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Energy concentration limits in solar thermal heating applications

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ABSTRACT

Global demand for heating accounts for more than 50% of primary energy consumption. Thermal energy for such purposes is produced mainly by natural gas, electricity, biomass, geothermal, and solar thermal technologies. Solar energy is an abundant, but low density, resource which can be harvested with little environmental impacts. In order to achieve outputs suitable for commercial and industrial applications, *optical* concentrators are conventionally required to increase the temperature and efficiency of a solar thermal system's output. In this paper, we instead explore the potential for utilizing *energy* concentrators to boost the performance of solar thermal collectors. To determine the feasibility of this approach, engineering limitations are established for realistic energy concentrators. Our analysis reveals that maximum effective energy concentration ratios of 176 and 2208 are possible for passive and active energy concentrators, respectively. Overall, this study demonstrates the potential of this concept for solar thermal collectors and other low-grade sources of heat.

1. Introduction

The average global energy demand is predicted to reach 16.5 billion tons of oil equivalent by 2030, with an increase of 1.7% per year [1]. Of this, global demand for heating accounts for about half of global energy consumption, much greater than the energy required for transport (27%), electricity (17%) and other uses (9%) [2,3].

Heat flux density is a key factor in heat transfer systems, which defines the energy receiving temperature, heat transfer rate or heat exchanging area. High energy/heat flux density is desirable in many applications, such as power generation, heating, manufacturing etc. For instance, a higher industrial combustion furnace heat flux density would result in a higher furnace temperature which is more desirable since it can be more efficiently converted to work [4–19]. In the thermoelectric generator (TEG) applications, the reduced thermoelectric materials and an enhanced efficiency can be achieved by increasing the heat flux density into the TEG [20–22]. Moreover, working heat fluxes may exceed 10 MW/m^2 in applications such as cutting lasers and plasma-arc welding [23,24]. Additionally, a high heat flux density is required to package large power conversion or transfer devices into smaller volumes, a necessity in many areas such as nuclear technology and aerospace. High heat flux density applications are associated with either removing large rates of energy generation through small surface areas or reducing the size of the energy receiver [25].

Solar energy, while being a highly abundant renewable energy resource (~10,000 times the annual global energy demand is incident on the earth), only provides a flux density of around 1 kW/m^2. Since it is relatively easy to convert solar radiation to heat, many low cost solar thermal collectors are readily available and installed around the globe. At present, low temperature collectors are the largest solar energy producer – with over 180 GW$_{th}$ installed in China alone – as compared to ~140 GW$_e$ of global photovoltaic capacity [26,27]. Most of the installed solar thermal capacity is meant for low temperature (<100 °C) operation. Many researchers have investigated advanced technologies, such as spectral beam splitting, optical concentrators and nanofluid-based optical receivers to improve the performance of solar thermal collectors [27–34]. To attain higher temperatures

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Nomenclature

A	area (m^2)
C_p	specific heat capacity (J/kg K)
COP	coefficient of performance
Cr	geometrical concentration ratio
$Cr\|_{eff}$	effective energy concentration ratio
D	diameter (m)
Eff	efficiency
F	fin efficiency, View factor
F′	collector efficiency factor
G	global solar irradiation (W/m^2)
h	enthalpy (J/kg), Heat transfer coefficient (W/m^2K)
I	electrical current through the thermoelectric module (A)
k	thermal conductivity (W/m-K)
L	length (m)
$\dot{m}$	mass flow rate (kg/s)
q''	flux density (W/m^2)
$\dot{Q}$	heat transfer rate (W)
R	thermal resistance (m^2 K/W)
S	specific entropy (J/Kg K)
SAHP	solar-assisted heat pump
STEG	solar thermoelectric generator
Rp	compressor pressure ratio
T	temperature (K)
TEC	thermoelectric cooler
U	overall heat transfer coefficient (W/m^2 K)
U_L	collector heat loss coefficient (W/m^2 K)
W	width (m)
$\dot{W}$	supplied electric power (W)
ZT	figure of merit

Greek letters

α	absorptance, Seebeck coefficient of thermoelectric module (V/K)
ρ	reflectance
τ	transmittance
σ	Stefan–Boltzman constant (W/m^2 K^4)
ε	emissivity
θ	incident angle (degree)
η	working efficiency

Subscripts

a	ambient
b	base
abs	absorber
air	air
b	bond
C	cold side of thermoelectric module
c	constriction
col	solar collector
comp	compressor
cond	condenser
conv	convection
Cu	copper
e	electricity
ev	evaporation
ex	exterior
f	fluid
g	glass cover
p	electricity power
P	pressure
eff	effective
H	hot side of thermoelectric module
i	interior
in	inlet
hp	heat pipe
HS	heat sink
loss	heat loss
m	mean
out	outlet
r	refrigerator
rad	radiation
sp	spreading
t	thickness
th	thermal
TIM	thermal interface material
u	useful
w	water

(>100 °C), optical concentrators are most commonly used, which are based on either reflective or refractive optical components. For example, a concentrating collector developed by Chromasun Inc., with a concentration ratio of 26, can deliver heat at temperatures up to 200 °C with 48% efficiency under a sun radiation of 1 kW/m^2 [35]. Solar furnace temperatures of up to 3400 °C have been experimentally reached, while concentration ratios up to 14,000 have been reported for solar thermal power plant systems [36–38]. Heat at such temperatures opens up many commercial and industrial applications, such as solar cooling, methanol reforming, industrial process heating and electricity generation [39,40].

In addition, 20–50% of industrial energy consumption is ultimately discharged as waste heat. The waste heat can be reused to generate domestic hot water, for space heating purposes, in low temperature process heating systems or (if concentrated/upgraded) could serve higher temperature applications [41].

Energy concentration, although rarely referred to as such, is a concept that is frequently employed in heat transfer systems. In this paper, energy concentration is defined as a method by which energy at low-flux density on one surface is delivered with a higher flux density to another surface. The effective energy concentration ratio is expressed by Eq. (1):

$$Cr|_{eff} = \frac{q''_{out}}{q''_{in}} = \frac{\dot{Q}_{out}}{\dot{Q}_{in}}\left(\frac{A_{in}}{A_{out}}\right) \quad (1)$$

where q''_{in} and q''_{out} are the flux density of the energy receiver and output sides and A_{in} and A_{out} denote the area of the energy receiving and output sides, respectively.

The effective energy concentration ratio also can be expressed by Eq. (2):

$$Cr|_{eff} = \eta Cr \quad (2)$$

where η represents the working efficiency of concentration system which is given by $\dot{Q}_{out}/\dot{Q}_{in}$, Cr denotes the geometric concentration ratio which is given as A_{in}/A_{out}.

A general schematic of this concept is shown in Fig. 1. This phenomenon, if designed for, may also provide an effective pathway for achieving high quality heat from low density sources.