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Performance analysis of a multi-pass solar thermal collector system under transient state assisted by porous media

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ABSTRACT

An enhanced forced convective multi-pass solar air heating collector (MPSAHC) system aided with granite pebble bed has been investigated in this present article. The air heating collector system was tested in the outdoor solar research site of Universiti Teknologi PETRONAS, Malaysia (4.385693° N and 100.979203° E). Transport pipe for movement of heated air around the system was eliminated in the design of the MPSAHC facility to minimise the thermal losses, pressure drop and the pumping cost of the hot air in the control volume. The daily ambient temperature and relative humidity range recorded during the repeated tests are 21.09–36.64 °C and 48.04–87.9%, respectively. The collector unit achieved a peak temperature of 80.29 °C while the optimum system air mass flow rate of 0.016 $kg s^{-1}$ was applied. Despite high relative humidity of the environment, the stream of ambient air was heated to 48.53 °C, 57.75 °C and 71.19 °C at different positions in the MPSAHC which correspond to single pass, double pass and multi-pass effects, respectively. The porous matrix exhibited slow energy discharge at night time with air temperature difference of 14.27 °C at 18:00 h to 4.54 °C at 24:00 h over environmental air temperature. MPSAHC system delivered specific energy demand (SED) of 11.51 kWh kg^{-1} while the maximum thermal collector and daily average transient collector efficiencies of 72.59% and 36.38% were achieved, respectively. A good agreement has been established between reported studies and the present investigation. Although continuity of system operation at night was achieved using porous matrix but improvement is still needed to optimise the system performance.

1. Introduction

Transformation of global energy demand from hydrocarbon source to sustainable energy sources would not be an easy task except every stakeholder in renewable energy sector takes pragmatic step to mitigate environmental pollution. In addition, there is need for improvement on the performance efficiency of solar energy based appliances to gain wide acceptability. The United Nations (UN) has supported the clean energy initiative with the launching of Sustainable Development Goals (SDG), while regional efforts such as vision 20-20-20 of European Union has been conceived to assist in protecting the environment from global warming and other adverse effects of fossil fuel.

Flat plate collector has been consistently used over the years for indirect solar space heating, drying operation and industrial application. Flat absorber is still relevant due to its architecture in different forms, operating temperature, fabrication cost and wide applications. Flat collector plate may maintain flat shape, chevron, v-grooved or any other shape that does not converge the reflected solar radiation. Flat plate solar collector is often relevant for low and medium range operating temperature (Karim and Hawlader, 2006a; Naphon, 2005).

Several propositions have been made to improve the performance of solar air heater (SAH). Ho-Ming and Chii-Dong (2009) investigated the relevance of using external recycle approach to enhance the performance of a solar air heating collector. Their proposal has been based on the improvement of air mass flow rate to ease convective heat transfer and mass transfer of moisture in drying application. However, reflux ratio of recycle air must be properly managed to reduce the negative impact of recirculation on the inlet air temperature. Recycle of exit air and creation of baffles on solar absorber have been reported as a means of improving the collector efficiency (Ho et al., 2005; Mohammadi and Sabzpooshani, 2014; Ravi and Saini, 2016; Yeh, 2012). Karim and Hawlader (2006a) studied a v-grooved solar absorber to improve the thermal performance of a corrugated solar air collector. Kumar and Kim (2015) employed the vortex technique to introduce disturbance (baffles

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Nomenclature

A	area, m^2
C	coefficient
C_e	evaporative capacity
C_p	specific heat capacity, $J(kg\,°C)^{-1}$
Ex	exergy, J
H	absolute humidity
h	heat transfer coefficient, $W(m^2\,°C)^{-1}$
h_v	heat of vapourisation, Jkg^{-1}
I	solar irradiance, Wm^{-2}
k	thermal conductivity, $W(m\,°C)^{-1}$
l	characteristic length, m
m	mass, kg
$\dot{m}$	air mass flow rate, kgs^{-1}
Nu	Nusselt number
P^1	pressure, Pa
P	power, W
Pr	Prandtl number
Re	Reynolds number
T	temperature, °C
t_g	glass thickness, m
t	time, s
U_{loss}	heat loss, $W(m^{2}\cdot°C)^{-1}$
v	velocity, ms^{-1}
V	volume, m^3
x,y,z	length, m

Greek letters

α	absorbance
δ	change in value
ε	emittance
ϵ	porous matrix porosity
ζ	coefficient
η	thermal efficiency,%
θ	absorber angle of tilt, degree (°).
ρ	density, kgm^{-3}
σ	Stefan-Boltzmann constant, $Wm^{-2}\cdot K^{-4}$
τ	transmittance
χ	number of glass cover
ψ	uncertainty
ω	coefficient

Subscript

0	inlet air at a point of consideration
c	convective
dk	drying deck
f	fluid
j	exit point of consideration
g	glass
m	cabinet load
mt	porous matrix
p	collector plate
r	radiative
w	wind

Abbreviations

MPSAHC	multi-pass solar air heating collector
SAH	solar air heater
SDG	Sustainable Development Goals
SED	specific energy demand
UN	United Nations
UTP	Universiti Teknologi PETRONAS

and ribs) along the air flow. This has improved the heat transfer to the stream of air in the control volume. It has been established that a considerable increase in Nusselt number (Nu) would lead to better performance but the pressure drop would come to play. El-Sawi et al. (2010) used chevron absorber plate to augment the heat energy delivery by the air heater. They achieved a 10 °C increase in outlet air temperature which yielded 20% improvement on thermal performance efficiency compared to the conventional solar collector.

Investigations have been conducted on the use of non-conventional solar collector to improve performance efficiency of solar collectors. Abdullah and Bassiouny (2014) reported a theoretical and experimental study of using plastic absorber for SAH. They developed a modelled that constitutes equations which were solved by Newton-Raphson iterative technique. Consequently, they successfully used polyvinylchloride as transparent cover and polyethylene (collector) materials were moulded to form cylindrical solar absorber which achieved performance efficiency range of 50–62%. Dorfling et al. (2010) reported an absorber made of polyethylene material which they argued that it could compete favourably with any typical solar collector. Concrete (Bilgen and Richard, 2002) and asphalt (Tang et al., 2014) as non-conventional absorbers have also been reported.

Peng et al. (2010) have modelled a solar flat plate collector made of steel material and tested under a steady state condition. The model assumed negligible value for the heat capacity of the system transparent cover. The solar absorber performance efficiency has been enhanced with the attachment of pin-type fins to the collector. It was argued that the installation of pin-type fin could triple the efficiency of ordinary flat plate collector. They emphasised that the size of their collector was chosen based on its availability in commercial quantity. Several studies have been conducted using fins as extended surfaces attached to the absorber to improve the thermal efficiency of solar collector (Al-Abidi et al., 2013; El-Sebaii et al., 2011; Fudholi et al., 2013a, 2013b; Ho et al., 2009; Karim and Hawlader, 2006b; Kumar and Rosen, 2011; Mahmood et al., 2015; Omojaro and Aldabbagh, 2010; Stojanović et al., 2010; Youcef-Ali and Desmons, 2006).

Hybrid technique is an approach that has contributed to the enhanced performance of solar collector especially at the time when low solar irradiation prevails. Suleman et al. (2014) combined solar thermal collector with a heat pump to augment solar system performance. Dryers with backup hybrid mode as a source of energy at night or during cloudy daytime have been reported (Čiplienė et al., 2015; Madhlopa and Ngwalo, 2007; Sekyere et al., 2016; Yassen and Al-Kayiem, 2016; Zeng et al., 2014). Porous matrix has been used as thermal mass to store heat energy during the day. The stored energy has been used to extend the drying operation of solar dryers at the off-sun period (El-Sebaii et al., 2007; Naphon, 2005; Ramadan et al., 2007; Sopian et al., 2009; Zhao et al., 2011).

Augustus Leon et al. (2002) emphasised the architecture of collector and the number of passes of air stream as influential factors that dictate the performance of a solar thermal collector. In the last two decades, significant contributions have been made on solar hot air heaters of single pass and double pass facilities. Indirect method of utilizing solar drying has been widely studied to rectify the deficiencies of direct open sun drying. Remarkable achievements have been made on both single and double pass solar air heating collector systems (Ampratwum and Dorvlo, 1998; Mahmood et al., 2015; Omojaro and Aldabbagh, 2010; Ramani et al., 2010; Sopian et al., 2009). Jain and Jain (2004) presented a study on the analytical model of a multi-pass solar air heating