Applied Thermal Engineering 59 (2013) 618–626

Contents lists available at SciVerse ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng

Free-cooling thermal energy storage using phase change materials in an evaporative cooling system

Brendan P. Walsh*, Sean N. Murray, D.T.J. O'Sullivan

Intelligent Efficiency Research Group (IERG), Department of Civil & Environmental Engineering, University College Cork, Ireland

HIGHLIGHTS

- PCMs are successful in industrially storing free-cooling.
- A reduction in chiller peak-time operation of 67% was achieved.
- A reduction in electrical cost of less than 2% was realized.
- Demand-side management was improved.
- Viability needs to be other than commercial due to PCM cost.

ARTICLE INFO

Article history:
Received 12 July 2012
Accepted 8 June 2013
Available online 19 June 2013

Keywords:
Phase change materials
Free cooling

ABSTRACT

Phase Change Materials (PCMs) offer a means of storing thermal energy when efficiently available and returning it when required. Evaporative cooling systems are considered to be efficient and environmentally friendly. This paper studies the application of PCMs to an industrial Evaporative cooling system to enable the capture and storage of night-time sensible free-cooling, as a means of reducing energy costs and improving demand-side management. The stored cooling is subsequently utilised in the cooling water system during a day-time peak demand to achieve the required cooling capacity at the required temperature, resulting in a reduction of the day-time refrigeration requirements. A computer model has been created using Matlab/Simulink, to simulate the operation with and without the PCM. The PCM, Chiller and Circulation Pump were simulated using manufacturer's data. The Cooling Tower performance was approximated from historical weather data and recorded electrical data. The output of the model demonstrates that the system is functional and successfully achieves a 67% reduction in chiller peak-time operation. It also calculates the power requirement and energy cost of both scenarios. The cost savings were determined along with an estimate of the capital investment required. A commercial viability sensitivity analysis has also been performed.

1. Introduction

1.1. Background

The management of energy is one of the most important challenges facing the international community and the criticality of demand-side management is now emerging, with energy efficiency widely accepted as being the first objective.

It is important to understand, as discussed by Stern [1], that unless the rebound effect, where energy-saving innovations induce an increase in energy consumption, is managed the improvements in energy efficiency may not reduce the total energy demand. However, as indicated by Linwei et al. [2], energy efficiency at all stages of the energy system is generally considered to be one of the most effective means of decreasing future energy requirements and reducing adverse environmental impact without reducing the quality of energy services rendered. Allwood provides a framework for assessing the global scale of opportunity for energy efficiency measures with Cullen [3] and by mapping the scale and complexity of global energy flow, the technical areas which are likely to deliver the largest efficiency gains can be identified. The European Union (EU) has issued a roadmap for moving to a competitive low carbon economy in 2050, which sets out key elements that should shape the EU's climate action; yet it will not meet its energy efficiency target unless further efforts are made [4].

* Corresponding author. Room 203, Department of Civil & Environmental Engineering, Civil Engineering Building, University College Cork, College Road, Cork, Ireland. Tel.: +353 21 420 5135; fax: +353 21 427 6648.
E-mail address: brendan.p.walsh@umail.ucc.ie (B.P. Walsh).

1359-4311/$ – see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.applthermaleng.2013.06.008

In Ireland, thermal uses account for 34% of the overall energy consumption [5] and the climate is suitable for free cooling, particularly at night. This paper researches the increase in efficiency available through the improved demand-side management of an industrial cooling process. This is achieved by storing free-cooling in a Phase Change Material (PCM) at night-time as illustrated in Fig. 1. The stored cooling is utilised the following day to chill the cooling water. The requirement to operate a dedicated refrigeration chiller is reduced, thus decreasing energy consumption, whilst also shifting the electrical load.

The cooling load is based on a chemical plant in a coastal location in Southern Ireland during the calendar years of 2009 and 2010 and is a stand-alone heat exchanger at the top of a continuous process column called an Absorber Tower. As the cooling tower is unable to provide adequate cooling at a sufficiently low temperature during the middle of the day, a chiller is normally utilised to satisfy the dedicated load of 300 kW between the hours of 12:00 and 16:00.

Cooling towers have previously been studied with a view to optimisation for other types of cold storage application. Gan and Riffat [6] presented a numerical technique for evaluating the performance of a closed wet cooling tower for chilled ceiling systems. Increasing the evaporative cooling potential in an HVAC system by storing the cooling in a micro-encapsulated PCM slurry and a building chilled ceiling was investigated by Xichun Wang et al. [7], resulting in chiller energy savings potential of between 10% and 80%. Once the individual components have been enhanced, the balance of the site's overall cooling and heating systems needs to be optimised and a means of achieving this is outlined by Soderman and Ahtila [8].

1.2. Phase change materials

One technology that may be utilised to store cold thermal energy is PCM, which has the advantages of an isothermal phase transition, a high energy storage density and a user-specified phase-transition temperature. However PCMs have disadvantages, including high cost and also degradation over time. An inexpensive form of PCM is ice-slurry, which is widely researched. Nevertheless, this material too has its restrictions and specific considerations. El Abbassi et al. [9] developed a model providing engineering information facilitating the design of efficient ice slurry systems.

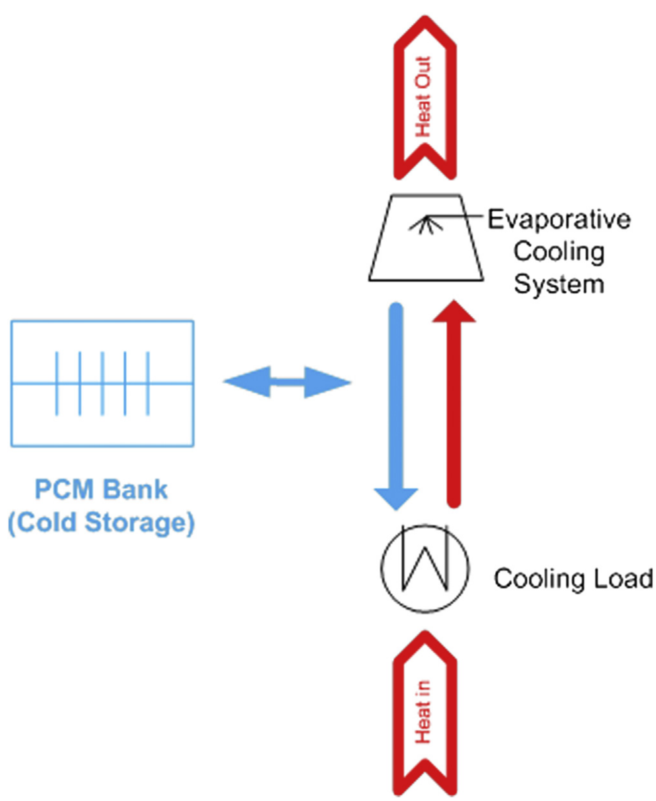

Fig. 1. PCM Bank being used for free-cooling storage.

The subject of free cooling of buildings using PCMs is reviewed comprehensively by Antony Aroul Raj et al. [10], whilst Baetens et al. [11] details the use of PCMs in panel boards, concrete and as an insulating material.

A PCM is required to have fundamental properties appropriate for thermal energy storage (TES), including a high latent heat of fusion, a high thermal conductivity and a minimum tendency for super-cooling. Secondary properties, specific to the application being considered, include a suitable melting/freezing temperature range and chemical stability. The cost effectiveness initially and also over the lifetime may also be important.

Applications of PCMs include building thermal mass increase. Ibánez et al. [12] presents a methodology for the energetic simulation of buildings including PCMs and Ravikumar and Srinivasan [13] used finite element analysis software to model the inclusion of a PCM in the roof of a room and hence demonstrate its benefits.

Other applications include building services along with industrial process bulk cooling storage and back-up. Fuqiao Wang et al. [14] investigated the novel application of PCMs at different positions in the refrigeration cycle circuit. This resulted in energy savings and system stabilisation, with the magnitude dependant on the position, whilst Turnpenny et al. [15] tested and modelled a novel air-conditioning system using heat-pipes embedded in a PCM.

PCMs may also be used for passive cooling of electronics components such as processors. Huang [16] describes how Building Integrated Photovoltaics integrated with two PCMs with different phase transient temperatures for improving heat regulation is being investigated.

A large number of PCMs (organic, inorganic and eutectic) are available in many temperature ranges and vary from a powder for filling into a carrier medium, to sealed spheres/panels. Delgado et al. [17] demonstrated an improvement in heat transfer of 25% when using micro-encapsulated PCM slurry compared to water. Agyenim et al. [18] summarises a list of companies that produce PCMs.

The most appropriate arrangement of PCM for this application is a Thermal Energy Storage bank, which is a vessel, within which the PCM flat panels are stacked with gaps in between to allow the flow of cooling water. The large surface area and relatively thin geometry of the panels allows quick freezing and melting. The quantity of panels is determined by the volume of cooling to be stored. Optimisation of the fundamental characteristics of the storage tank can also be of benefit, as illustrated by Kousksou et al. [19] where a tank orientated vertically was shown to perform better than one horizontally positioned.

2. Methodology

2.1. The selection and application of PCM

The temperature of freezing/melting is one of the primary considerations when selecting a PCM. As an application guideline, a temperature difference of 3 °C–4 °C is needed between the cooling medium, in this case cooling water, and the freezing temperature of the PCM. For melting, a similar temperature difference is required. Thus, combining both, the cooling water freezing the PCM needs to be approximately 8 °C cooler than the cooling water melting the PCM. The specified melting temperature of the PCM needs to be