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Experimental and numerical investigation of volumetric versus surface solar absorbers for a concentrated solar thermal collector

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ABSTRACT

A low-profile concentrated solar thermal collector (<15 cm in height) was proposed and investigated to demonstrate its potential to deliver heat energy in the range of 100–250 °C. We use both experimental and numerical methods to investigate of the effect of modifying the absorber in this collector. As such, a volumetric absorber (consisting of a multi-walled carbon nanotube nanofluid contained within a glass tube) was compared against a conventional surface absorber (consisting of a black chrome-coated copper tube). The experimental and computational fluid dynamics (CFD) results were found to be in good agreement for the thermal efficiency of these two receivers.

The analysis revealed that the vacuum-packaged volumetric receiver had an efficiency of 54% and 26% operating at 80 °C and 200 °C, respectively. This lower than a vacuum-packaged black chrome-coated receiver, which had an efficiency of 68% and 47% in the same concentrator, operating at the same temperatures, respectively. [Note that commercial linear concentration systems typically have efficiency in the range 44–57% at 200 °C.] The inferior performance of the volumetric receiver was found to be due to higher reflective optical and radiative heat loss from the surface of glass tube. Overall, this study reveals that the proposed low-profile collector design is suitable for utilisation in industrial and commercial heating applications, but that volumetric absorbers will require anti-reflective and good selective coatings to be competitive with surface absorbers. If these challenges can be overcome, nanofluid receivers may have a cost/manufacturing advantage since glass-to-glass vacuum sealing is easier to achieve than metal-to-glass.

1. Introduction

Although the sun continuously creates - and provides free delivery on - an enormous amount of clean, renewable energy, <0.0005% of this resource is currently harvested on earth (Solangi et al., 2011). Due to increasing energy demand and environmental pressures, solar energy utilisation is rapidly expanding (Solangi et al., 2011). Photovoltaics (PV) may garner more recognition, but solar thermal technology still represents the majority (∼70%) of the global installed capacity of solar energy (410 GW_{th} of 590 GW in total) (Renewables 2015 Global Status Report, 2015). Of this solar thermal capacity, collectors which provide domestic hot water cover the lion's share, with more than 289.5 GW_{th} installed in China alone (Weiss et al., 2010; Xu et al., 2012). For reference, the global installed capacity of PV was ∼178 GW_e at the end of 2014 (Weiss et al., 2010; Xu et al., 2012).

Rooftop integrated solar thermal systems can, in theory, supply medium to high temperatures (100–400 °C) directly to industrial heating, air-conditioning and commercial steam application (Shirazi et al., 2016a, 2016b). This could open a huge commercial and industrial market for high quality heat (to offset volatile gas prices behind the metre), while also minimising our ecological footprint (e.g. land-use) (Kalogirou, 2003; Al-mulali et al., 2016).

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Nomenclature

A	area (m^2)
A	absorbance
C_p	specific heat capacity (J/kg K)
Cr	Geometrical concentration ratio
D	diameter (m), dimension
G	global solar irradiation (W/m^2)
K	incidence angle modifier
L	litre
$\dot{Q}$	heat transfer rate (W)
R	reflectance
SWA	Solar weighted absorbance
T	Temperature (K)
T	transmission
UV	ultraviolet (0.01–0.4 μm)
U_L	collector heat loss coefficient (W/m^2 K)
V	wind speed
Vis	visible (0.4–0.7 μm)

Greek letters

α	absorptance
ρ	reflectivity, density
τ	transmissivity
σ	Stefan–Boltzman constant (W/m^2 K^4)
ε	emissivity
θ	incident angle (°)
η	efficiency
λ	wavelength

Subscripts

a	ambient
aper	aperture
b	beam radiation
bf	base fluid
b_m	mean value of beam radiation
abs	absorber
air	air
col	solar collector
conv	convection
Cu	copper
d	diffuse
d_m	mean value of diffuse radiation
dh	directional-hemispherical
e	electricity
f	fluid
g	glass
gl	global
in	inlet
loss	heat loss
m	mean
opt	optical
o	outlet
r	receiver
rad	radiation
th	thermal

Abbreviations

BCCCT	black chrome-coated copper tube
CFD	computational fluid dynamics
CPC	compound parabolic concentrator
DASC	direct absorption solar collector
DNI	Direct Normal Irradiance
IAM	incidence angle modifier
MWCNT	multi-walled carbon nanotube
NIR	near infrared (0.7–2.5 μm)
PV	photovoltaics

Unfortunately, only a few collectors have been commercially developed which can fit the needs of the industrial process heat market. A key barrier for most concentrated solar systems is that integration with rooftops is relatively complex and cumbersome in comparison with PV panels (Munari Probst and Roecker, 2007). In order to avoid wind loading issues and to be easy integrated with building roofs, low-profile collectors are desirable. A rooftop solar concentrating collector, developed by Chromasun, can deliver heat at temperatures of up to 200 °C at 44% efficiency (when the Direct Normal Irradiance (DNI) is 850 W/m^2) (Chromasun, xxxx). TVP Solar has developed a high vacuum, flat plate solar thermal panel which is able to maintain efficiencies of 50% when the working temperature reaches 200 °C (when the global horizontal irradiation of 1000 W/m^2) (Calise et al., 2015). Several parabolic trough technologies have been developed, including the PolyTrough 1800 solar collector (developed by NEP Solar) (Xie et al., 2011), the SOLITEM PTC1800 (developed by Solitem Company) (Platzer, 2011), and the SopoNova™ MicroCSP (developed by Sopogy Inc.) (Brogren et al., 2003). In some cases these have been designed for rooftops, but parabolic trough collectors are more typically ground mounted (Calise et al., 2015; Xie et al., 2011; Platzer, 2011). Due to their relatively high concentration ratio, parabolic troughs can deliver heat at a temperature of 200 °C with between 53% and 57% efficiency under a DNI of 800–850 W/m^2 (Xie et al., 2011; Fernandez-Garcia et al., 2010). As a consequence of the growing interest in this technology, several public and private institutions have recently developed a number of prototypes for this market. For example, the PTC-1000 prototype developed by German research institutions, has an efficiency of around 59% at a DNI of 800 W/m^2 and a temperature of 200 °C (Weiss and Rommel, 2005). The Parasol prototype, under development at the Austrian Institute for Sustainable Technologies, has a measured efficiency of 43% at a temperature of 200 °C with a DNI of 800 W/m^2 (Weiss and Rommel, 2005). An External Compound Parabolic Concentrator (XCPC) collector developed at the University of California, Merced, is able to achieve a 200 °C fluid temperature with an efficiency of 36–40%, as a DNI of 800 W/m^2 (Winston et al., 2014). The co-authors (Zheng et al., 2014, 2015; Li et al., 2014) have also recently developed a compact concentrator (<15 cm height) design when employs Fresnel lenses and a CPC reflectors to provide a concentration ratio of ~5×.

Most of these solar thermal collectors use receivers with ‘surface-based’ absorbers - e.g. an opaque metal surface coated with a selective thin film to efficiently convert solar radiation into thermal energy (Li et al., 2016). Although this configuration seems to be straight-forward, selective films (e.g. TiNOx) consist of multiple layers of vapour deposited, high purity materials (Selvakumar and Barshilia, 2012). In addition, heat from the outer surface must first conduct through the solid plate/tube and then be transferred into a working fluid. A temperature drop is caused by conductive and convective resistances between the outer absorber surface and the working fluid. Additionally, from a heat loss perspective, applying the highest temperature on the outer absorber surface is not ideal since it ultimately drives the heat loss with the surroundings (Hewakuruppu et al., 2015).