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Heat transfer and pressure drop studies on a PCM-heat exchanger module for free cooling applications

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A R T I C L E I N F O

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A B S T R A C T

Free cooling/Night ventilation is the process of storing the cool energy available in the night time ambient air in a storage device. During the day time the cool energy is retrieved from the storage device in order to cool the building using mechanical ventilation system. The modular heat exchanger developed in this work is a shell and tube type with phase change materials in the shell portion of the module and passage for the flow of air through the tubes. The modules of the modular heat exchanger are stacked one over other with air spacers in between each module. This modular heat exchanger arrangement is suitable for free cooling application where the diurnal temperature variation is low. Transient and steady state CFD modeling is carried out for a single module and two air spacers. Conjugate heat transfer analysis is carried out for the fluid and PCM of heat exchanger module. The latent heat value of the PCM is modeled using apparent heat capacity method with suitable profile approximated from the experimental results. The CFD results are validated with the experimental results. The steady state CFD analysis is useful to determine the pressure drop across the module and the spacers and to know the flow and temperature variation of heat transfer fluid in the module so as to select the geometrical and flow parameters for a given surface temperature and inlet condition. The transient analysis results are useful to determine the PCM solidification characteristics and to verify the suitability of the selected geometrical dimensions. The air spacers provided between the module increases the retention time of the air for better heat transfer and its effect is more pronounced at the lower velocities and decreases as the frontal velocity increases and its effect is negligible above the frontal velocity of 2 m/s.

1. Introduction

A comfortable home with minimum energy consumption is the dream of the common people, governments and researchers. Earlier the researchers were interested in reducing the cost of energy and save the depleting fossil fuels. However recently the motivation has changed from these goals toward minimizing the carbon dioxide emission from the environmental perspective. Hence energy efficiency, use of clean and renewable energy has gained major attention by the researchers and policy makers of the developed and developing countries.

There are various methods adopted for passive cooling of buildings. Night ventilation is one such method by which the structural components are cooled, thus providing reduced temperature of indoor air conditions for the following day. In places where the daily variations of the ambient temperature are high, night ventilation is highly suitable. In free cooling, apart from sensible storage system, the latent heat thermal energy storage system (LHTES) is also used as storage medium which stores the coldness of the ambient air during early morning and supplies it with a time delay during the day. Phase change materials become the natural storage options because of the small temperature difference between day indoors and night outdoors. Free cooling concept is site specific and climate dependent. Free cooling is suitable for the less humid interior and desert regions. The benefit is less in the coastal area because temperature moderation is done by sea and land breeze. In the recent years experimental investigation have been conducted and reported by few researchers on the studies of feasibility of free cooling for various locations with various geometries of PCM-heat exchanger and PCM encapsulation. Flat plate encapsulate was used by Zalba et al. [1] to study the feasibility of free cooling with PCM melting temperature of around 20–25 °C. The parameters influencing charging and discharging time were discussed in detail. Nagano et al. [2] embedded PCM directly on the floor board in the form of granules of several mm in diameter. Arkar et al. [3–5] suggested a single cylindrical LHTES

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containing optimal diameter of spheres encapsulated with PCM. Turnpenny et al. [6,7] attempted an experiment on free cooling or ventilation cooling with heat pipe embedded in PCM to enhance the heat transfer. Panels and pouches were used as encapsulate for free cooling by Lazaro et al. [8] and it was found that PCM panel was found superior to pouches.

The concept of free cooling system proposed in the present study is shown in Fig. 1. The set up consists of a PCM regenerative heat exchanger with a series of bulk cylindrical disc modules containing PCM on the shell side and the passages for flow of air through the tubes. These modules are stacked one over other with air spacers in between each module. The cool air available at the early morning is made to pass through the PCM regenerative heat exchanger and this cool energy is stored by freezing the PCM. The stored cool energy is retrieved during day time for space cooling. During the night time when dampers 2 and 3 are in close position and 1 and 4 are in open position, the cool energy available in the atmospheric air is made to pass through the modular heat exchangers using a fan or blower. As the cold air is passing through the PCM regenerative heat exchanger, the PCM in the modules will freeze and store its cool energy. A fan is used for air circulation during night time and the dampers are adjusted to control the flow rate of air. During the day time when the dampers 2 and 3 shown in Fig. 1 are in open position and 1 and 4 are in closed position, the hot air from the room goes to the PCM module by natural circulation or small capacity fan and the PCM releases the stored cool energy to the room at a slower rate to cater the cooling need throughout the day. Phase change material should be selected such that the melting/solidification temperature lies in the middle of diurnal temperature variation of the ambient air.

The free cooling concept is best suited for places where the diurnal temperature variation is at least 15 °C. However for some regions like Bangalore city in India the diurnal temperature variation is approximately 10 °C. In these locations, where the temperature difference available for heat transfer is small, the area of the heat exchanger has to be increased. However the addition of fins will make the system complicated and also increase the frictional resistance which is not suitable where the natural circulation is also aimed during discharging. Hence in the present work a modular heat exchanger concept with air spacers between each module of heat exchangers is introduced for free cooling application. The air spacers are provided in between modules to provide more heat transfer surface area for the selected PCM volume and it provides

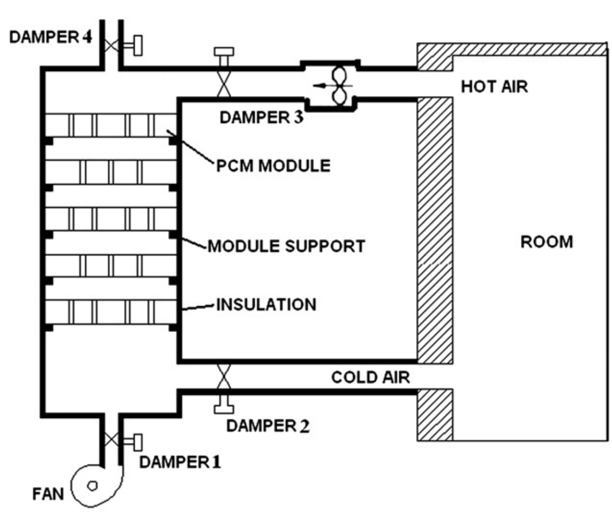

Fig. 1. Operation of the free cooling system.

better mixing of air before the entry to the next PCM module. The residence time of heat transfer fluid in the heat exchanger is also increased due to the provision of air spacers. In the proposed concept as the HTF is made to pass through the air spacer of modular heat exchanger heat transfer is increased when compared to the shell and tube heat exchanger of equivalent length without spacer. This type of heat exchanger increases the heat transfer surface area for the selected PCM volume. PCM regenerative heat exchanger discussed above consists of series of modules containing the PCM stacked one over the other with air spacers in between each module. In the present work, one module with PCM and two air spacers of the PCM regenerative heat exchanger are considered for the analysis.

There are lots of numerical model to study the solidification and melting characteristics for PCM encapsulations for various configurations. The two types of numerical approach for solving a phase change problems are temperature based models and enthalpy based models. In the temperature based models, also called as variable domain models the temperature is the sole dependent variable. The volume of each region changes with respect to time. Hence separate equations are required to track the liquid and solid region and the interface equation is also required to track the interface. In the enthalpy model the solution of the phase change problem is reduced to solve a single equation in terms of enthalpy. The advantage is that enthalpy method can accommodate the material that changes its phase over a range of temperature. There is no boundary condition to be satisfied in the interface region. Meyer [9] adopted the enthalpy model for the PCM that changes its phase over a small range of temperature. Voller and Cross [10] showed that the accuracy of the scheme is dependent on the choice of temperature range of phase change, elemental control volume and time step. Shamsunder and Sparrow [11] have developed an integral relation for the enthalpy model and the value of T is recovered from $H{-}T$ relationship while tracking the node to identify the two phase and single phase nodes. Date [12] has generalized the $H{-}T$ relationship in such a way that no tracking is required. Velraj et al. [13] modified this relationship to accommodate for the materials having a range of phase change temperatures.

An alternate formulation called apparent heat capacity method is employed to solve melting and solidification problem by including the effect PCM storage through apparent heat capacity model in the energy equation. Various shapes of apparent heat capacity like rectangular and triangular profiles were studied by Beasley et al. [14] and Lamberg et al. [15]. Hed and Bellander [16] developed a mathematical model for flat plat PCM air heat exchanger for free cooling considering the shape of $c_p(T)$ curve. Numerical studies pertaining to free cooling have been studied extensively by Arkar and Medved [5]. They used the results of DSC analysis curve for the PCM to model the apparent heat capacity for solving continuous solid phase model by finite difference method using Mathematica software for studying the solidification characteristics of PCM. A three dimensional transient conjugate heat transfer analysis using phase change material and heat transfer fluid is done in the present work, using CFD software. In the present work this apparent heat capacity modeling concept is integrated with the existing CFD code.

The objective of the present work is to carry outflow and heat transfer studies for the fluid flowing through the tube in the heat exchanger module and air spacer kept in the top and bottom of the module in conjunction with transient heat transfer analysis for the PCM encapsulated in the shell portion of module using apparent heat capacity model for phase change in FLUENT software. The results are validated with experimental solidification time determined for the selected air frontal velocity of 0.7 m/s and the comparison between the experimental and calculated values are