The effect of solid particle recirculation on the efficiency of a cavity-type solar receiver

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To my late parents

Abstract

High temperature steam or gas is used as the working medium for operation in advanced power conversion units, such as gas turbines or combined cycle power plants. The use of Concentrated Solar Power (CSP) technologies for energy generation relies on the heating of fluids to high temperatures. Conventional tubular or porous absorber volumetric receivers usually suffer from a relatively low thermal efficiency, less than 70%, and from high thermal losses. The solid particle solar receiver, in which the incoming solar radiation is directly absorbed by the solid particles and inner walls of the cavity receiver, promises to achieve higher thermal efficiency due to the enhanced heat transfer to the working fluid and the reduction in thermal losses. The main challenge in designing a high temperature solar receiver is to maximize the solar energy absorption and its efficient transfer to the working fluid, e.g. air. The objective of this research project is to characterize the thermal behaviour of a proposed cavity-type solar receiver concept based on the application of recirculating solid particles to achieve high temperature outlet air. In this concept, solar energy is absorbed by recirculating solid metallic particles, which, at the same time, transfer the absorbed thermal energy to the surrounding air in a cavity-type receiver. The cavity-type solid particle receiver is a well-insulated enclosure, designed to capture the incident solar radiation effectively, which allows the incident radiation directly through an aperture.

In this study, a well-insulated cavity-type enclosure was designed and constructed. The designed solar receiver consisted of an externally insulated cylindrical cavity with a circular aperture at the top covered by a quartz glass, a recirculating fan installed at the bottom of the chamber and with an inlet and an outlet installed on the chamber wall. A series of experiments were conducted to characterize the fluid dynamics and thermal behaviour of the solar receiver. The results showed that the direction of the total air flow velocity was vertically

upward from the outer periphery of the fan and vertically downward through the centre of the receiver. The measured air flow velocity was normalized by against the particle terminal velocity. The results showed that the normalized flow velocity was 3 times higher than the particles terminal velocity and 45 times higher than the minimum fluidization velocity of particles for the same case. Hence the particle can be recirculated in the cavity. The particles' concentration at different regions of the solar receiver was also measured using a laser-based light-scattering technique. Black SiC of 70micron and 200micron SiC particle were used during this experiment. The effect of particle size and fan RPM on the particle concentration at different regions of the solar receiver was optimized using the test results of the particle concentration measurements.

At an RPM of 1250, the measured opacity of the particle cloud's concentration was 0.95 for 70micron and 0.80 for 200micron particle at a specific freeboard height of the cavity. It is an indication that particles' concentration and opacity at a different region is dependent on the particle size and air flow velocity. The results showed that the particle concentration and opacity increased exponentially with the RPM. The opacity is a measure of the irradiation penetration characteristics of the Xenon arc radiation beam into the cavity.

The calculation of Stokes number and turbulence intensity from these measurements helped in understanding the slip velocity and velocity fluctuation of air and particles in the cavity. The maximum Stokes number was 0.50 for 70micron particle whereas it was 4 for 200 micron particle measured at 500RPM. Hence, when comparing the Stokes numbers it becomes clear that the slip velocity was higher for 200micron particles which denote more interaction with air. Turbulence intensity measurement showed that an average turbulence intensity of 38% was observed near the cavity wall and 30% at the centre of the cavity. Therefore, a better forced convection heat transfer was expected between the particle, air and cavity wall surface in the proposed receiver.

Finally a thermal test was performed to assess the thermal performance of the designed solar receiver. Black SiC and brown alumina particles at two sizes (70 and 200microns) were used in these experiments. The results showed that the air temperature in the solar receiver, when radiated by a 5kW Xenon arc lamp, increased by up to 83K resulting in a thermal efficiency of 55% for the proposed solar receiver. Here the air flow rate was set to 0.0055kg/s at an inlet temperature of 295K with no particles or fan forced circulation. When particles were added to the receiver, a 0.034% volume fraction, and the installed fan induced forced recirculation in the receiver the air temperature at the outlet of the receiver increased by 123K and the thermal efficiency reached 89% for the same air flow rate as before. The results of normalized thermal and power generation efficiency indicate that the use of recirculating particles enhances the thermal efficiency by 49% and power generation efficiency by 90%, when compared with the air only cavity-type solar receiver. Moreover the proposed recirculating flow receiver exhibits a more uniform temperature distribution than a conventional cavity-type solar receiver due to better mixing of air and particles, along with more effective radiation and convection heat transfer between them.

A stand-alone feature of this solar receiver concept is that the air with particles is directly exposed to concentrated solar radiation monotonously through the recirculating flow inside the receiver and results in an efficient irradiation absorption and convective heat transfer to the air. The increase of thermal and power generation efficiency of more than 50% proved that the developed concept has the potential to enhance heat transfer from metallic particles to air through maximizing the heat carrying capacity by the particles and air from the receiver.

Declaration of originality

This work contains no material that has been accepted for the award of any other degree or diploma in any university or other tertiary institution and, to the best of my knowledge and belief, contains no material previously published or written by another person, except where due reference has been made in the text. I give consent to this copy of my thesis, when deposited in the University Library, being made available for loan and photocopying, subject to the provisions of the Copyright Act 1968. I also give permission for the digital version of my thesis to be made available on the web, via the University's digital research repository, the Library catalogue, the Australasian Digital Theses Program (ADTP) and also through web search engines, unless permission has been granted by the University to restrict access for a period of time.

Signed:

(Md. Rabiul Islam Sarker)

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Nomenclature

η	Efficiency
α	Absorption coefficient
$Q_{aperture}$	Power at aperture
ε	Emissivity
$A_{aperture}$	Aperture area
T	Temperature
Q	Solar power (Watt)
C	Concentration ratio
$r_{aperture}$	Aperture radius
r_{opt}	Optimum aperture radius
μ	Standard deviation
F_{peak}	Maximum flux density
I	Scattered light Intensity
l	Reference path length of medium
λ	Wavelength
x	Particle size
n	Index of refraction
θ	Scattered angle
c	Particle concentration
v_t	Terminal velocity
v_t^*	Dimensionless terminal velocity
μ_g	Viscosity of gas
ρ	Density
g	Acceleration
d_p	Particle diameter
D	Receiver diameter
τ	Response time
Nu	Nusselt number
Re	Reynolds number
Pr	Prandtl number

St	Stokes number
h	Heat transfer coefficient
A	Cavity surface area
I_G	Incident irradiation
k_f	Thermal conductivity of fluid
U_0	Free stream velocity of fluid
α_{sf}	The porosity of the porous medium
α_p	Particle volume fraction
V_{rms}	Root mean square air velocity
V	Total velocity of air
V_y	Axial component of air velocity
V_θ	Tangential velocity component
V_t	Volume of the whole receiver
M	Suspended particle concentration in air
N	Rotational speed of fan
CSP	Concentrated Solar Power
CST	Concentrated Solar Thermal
SPSR	Solid Particle Solar Receiver
HTM	Heat transfer medium
HTF	Heat transfer fluid
CPC	Compound Parabolic Collector
PLVCR	Pressurized Loaded Volumetric Ceramic Receiver
DIAPR	Directly Irradiated Annular Pressurize Receiver
NREL	National Renewable Energy Laboratory
SNL	Sandia National Laboratory
DLR	German Aerospace Centre
CIEMAT	Organisation of Plataforma Solar de Almeria
CSIRO	The Commonwealth Scientific and Industrial Research Organisation , Australia

Suffix

a	air
c	cavity
g	gas
m	mixture

p	particle
τ	thermal
o	overall
a,in	inlet air
a,o	outlet air