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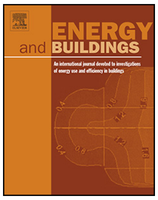

Theoretical investigation of the thermal performance of a novel solar loop-heat-pipe façade-based heat pump water heating system

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ABSTRACT

The aim of the paper was to present a dedicated theoretical investigation into the thermal performance of a novel solar loop-heat-pipe façade based heat pump water heating system. This involved thermo-fluid analyses, computer numerical model development, the model running up, modelling result analyses and conclusion. An energy balance network was established on each part and the whole range of the system to address the associated energy conversion and transfer processes. On basis of this, a computer numerical model was developed and run up to predict the thermal performance of such a system at different system configurations, layouts and operational conditions. It was suggested that the loop heat pipes could be filled with either water, R134a, R22 or R600a; of which R600a is the favourite working fluid owing to its relatively larger heat transfer capacity and positive pressure in operation. Variations in the system configuration, i.e., glazing covers, heat exchangers, would lead to identifiable differences in the thermal performance of the system, represented by the thermal efficiency and COP. Furthermore, impact of the external operational parameters, i.e., solar radiation and ambient air temperature, to the system's thermal performance was also investigated. The research was based on an innovative loop-heat-pipe façade and came up with useful results reflecting the thermal performance of the combined system between the façade and heat pump. This would help promote development and market penetration of such an innovative solar heating technology, and thus contribute to achieving the global targets in energy saving and carbon emission reduction.

1. Introduction

It has been well known that global energy demand is in the trend of continuous growth, and buildings are consuming one third of the total energy supply in developed countries and one fourth in developing countries [1]. Reducing energy demand and making good use of renewable energy are thought to be the major routes towards the low energy and sustainable future, in particular, for the building sector.

Solar technologies have been well developed for many years and are regarded as the most feasible renewable solutions for the building application. Solar thermal, as the most mature technology among all currently available solar technologies, is proven to have relatively higher solar conversion efficiency [2]—two to four times higher than that in solar photovoltaic (PV) systems [3]. Further, solar thermal, owing to the worldwide application and massive scale production, has a much shorter payback period compared to its lifetime. Over the past four decades, solar water heating systems have gained widespread applications in the building sector globally. Most of the solar water heaters were made with flat-plate or heat pipes arrays installed on roofs for layout convenience. This system has been identified with a number of problems that would prevent their promotions, e.g. the installation detracts the aesthetics of the building and requires the long run of water transportation.

In recent years, many façade-based solar water heating systems have been developed and utilized in high-rise building projects, particularly in China. In these systems, the solar collectors (called 'absorbers') could be fixed to the south-facing balcony of each flat unit [4–6]. This layout can prevent the occupation of the roof space and shortens the distance of pipe runs, thus enabling improvement of the building's aesthetic effect. However, façade based solar heating systems face a series of challenges: (1) lower solar radiation

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Nomenclature

A_m	effective module area (m^2)
$A_{c,r}$	cross area of refrigerant flow (m^2)
$A_{hx,r}$	cross area of refrigerant in heat exchanger (m^2)
$A_{hx,s}$	surface area of the plate heat exchanger (m^2)
C_p	specific heat capacity (J/kg K)
D	diameter (m)
g	gravity acceleration (m/s^2)
h	convective heat transfer coefficient (W/m K)
h_{fg}	latent heat of vaporization (J/kg)
h_r	refrigerant heat transfer coefficient (W/m K)
$h_{r,l}$	heat transfer coefficient of liquid refrigerant (W/m K)
h_R	radiative 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 flow rate (kg/s)
n	mesh number; rotation speed (rpm)
N	number
N_{in}	compressor power consumption (W)
Nu	Nusselt number
Pr	Prandtl number
p	pressure (Pa)
Q	energy rate (W)
R	thermal resistance (K/W)
R_0	universal gas constant (kJ/kmol K)
Ra	Rayleigh number
Re	Reynolds number
t	temperature (°C)
U	overall heat coefficient (W/m K)
W	width (m)

Greek

α	absorption ratio; thermal diffusivity (m^2/s)
β	factor of expansion (K^{-1})
δ	thickness (m)
ε	effectiveness (%); porosity
η	efficiency
μ	dynamic viscosity (kg/m s)
ν	viscosity (m^2/s)
ρ	density (kg/m^3)
σ	Stefan–Boltzman constant
τ	visual transmittance
χ	vapour quality

Subscripts

a	air
abs	absorption
c	cover
c,c	condenser coil
c_1	internal cover sheet
c_2	external cover sheet
d	discharge
e	evaportator
e,t	evaporation thermal energy
f	three-way fitting
g	glazing cover
hp	heat pipe
hp,e	heat pipe evaporator
hp,in	inner heat pipe
hp,o	outer heat pipe
hx	heat exchanger
l	liquid
L	loss
m	mean
p	heat pipe wall
r	refrigerant
s	solid; isentropic
s,tk	secondary water tank
th	thermal; theoretical
tk	primary water tank
tl	transporting line
tp	two-phase flow region
u	useful
v	vapour; volumetric
wi	wick

compared to that on the tilt roof; (2) limited installation area; (3) limited space in kitchen or washroom that may restrict the safe installation of the water tank. All these together may lead to inefficient operation of the system, particularly at high temperature condition.

To overcome the above difficulties, solar heat pump water heating system has been proposed and studied by various researchers [7–11]. This concept could lower the temperature of the solar absorber by controlling evaporation temperature of the refrigerant, thus improving the solar efficiency of the system. However, long run of the refrigerant pipes between the outer façade and inside kitchen or washroom may lead to significantly higher refrigerant flow resistance and consequently, power needed for operating the compressor would be increased.

To further improve the performance of the solar water heating systems, a novel loop-heat-pipe (LHP) façade based heat pump water heating system is thereby proposed. The LHP is a two-phase heat-transfer measure with the working fluid circulating across the loop, thus enabling remote, passive heat transfer at the enhanced capacity. The LHP has been widely ultilized in thermal control of satellites, spacecrafts, electronics and cooling/heating systems [12,13]. Use of LHP for solar energy collection and transportation is the only recent development 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 [14,15].

To understand the insights of the innovative LHP façade based heat pump water heating system, a theoretical investigation into the thermal performance of such a system will be carried out by the combined effort of thermo-fluid analyses, computer numerical model development, model running up, modelling result analyses and conclusion. This research will help promote development and market penetration of such an innovative solar heating technology, and thus contribute to achieving the global targets in energy saving and carbon emission in the building sector.

2. System descriptions

The proposed system is schematically shown in Fig. 1, which can be clearly divided into two elements, i.e., outdoor and indoor parts. The outdoor part is a modular package, which receives the solar irradiation and converts it into heat energy in the form of low-temperature vapour. The indoor part consists of a number of components including heat pump compressor, secondary water tank with heat exchanger (heat pipe condenser and heat pump evaporator), expansion valve, primary water tank with embedded heat-exchanging coils (heat pump condenser) and the associated