Applied Energy 136 (2014) 32–42

Contents lists available at ScienceDirect

Applied Energy

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

Climate responsive behaviour of heat pipe technology for enhanced passive airside cooling

Hassam Nasarullah Chaudhry [a,*], Ben Richard Hughes [b]

[a] School of Energy, Geoscience, Infrastructure and Society, Heriot-Watt University, P.O. Box: 294 345, Dubai, United Arab Emirates
[b] School of Civil Engineering, University of Leeds, Leeds LS2 9JT, United Kingdom

HIGHLIGHTS

- Transient thermal response of heat pipes investigated for passive cooling.
- Cooling capacity increased by 0.1 °C for every 1 °C rise in inlet temperature.
- Cooling capacity decreased by 0.3 °C for every 1 °C drop in inlet temperature.
- Highest convective heat transfer of 1546 W achieved at 13:00 h.
- Superior day-time cooling duty in comparison to night operation.

ARTICLE INFO

Article history:
Received 5 February 2014
Received in revised form 14 July 2014
Accepted 7 September 2014

Keywords:
Heat pipe
Passive cooling
Temperature
Thermal imaging
Wind tunnel

ABSTRACT

A detailed investigation into determining the passive airside cooling capability of heat pipes in response to gradually varying external temperatures was carried out. The city of Doha, Qatar was taken as the location of case-study and the climatic data for June 21st, 2012 was incorporated in the transient thermal modelling. The physical domain comprised of 19 cylindrical heat pipes arranged in a staggered grid subjected to varying source temperatures. Wind tunnel testing was carried out for the duration of 24 h in order to establish a relationship between the source temperatures and their effect on the climate responsive behaviour of heat pipes. Infrared thermal imaging was used to capture the surface temperature formations at regular intervals of time during the test. The findings from the study showed that under a low Reynolds Number airstream, the cooling capacity of heat pipes increases by 0.1 °C for every 1 °C rise in external source temperature. Conversely, the investigation showed that the thermal response of heat pipes reduces by 0.3 °C when subjected to decreasing source temperature gradients of 1 °C, thus indicating a low effectiveness. The highest temperature reduction was recorded at 2.3 °C indicating a convective heat transfer of 1546 W and a heat pipe effectiveness of 8.5%. The test confirmed that in general, the heat pipes performed better during the day-time when external temperatures reached over 40 °C in comparison to night-time operation when external temperatures dropped below 35 °C. The present work successfully characterised the sustainable operation of heat pipes in reducing air temperatures without the requirement of any mechanical intervention.

1. Introduction

Passive or natural ventilation systems such as wind towers are appropriate alternative solutions to mechanical methods in maintaining the fresh-air and thermal comfort requirements of a built environment. Conventional wind towers architecture can be integrated into the design of new buildings, to provide required levels of fresh air supply for the built environment. However, at present, the key limiting factor of implementing these systems in hot countries includes insufficient delivery of indoor temperatures due to their complete dependence on outdoor climates. In order to confront the subject, there is a need for incorporating heat transfer mechanisms within natural ventilation systems in order to carry out the cooling duty. If integrated with heat pipes as heat transfer devices, the overall effectiveness of natural ventilation technology can be enhanced in terms of providing adequate indoor temperatures [1,2]. Wind tower systems incorporating heat transfer devices such as heat pipes have been numerically investigated in the past to meet the internal comfort criteria in hot and dry

* Corresponding author. Tel.: +971 (0)4 435 8775.
E-mail address: H.N.Chaudhry@hw.ac.uk (H.N. Chaudhry).

http://dx.doi.org/10.1016/j.apenergy.2014.09.017
0306-2619/

Nomenclature

A	cross sectional area (m^2)	c_p	specific heat capacity of liquid (J/kg K)
ρ	density of liquid (kg/m^3)	ΔT	temperature difference (K)
ε	effectiveness of heat exchanger	$T_{c,inlet}$	temperature at inlet to condenser (K)
g	gravitational acceleration (m/s^2)	$T_{e,inlet}$	temperature at inlet to evaporator (K)
q_{actual}	heat transfer, actual (W)	$T_{e,outlet}$	temperature at outlet from evaporator (K)
q_{max}	heat transfer, ideal (W)	U	velocity (m/s)
q_e	heat transfer rate to evaporator (W)		
h_{fg}	specific enthalpy (J/kg)		

conditions (Fig. 1) and there lies broad scope into the advancement of this technology.

Heat pipes function on a closed-loop heat transfer cycle without requiring external electricity for its operation, thereby making itself entirely adaptable for use within natural ventilation systems. Retrofitting heat pipes into heat exchangers for the purpose of pre-cooling and heat recovery has become an important economic consideration since the utility of heat pipes for environmental management is cost effective and environmentally sound. Since the first basic heat pipe concept was proposed by Gaugler [3], heat pipes have been widely applied to a variety of both simple and complex designs for space and terrestrial applications. Heat pipes are devices used for efficient transport of heat over large distances. Under typical operation, a metal container such as aluminium or copper contains a small amount working fluid pressurised to its saturation point. The heat transfer system is based on the continuous cycle of evaporation and condensation process. When heat is applied to the outer area of the tube, the liquid inside the tube boils and vaporises into a gas that moves through the tube seeking a cooler location where it condenses, giving off its latent heat. Using capillary action, the wick transports the condensed liquid back to the evaporation section [4,5].

For gravity-assisted heat pipes, the liquid is condensed back to the evaporator section by means of gravity [6]. The appropriate choice of working fluid along with the inclination angle is therefore a major factor in heat transfer obtainable from heat pipes [7]. When used in the 90° or vertical orientation, the temperatures at the condenser region of the heat pipes can be maintained by using a constant cold water or ice bath [8] in a fixed control volume.

In relevance to building economics, previous studies of using a heat pipe heat exchanger for energy recovery in air-conditioning streams have indicated a payback time of 3 years on recovery profit making the technology to appeal financially [9]. Heat pipe heat exchangers are readily employed as a heat recovery unit in air-conditioning systems for the built environment although the prospect of achieving passive cooing from natural ventilation air streams is not well-established. Hence, the aim of this study is to classify the dynamic thermal performance of heat pipes in response to external climatic data obtained for the city of Doha, Qatar [10] in order to determine their cooling performance under gradually varying hot source temperature conditions.

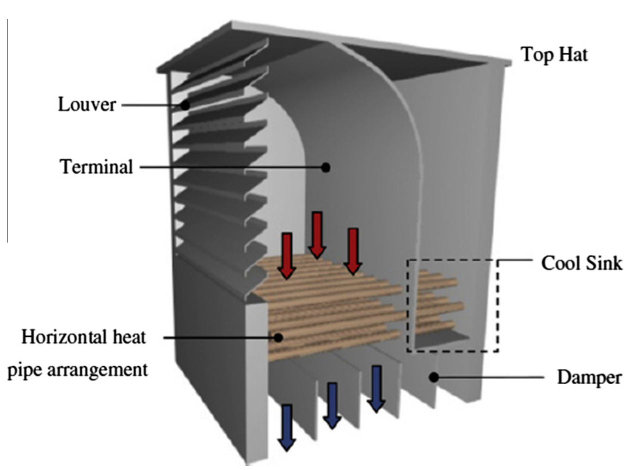

Fig. 1. Conceptual design of a wind tower system incorporating horizontal heat pipe arrangement [21].

2. Previous related work

The use of heat transfer mechanisms incorporating heat pipes in building sectors have been emphasised in literature to decrease the operational costs of the system in order to reach energy saving capacity [11]. Hughes et al., [12] carried out a numerical investigation on scrutinising the performance of a heat pipe integrated heat exchanger for heat recovery in natural ventilation air streams. The results of the study showed the heat pipe system was capable of increasing the temperature from 293 K (20 °C) to 296.3 K (23.3 °C) for heat recovery purposes. Maximum sensible heat transfer for the airstream at the condenser section was determined at 115 W.

Mathur [13] investigated the impact on overall energy consumption of treating ventilation air by retrofitting a heat pipe heat exchanger unit. Using the climatic conditions of St. Louis, Missouri, an in-depth performance investigation was carried out for the year round operation of the HVAC system equipped with the heat exchanger. The heat exchanger comprised of six rows of heat pipes in a horizontal orientation with an effectiveness of 60%. The findings of the study revealed that a heat pipe heat exchanger may be effectively used for increasing the efficiency of the existing HVAC systems.

Wu et al. [14] investigated the potential of using gravity-assisted wickless heat pipes or thermosiphons as cold energy storage systems for cooling data centres. The emphasis of the study dealt with reducing electricity consumption of the facility. A large heat load of 8800 kW was applied on the thermosiphon modules. The work revealed that the system was capable of taking up to 60% of the total cooling load with a payback time of approximately 3 and a half years. In addition, with the reduction of external power consumption, the work revealed that up to 10.4 kilotons of carbon dioxide emissions can be reduced per year. However, when operating with thermosiphon units, it must be ensured that the temperatures at the condenser section or the cold interface must be lower than the evaporator end.

In order to investigate the performance of heat pipes, wind tunnels have been commonly employed to undertake the experimental evaluation. Noie-Baghban and Majideian [15] carried out work on the design and build of a heat pipe arrangement to be installed in a heat pipe heat exchanger for the purpose of heat recovery in buildings where high air change is a primary requirement. The experimental apparatus included a test-rig comprising of two fans to deliver a flow rate of 0.103 m^3/s through evaporator and