and density at liquid state were also examined and found 2.66 kJ kg^{-1} K^{-1}, 0.151 W m^{-1} K^{-1} and 774 kg m^{-3}, respectively.

1. Introduction

Nowadays, rapidly increasing building energy consumption has become a major problem. In developed countries, buildings are responsible for 20–40% of the total final energy consumption [1–5]. In 2006, as demonstrated by the U.S. energy department, the building sector consumed 38.9% of the total primary energy used in U.S. whereas 34.8% of this energy is used for thermal comfort in buildings [6]. In 2009, about 40% of the total fossil energy was consumed by the buildings in U.S. and EU [7]. Al-Abidi et al. [8] reported that HVAC systems were accountable for around 55% of the total building energy consumption. In this context, advancement of sustainable technologies have explored the application of latent heat storage (LHS) using phase change material (PCM) for thermal comfort in buildings [9]. Since 1970s, many researchers have been involved for utilizing PCM in lightweight buildings for thermal control applications [10] and economic advantages [11]. The multipurpose applications of LHS with PCM in building sector for thermal comfort have been demonstrated by Refs. [12–16]. Many researches have been done by incorporating PCM into building material. Although it is quite impossible to impose this technology in the present structure, there is still an option to replace the present air-conditioning system by active free air cooling system.

The active free air cooling system uses the outdoor fresh air at night to store coldness through PCM in discharging process. In this system, only fan is used for the suction of air from the environment. There are number of articles have been reported on the application of this kind of ventilation system through PCM [8]. It is also reported that LHS system can be an economical solution for HVAC applications [17]. The present building energy consumption problem can be optimized with this brilliant technique. The coldness is used in this system for indoor thermal comfort during daytime applying outdoor hot air which is charging process of PCM. On the other hand, the reverse process is used in winter season [18,19]. Hence, this technique can be very useful for the countries with hot climate where shifting the electric loads to off-peak is major concern as the building cooling load plays considerably to the electricity peak load at noontime period [20–22]. In this context, the selection of PCM with appropriate melting temperature is also very important factor for this system to maintain human comfort temperature [23]. In this study, heptadecane PCM has been characterised to examine its suitability for air cooling application.

Generally, active cooling with LHS system consists of a heat exchanger where a passage is kept for air flow and PCM is kept

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Nomenclature

C	specific heat [J kg^{-1} K^{-1}]
C_h	hydrodynamic entrance length co-efficient
D	inner diameter of the tube [m]
E_{fan}	energy consumed by fan [J]
f	friction loss
F_o	Fourier number, $\alpha_p t/r_i^2$
G_n	constant in Eqs. (13) and (14)
H	latent heat [J kg^{-1}]
K	thermal conductivity [W m^{-1} K^{-1}]
L_t	thermal entrance length [m]
L_h	hydrodynamic entrance length [m]
M	number of time interval
N	number of section of dimensionless thermal entrance length
Nu	local nusselt number, hD/k_f
P	pressure drop, [N m^{-2}]
$Q_{cooling}$	heat extraction from air [kJ]
Q_{PCM}	PCM heat gain, [kJ]
Q_s	sensible heat transfer rate [kW]
R	position along the radial direction [m]
R	dimensionless position along the radial direction, r/r_i
S	solid–liquid interface radius [m]
S	dimensionless solid–liquid interface radius, s/r_i
Ste	Stefan number
T^0	temperature [K]
T	dimensionless temperature
t	time [s]
U	velocity [m s^{-1}]
U_m	average velocity [m s^{-1}]
$\dot{V}$	volume flow rate [m^3 s^{-1}]
$\dot{m}$	mass flow rate [kg s^{-1}]
X	dimensionless co-ordinate along the axial direction, L_t/D

Greek symbols

α	thermal diffusivity [m^2 s^{-1}]
λ_n	constant in Eqs. (13) and (14)
ρ	density [kg m^{-3}].
η_{fan}	fan efficiency (%)

Subscript

b	bulk
f	transfer fluid
i	inner radius of the tube, or node number in axial direction
in	inlet
m	melting
o	outer wall of thermal energy storage system
p	PCM
w	inner surface of the tube or tube wall
wo	outer surface of container wall

Abbreviations

CHF	constant heat flux
COP	co-efficient of performance
CWT	constant wall temperature
HTF	heat transfer fluid
PCM	phase change material
LHS	latent heat storage

inside a shell or slab. In recent years, many theoretical analyses regarding active cooling of air through LHS system with rectangular geometry have been undertaken. Vakilaltojjar and Saman [24] presented a semi-analytical analysis of latent heat storage (LHS) system to predict the performance of an air conditioning application. Saman et al. [25] carried out a 2D numerical analyses based on enthalpy formulation to examine thermal performance of a rectangular thermal storage unit. Halawa et al. [26] also analyzed the LHS system with the same rectangular geometry for a roof integrated solar heating system. They applied finite difference enthalpy method of Voller [27] considering two dimensional heat transfer mode to analyze the roof integrated solar heating LHS system with varying wall temperature. Rostamizadeh et al. [28] also developed a model using enthalpy formulation to simulate air cooling with flat PCM slab and also investigated the optimum PCM slab thickness for the effective air cooling. Afterward, Waqas and Kumar [29] studied experimentally free cooling of air in hot and dry climatic condition using three rectangular PCM container. They found that the PCM storage could be used to control the air temperature using coldness stored in the PCM during night time. Mosaffa et al. [11] again investigated the same storage system using multiple PCM inside flat slab for air cooling. They performed a 2D numerical analysis using COMSOL multiphysics and validated with experimental data. Certainly, they got a very good agreement between analytical and experimental data. Arzamendia Lopez et al. [30] also developed a numerical model to simulate parallel PCM slab to air heat exchanger for air cooling–heating application and validated with the experimental data. In a recent study, Rouault et al. [31] also developed a one dimensional dynamic differential model to simulate the heat transfer in between air and LHTS made of a bundle of box section tubes filled with PCM and compared with the experimental results.

However, there are very few works on shell and tube type LHS system for active cooling of air experimentally. This shell and tube type of LHS system for air cooling–heating also should be analyzed to reduce heat loss from the system as there is a scope to reduce heat loss using cylindrical shell geometry [32–34]. The study of active air cooling with shell and tube type LHS system is a conjugate phase change/convection problem [35]. Here, tube is placed inside a shell for HTF flow. The shell contains PCM. In this type of arrangement, forced convective heat transfer is experienced in the thermal and hydrodynamic entry region of the tube. Zhang and Faghri [35] has reported that a major error is expected, if a steady state fully developed heat transfer correlation is applied to calculate the heat transfer co-efficient. Hence, this forced convective heat transfer inside the tube is not occurred due to constant wall temperature and constant heat flux. In order to solve this problem, they demonstrated a simple approach to calculate the local nusselt number for varying wall temperature using the analytical method given by Kays and Crawford [36]. Following similar analytical approach, Anisur et al. [33] demonstrated different design parameters of shell and tube heat exchanger for cooling of air using potassium fluoride tetrahydrate PCM. A schematic diagram of a shell and tube LHS system is shown in Fig. 1 [33].

The aim of this paper was to obtain a physical validation of the analytical predictions produced using the similar analytical approach as reported by Anisur et al. [33]. This validation was obtained through a comparison of experimental and analytical outlet air temperature for identical inlet temperature. Furthermore, parametric studies of the LHS system were also performed. On the other hand, before analytical and experimental investigation, thermophysical properties of heptadecane PCM have been characterised. In literature, to the best knowledge of the author, specific heat, thermal conductivity and density of liquid heptadecane have never been reported yet.