Applied Energy 146 (2015) 371–382

Contents lists available at ScienceDirect

Applied Energy

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

Operational performance of a novel heat pump assisted solar façade loop-heat-pipe water heating system

Wei He [a,b,*], Xiaoqiang Hong [a], Xudong Zhao [b,*], Xingxing Zhang [b], Jinchun Shen [b], Jie Ji [a]

[a] Department of Thermal Science and Energy Engineering, University of Science and Technology of China, Hefei 230026, China
[b] School of Engineering, University of Hull, Hull HU6 7RX, UK

HIGHLIGHTS

- A novel loop heat pipe (LHP) was integrated into the building façade to convey the façade solar heat into inside building.
- A heat pump was implemented into the LHP system to enhance its thermal efficiency.
- The model accuracy was validated by experiment giving less than 7% in error.
- The thermal efficiency of the LHP module was increased by 22.2%, with the integration of the heat pump.

ARTICLE INFO

Article history:
Received 1 June 2014
Received in revised form 7 January 2015
Accepted 25 January 2015
Available online 9 March 2015

Keywords:
Loop heat pipe
Façade
Heat pump
Water heating
Building integration
Operational performance

ABSTRACT

This paper aims to present an investigation into the operational performance of a novel heat pump assisted solar façade loop-heat-pipe (LHP) water heating system using both theoretical and experimental methods. This involved (1) development of a computer numerical model; (2) simulation of the operational performance of the system by using the model; (3) test rig construction; and (4) dedicated experiment for verification of the model. It was found that the established model is able to predict the operational performance of the system at a reasonable accuracy. Analyses of the research results indicated that under the selected testing conditions, the average thermal efficiency of the LHP module was around 71%, much higher than that of the loop heat pipe without heat pump assistance. The thermal efficiency of the LHP module grew when the heat pump was turned-on and fell when the heat pump was turned-off. The water temperature remained a steadily growing trend throughout the heat pump turned-on period. Neglecting the heat loss of the water tank, the highest coefficient of the performance could reach up to 6.14 and its average value was around 4.93. In overall, the system is a new façade integrated, highly efficient and aesthetically appealing solar water heating configuration; wide deployment of the system will help reduce fossil fuel consumption in the building sector and carbon emission to the environment.

1. Introduction

Solar energy technology is one of the most cost effective renewable energy technologies and is especially appropriate for meeting the buildings' requirement for electricity and hot water provision. Solar thermal, as the most mature technology among all currently available solar technologies, is proven to have a shorter payback period compared to its lifetime and have relatively higher solar conversion efficiency [1] – two to four times higher than that in solar photovoltaic (PV) systems [2]. Over the past four decades, solar thermal systems have gained wide applications in the building sector globally. It, representing more than 90% of the world-installed solar capacity, has been continuously growing since the beginning of the 1980s and in Europe, solar thermal market was tripled from 2002 to 2006 and is still in booming [3]. By 2020, the EU will be expected to reach a total operational solar thermal capacity of between 91 and 32 GW, thus saving equivalent to at least 5600 tons crude oil [4]. The European Solar Thermal Technology Platform (ESTTP)'s vision plan indicates that by 2030, up to 50% of the low and medium temperature heat energy within Europe will be delivered through solar thermal systems, and truly building integrated solar systems can be a potential solution

* Corresponding authors at: Department of Thermal Science and Energy Engineering, University of Science and Technology of China, Hefei 230026, China. Tel.: +86 551 6360 7390; fax: +86 551 6360 6459 (W. He). Tel.: +44 116 257 7971; fax: +44 116 257 7981 (X. Zhao).

E-mail addresses: hwei@ustc.edu.cn (W. He), xzhao@dmu.ac.uk (X. Zhao).

http://dx.doi.org/10.1016/j.apenergy.2015.01.096
0306-2619/

Nomenclature

A	area (m^2)
c	specific heat capacity (J/kg-K)
D	diameter (m)
Ex	exergy rate (W)
g	gravity acceleration (m/s^2)
h	heat transfer coefficient (W/m-K)
H	high (m); thermal enthalpies (J/kg)
K	thermal conductivity (W/m^2-K)
k	adiabatic compression index
L	length (m)
M	mass (kg)
m	mass flow rate (kg/s)
n	mesh number; rotation speed (rpm)
N	number; compressor power consumption (W)
Nu	Nusselt number
Pr	Prandtl number
p	pressure (pa)
Q	energy rate (W)
R	thermal resistance (K/W)
Ra	Rayleigh number
Re	Reynolds number
T	temperature (°C)
u	flow velocity (m/s)

Greek

α	absorption ratio; thermal diffusivity (m^2/s)
β	factor of expansion (K^{-1})
δ	thickness (m)
ε	porosity; emissivity
η	efficiency
θ	collector slop (degree)
μ	dynamic viscosity (kg/m-s)
v	kinematic viscosity (m^2/s)
ρ	density (kg/m^3)
σ	Stefan–Boltzman constant
τ	visual transmittance, time
χ	vapour quality

Subscripts

a	air
ab	absorption
b	base panel
a	air
c	cover
cp	condenser pipe
com	compressor
con	condenser
e	evaporator
f	friction
hp	heat pipe
hp,e	heat pipe evaporator
hp,in	inner heat pipe
hp,o	outer heat pipe
i	inner
hx	heat exchanger
l	liquid
lf	liquid film
m	mean
s	surface; solid
s,tk	secondary water tank
th	thermal
tp	two-phase flow region
v	vapour; volumetric
wi	wick
w	water; wall

towards the enhanced energy efficiency and reduced operational cost in the contemporary built environment [3].

Most of the solar water heaters, as the key element of the solar thermal systems, were made in flat–plat or conventional heat pipes configuration and installed on roofs for layout convenience. This system has been identified with a number of problems that would prevent their wide application, e.g. the installation detracts the aesthetics of the building and requires the long run of water transportation. Integrating the solar collectors (or called 'absorbers') into the building, which can be fixed to the south-facing wall or balcony of each flat unit [5,6], can shorten the distance of pipe runs, and thus enabling improvement of the building's aesthetic effect and requiring no additional area. For these distinct merits, many façade-based solar thermal systems have been developed and utilized in several building projects as a part of passive solar thermal façade to transfer heat through an insulated wall to a storage tank inside the building [7–11].

However, the façade based solar heating systems still require the transportation of water from inside of the building to the outside, which may cause the hazard of pipe freezing during winter operation. For distant heat energy transportation, loop heat pipe (LHP) is a suitable solution that could transport solar heat from the outer façade surface to the inside of the building. Loop heat pipe, as a special type of heat pipe, is a two-phase heat-transfer device enabling the remote, passive heat transfer for distances up to several tens of meters in the horizontal position [12–15]. LHP has been widely utilized in thermal control of satellites, spacecrafts [16], electronics [17,18] and cooling/heating systems [19,20]. Rittidech et al. [21] described a circular glass tube solar collector with a set of closed-loop oscillating heat-pipes with check valves. Wang et al. [22] presented a novel kind of micro-heat pipe array flat plate solar water heater with an annual average system efficiency of 58.29%. Use of a novel LHP for solar heat collection and transportation was recently proposed by Zhao et al. [23] and still at the research stage. Recent research indicated that LHPs used in the buildings' hot water systems could achieve the enhanced performance if the solar absorber and heat exchanger are adequately selected and coupled [23,24].

In other side, solar heat pump water heating systems have been well studied by a number of researchers [25–27]. To give a brief, Kuang and Wang [28] reported on the long-term performance of a multi-functional DX-SAHP system, with heating and cooling COP's of 2.7 and 2.9. Guoying et al. [29] and Chow et al. [30] reported numerical and theoretical investigations of solar assisted heat pump in their literatures. An ISAHP for water heating coupled to gas burners was reported by Scarpa et al. [31] to perform a better performance of free energy use and obtain high COP values up to 8. Gang et al. [32] performed an experimental study of PV-SAHP system, and obtained PV-SAHP COP of 9.0, a conventional SAHP COP of 6.3 an PV efficiency of 13.2%.

However, there is so far no report found in combined operation between the LHP thermal façade module and heat pump for hot water generation. The most relevant research was a combined PV/LHP heat pump system, which, recently undertaken by the authors [33,34], has an effective absorbing area of 0.612 m^2, was installed at 30° angle relative to the roof, and kept a continuous heat pump operation (unlike the intermittent heat pump operation in the proposed research). This system mainly focused on