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Novel non-concentrating solar collector for intermediate-temperature energy capture

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Abstract

Tremendous research efforts have been conducted studying the capturing and conversion of solar energy. Solar thermal power systems offer a compelling opportunity for renewable energy utilization with high efficiencies and excellent cost-effectiveness. The goal of this work was to design a non-concentrating collector, capable of reaching stagnation temperatures above 250 °C and fluid outlet temperatures under flow above 200 °C at 1000 W/m^2 solar irradiance. The study provides a detailed description of the methods and materials for construction of non-concentrating, high-temperature, evacuated solar collectors, the output fluid temperature depending on the input flow rate of working fluid in a low-flow rate, high-temperature regime, and an analytical description of the heat transfer between the collector and the working fluid. Temperature gains compared to ambient far above 200 °C were possible under solar irradiance of 1000 W/m^2 with collector efficiencies of 30% and more. For a temperature gain of 227 °C (fluid outlet temperature 253 °C), the collector efficiency was 30%, and for a temperature gain of 214 °C (fluid outlet temperature 240 °C), the collector efficiency was 49%. This result opens up many new uses for non-concentrating solar collectors in fields such as power generation, fuel reforming, and catalysis.

Keywords: Solar energy; Renewable energy; Heat transfer; Solar collector; Evacuated tube collector; Non-concentrating

1. Introduction

Enormous research efforts have been conducted to find better ways to capture solar energy to meet the growing energy demands of the modern world. Solar energy is clean, renewable, abundant, and easily captured. Photovoltaic (PV) cells are one of the most popular ways to capture solar energy, but their relatively low efficiency and high cost have impeded wide-spread use (Delucchi and Jacobson, 2011). Furthermore, there is concern over the limited availability of high-quality silicon produced for traditional silicon PV cells (Jacobson and Delucchi, 2011). Solar thermal power systems offer a compelling alternative with efficiencies above 40% (Kalogirou, 2004; Sakhrieh and Al-Ghandoor, 2013), and excellent cost-effectiveness among renewable energy sources (Fernandez-Garcia et al., 2010; Quaschning, 2004; Speyer, 1965).

Systems for collecting solar thermal power can be categorized broadly into two groups: concentrating and non-concentrating. Concentrating collectors typically use mirrored surfaces to focus light from a large area to a smaller area where the absorber material is located. By comparison, non-concentrating systems directly absorb light which is incident on their surface (Kalogirou, 2004).

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Nomenclature

A	area of the absorber plate (m^2)
A'_{ij}	intermolecular energy exchange parameter between components i and j
a_1	coefficient for solar collector efficiency ($W/(m^2\,K)$)
a_2	coefficient for solar collector efficiency ($W/(m^2\,K^2)$)
C	coefficient
$C_{p,l}$	specific heat of liquid (J/(kg K))
$C_{p,v}$	specific heat of vapor (J/(kg K))
D	pipe inner diameter (m)
ΔH	total enthalpy rate captured by working fluid (W)
ΔH_{vap}	specific heat of vaporization (J/kg)
h	convective heat transfer coefficient ($W/(m^2\,K)$)
I	incident solar irradiance (W/m^2)
k^*	thermal conductivity of mixed gas (W/(m K))
k_i	thermal conductivity of component i (W/(m K))
k'_i	mixture adjusted thermal conductivity of component i (W/(m K))
k_f	thermal conductivity of fluid (W/(m K))
k_S	thermal conductivity of solid porous material (W/(m K))
k_G	thermal conductivity of fluid in porous medium, geometric mean (W/(m K))
M_i	molecular mass of species i (g/mol)
$\dot{m}$	mass flow rate (kg/s)
Nu_D	Nusselt number based on D
q''	heat flux (W/m^2)
S_i	Sutherland constant of species i (K)
T_o	outlet temperature (K)
T_i	inlet temperature (K)
T_b	boiling temperature (K)
T_W	wall temperature (K)
T_m	mean temperature (K)
ΔT_m	Difference in mean temperature (K)
v_i	volume concentration of component i
V_{steel}	volume of steel wool fibers (m^3)
V_{plug}	volume of porous medium (m^3)

Greek symbols

α	absorptivity
γ_i	coefficient
ε	emissivity
η	solar collector efficiency
η_0	coefficient for solar collector efficiency
κ	ratio of adjusted thermal conductivities
σ_i	collision diameter of species i (m)
ϕ	void fraction

Acronyms

ETC	evacuated tube collector
FPC	flat-plate collector
GCR	geometric concentration ratio
NRTL	non-random two-liquid
PV	photovoltaic
PTC	parabolic trough collector

In a concentrating collector, the ratio of the collector area to the absorber area is known as the geometric concentration ratio (GCR). Parabolic trough collectors (PTCs), the most common type of concentrating collector, typically have GCRs of 15–30 and can reach temperatures of 300–400 °C (Fernandez-Garcia et al., 2010; Grass et al., 2004; Kalogirou, 2004; Kumar and Reddy, 2009; Price et al., 2002; Rabl, 1985). There are, however, disadvantages associated with PTCs and any other concentrating collector. They require large concentration rations in order to reach high temperatures, and as the concentration ratio increases, the collector's field of view decreases (Rabl, 1985). This renders diffuse light less and less effective (Kalogirou, 2004; Rabl, 1985). Using only direct sunlight requires complex and expensive sun-tracking systems (Fernandez-Garcia et al., 2010; Kalogirou, 2004; Rabl, 1985), and causes the system to be inoperable during inclement weather. The reflective surfaces used by PTCs can also degrade over time (Kalogirou, 2004), particularly in the sandy desert conditions where they are commonly operated.

Of the two broad categories, concentrating and non-concentrating collectors, numerous subtypes of collectors can be defined by their geometry and method of thermal insulation. The simplest and most common non-concentrating solar collector design is the flat-plate collector (FPC). As the name suggests, these collectors use a flat absorber surface to capture light. They transfer heat to a working fluid, and use traditional insulation materials such as foam or fiberglass to retain heat. FPCs are commonly found in residential applications, being well suited to provide thermal energy for water and space heating. However, high thermal losses prevent these systems from operating efficiently above 100 °C (Eaton and Blum, 1975; Kalogirou, 2004; Rabl, 1985; Sakhrieh and Al-Ghandoor, 2013).

Previous research has shown that thermal losses could be reduced by replacing conventional insulation materials with a moderate vacuum (Eaton and Blum, 1975; Zimmerman, 2011). This eliminated, or at least reduced, convective losses from the absorber to its enclosure and raised the operational temperatures to 150 °C at 45%