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Minimising energy usage for domestic cooling with off-peak PCM storage

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ABSTRACT

Achieving energy savings with domestic off peak air conditioning using phase change materials (PCMs) has always proved a challenge. Although the energy efficiency ratio of an air conditioner is higher during the night, this improvement often does not offset the exergy loss experienced when using thermal storage. Simulations have been conducted using the effectiveness-number of transfer units (ε-NTU) representation of a PCM system to determine the instantaneous heat transfer when coupled to an inverter chiller cooling system. Results show that although 85% of the energy consumption for cooling could be shifted to the off-peak period with an ice based system, the energy demand increased by 7.6%. The investigation demonstrated that by using a PCM with a melting point of 4 °C, it is possible to achieve an energy saving for cooling. A savings of around 13.5% can be achieved using a PCM with a melting point of 10 °C. Energy usage was increased with a more efficient PCM storage system. This unexpected result was due to which period the storage system was charged. A more efficient storage system charged quicker during the warmer part of the evening. Therefore energy minimisation requires optimal charging during the coldest part of the night.

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1. Introduction

Worldwide the residential sector is a significant contributor to energy use [1,2]. A large proportion of electricity consumption in homes is currently consumed for air conditioning, and furthermore there is a tendency for an increasing uptake of air conditioning by households. With the expectation of rising global temperatures in the future, the heavy reliance on the use of air conditioning in the residential sector is expected to continue and increase. Space cooling is also a major contributor to peak electricity load. Energy associated with this can be reduced by minimising the cooling load with better insulation systems [3] and more efficient cooling generating equipment such as indirect evaporative cooling systems [4].

Thermal storage can potentially reduce cooling energy in buildings by allowing the equipment that generates the cooling to operate during times when they run more efficiently. They can also be used to store cooling from air conditioning equipment when operating from a renewable energy source. Thermal storage also has financial benefits when the electricity is more costly during the peak as compared to the non-peak hours and it can also serve as a backup in the event of a breakdown of the cooling plant [5,6]. Many countries are making use of thermal storage to shift the peak load to off-peak hours for air-conditioning demands [7–10]. These systems mostly use water or ice as the thermal storage media and are limited to commercial applications. A major drawback of ice based systems is they often do not achieve an energy saving [11]. Other phase change material (PCM) applications are limited due to the high cost of these systems, and the lack of clarity as to any energy savings achieved. Without extensive simulation it is not clear if off-peak storage can achieve an energy saving with PCMs.

In previous research the authors have developed an effectiveness-number of transfer units (ε-NTUs) method which can be used to characterise the heat transfer within PCM storage systems [6,12]. This method has the principle advantage of readily identifying the thermal performance of a PCM system in terms of heat exchange effectiveness. In previous research [13–15], the authors have extensively investigated a PCM storage system with a tube-in-tank type arrangement. Bulk storage of PCM generally achieves higher energy storage density and lower cost than encapsulated PCM. The effectiveness was demonstrated to be a

Abbreviations: CFD, computational fluid dynamics; EER, energy efficiency ratio; ε-NTU, effectiveness-number of transfer units; HTF, heat transfer fluid; NTU, number of transfer units; PCM, phase change material.

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Nomenclature

$R_{T\delta}$	total thermal resistance (K/W)
R_{HTF}	thermal resistance of the HTF (K/W)
R_{WALL}	thermal resistance of the tube wall (K/W)
R_{PCM}	thermal resistance of the PCM (K/W)
R_i	inner radius of the tube (m)
R_o	outer radius of the tube (m)
R_{max}	radius of PCM when point of intersection with neighbouring phase change front (m)
L	length of the tube (m)
H_L	latent heat energy (kJ/kg)
h_f	heat transfer coefficient of the HTF (W/(m^2 K))
k_{HTF}	thermal conductivity of the HTF (W/(m K))
k_w	thermal conductivity of the tube wall (W/(m K))
k_{PCM}	thermal conductivity of the PCM (W/(m K))
$\Delta\delta$	change in phase change fraction (–)
Δt	change in time (s)
δ	phase change fraction (–)
ε_δ	heat exchanger effectiveness (–)
$\dot{m}$	mass flow rate of HTF (kg/s)
m	mass of PCM (kg)
μ	dynamic viscosity of HTF (mPa s)
ρ	density of HTF (kg/m^3)
C_p	specific heat of the HTF (kJ/(kg K))
Q_c	cooling capacity (kW)
$T_{htf,in}$	inlet temperature of the HTF (°C)
$T_{htf,out}$	outlet temperature of the HTF (°C)
T_a	ambient air temperature (°C)
IP	input power (kW)
l_c	load correction factor for input power (–)
l_{hp}	heat pump load (% of rated load)
IP_l	corrected input power for the operating load (kW)

function of the phase change fraction based on a one dimensional heat transfer between the heat transfer fluid (HTF) and the PCM at the phase change boundary. A computational fluid dynamics (CFDs) model of a tube-in-tank PCM system has been developed and validated through experimental results by Tay et al. [15,16]. This model confirmed that the heat transfer through the PCM is essentially one dimensional. Therefore, a mathematical model was developed by Tay et al. [12] and experimentally validated based on the average ε-NTU technique for tubes in a phase change thermal energy storage system. This characterisation has been used to design a suitable PCM storage system for cooling a commercial building [17]. This analysis was based on determining the system size for a given phase change fraction. However, as presented by Belusko et al. [18], the effectiveness can determine the heat transfer at any phase change fraction, and therefore can be used to simulate the heat exchange over time. Consequently, it will be possible to investigate and design an off-peak cooling system which can achieve an energy saving, using the instantaneous effectiveness.

A particular advantage of the ε-NTU method is that the impact of heat transfer improvements can be quickly identified. PCMs have a low thermal conductivity, and heat transfer improvements such as fins can improve heat transfer, however it has been difficult to identify whether the PCM system is actually 'better'. Using the ε-NTU the impact of heat transfer improvements can be shown by applying an effective thermal conductivity to the PCM. A new concept of heat transfer enhancement for a tube-in-tank phase change thermal energy storage system has been investigated by the authors [19]. Melted paths in the frozen PCM are created using pre-melt tubes. This melted PCM is then recirculated using a pump. The flow of the melted PCM causes mixing and increases the overall heat transfer. This method achieves an effective conductivity of twice that of the liquid PCM.

The ε-NTU method determines the thermal resistance independent of temperature. Natural convection is a function of the temperature difference experienced in the PCM liquid. However, over small temperature ranges a constant effective thermal conductivity is possible. Bedecarrats et al. [20] demonstrated this effect by determining an effective thermal conductivity for liquid water, when modelling the heat transfer of a thermal storage system with PCM encapsulated in spheres. A constant effective thermal conductivity of 1.1 W/m K was found.

This paper investigates the tube-in-tank PCM storage system for domestic space cooling applications. The ε-NTU technique is used along with building load, weather and chiller thermal performance data to carry out simulations to evaluate the thermal performance of a space cooling system with off-peak PCM thermal storage, investigating the conditions under which energy savings can be achieved.

2. Effectiveness-NTU technique

A tube-in-tank thermal storage system is where the bulk of the PCM is in the tank and heat transfer fluid transfers the heat to the PCM through the tubes that are in the tank (Fig. 1). This arrangement of PCMs maximises the volume of PCM. When operating as an off-peak storage system, energy is stored in the PCM during the solidification or charging of the PCM and released from the PCM during the melting or discharging process.

A PCM thermal storage system can be described as a heat exchanger with varying heat exchange effectiveness over the phase change process. The ε-NTU representation developed by Tay et al. [12,15] was used to design the tube-in-tank phase change thermal energy storage system. This design has the advantage over traditional sphere in tank systems of having a high compactness factor. The compactness factor is the ratio of the PCM to total tank volume and typically is around 0.9 for shell and tube designs compared to 0.6 for sphere in tank designs [14].

The tube-in-tank PCM system under analysis is analysed as a single straight tube surrounded by a cylindrical volume of PCM with HTF flowing through the tube (Fig. 2). This is a one dimensional mathematical representation of the heat flow between the HTF and the PCM at the phase change profile. The number of transfer units (NTU) is determined from the thermal resistance to the heat flow within the HTF and the section of the PCM which has undergone phase change. The mathematical representation defines that the resistance in the PCM is assumed to be uniform along the length of the tube (Fig. 2(a)). The HTF flows inside the tubes of radius, R_i. Fig. 2(b) shows the thermal circuit for the models.

In order to formulate the effectiveness, the total thermal resistance, $R_{T\delta}$, needs to be determined and is given in Eqs. (1) and (2) where R_{HTF} is the resistance of the HTF, defined by forced internal convection, R_{WALL} is the resistance of the tube wall and R_{PCM} is the resistance in the PCM, defined by conduction and the relevant conduction shape factor. The shape factor refers to the conduction between two concentric cylinders, representing heat flowing from the tube to the phase change front at the phase change temperature. This front will vary with time beginning at the tube wall and increasing to the maximum radius (R_{max}). This R_{max} defines when the phase change front from one tube intersects the phase change front from a neighboring tube.

$$R_{T\delta} = R_{HTF} + R_{WALL} + R_{PCM} \quad (1)$$

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