Mitigating Particle Deposition on the Glass Window of a Fluidised Bed Solar Receiver

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I would like to dedicate my thesis to my beloved parents
Sahera Begum & Abu Jafor Molla, and my wife Sadia Ahmed.

Summary

Concentrated solar energy can be utilised for many thermal processes that require high temperatures. A solar receiver is one such device that receives concentrated solar radiation. Different types of solar receivers such as fluidised beds, packed beds and solid particle solar receivers are used in different thermal applications. The focus of this study is to investigate the flow behaviour in a Fluidised Bed Solar Receiver (FBSR). One of the major limitations in the use of an FBSR under direct irradiation is particle deposition on the receiver glass window. This has two consequences: it reduces solar radiation transmission into the receiver and results in the failure of the glass window.

There have been a number of investigations on mitigating particle depositions onto the glass windows of solar receivers. However, the aerodynamics of solar receivers using particles is still not well understood. The aim of this project is to mitigate particle deposition on the glass window of an FBSR by developing a better understanding of the flow patterns under different operating conditions, which can assist in the development of an aerodynamic seal. Continuous operation of the FBSR can result in particle deposition on the glass window, which is directly related to the flow behaviour of the receiver. Therefore, it is essential that the flow pattern in an FBSR is investigated under single and two-phase flow conditions. Analysing the flow behaviours under various conditions, enables the mechanisms of particle deposition on a glass window to be understood.

Due to the complexity of the actual FBSR, a scaled FBSR was selected for this study. A well-defined and uniform in-flow condition was introduced below the aperture of the receiver. Computational Fluid Dynamics (CFD) were utilised to model the flow under gaseous and particle-laden conditions. The Renormalised Group Theory (*RNG*)-based k-ε turbulence model was used to capture the flow pattern at steady conditions. The Discrete Particle Model (DPM) was used to investigate the two-phase flow behaviour.

The single phase flow results were validated against experimental data collected inside a similar device operating under the same conditions. The turbulent flow velocity was measured using a Turbulent Flow Instrumentation (TFI) cobra probe and a Pitot tube. The three-dimensional velocity components were measured at different radial and axial positions in the receiver for different Reynolds numbers.

The FBSR was oriented vertically; consisting of a cylindrical cavity, above which were located a converging-diverging secondary cavity and a window glass. The bottom of the FBSR was considered as an inlet, with two tangential outlets placed closer to the secondary cavity. The results of this investigation revealed that mass flow into the secondary concentrator of the receiver was reduced significantly when the ratio between the outlets and inlet areas was 0.5, and the ratio between the aperture and receiver diameter was 0.41. Since the glass window was located at the top of the secondary concentrator, the lower circulation of the inlet flow into the secondary concentrator resulted in lower particle deposition on the glass window. When using window shielding jets, the number of jets were found to be critical for preventing particle deposition. At a constant mass flow rate, increasing the number of window shielding jets reduced the suction pressure from the core to the aperture. Consequently, the outward axial velocity towards the glass window was reduced.

It was found that the introduction of particles into the flow influenced the flow pattern inside the receiver and affected the flow velocity on the glass window. In a gas-particle flow analysis, gravity was found to be important for capturing the flow patterns in the receiver accurately. When assessing the effect of particles on flow patterns under the same operating conditions, it was found that the average outward axial velocity, the maximum velocity and the aperture area with outward axial velocity were higher than for a single-phase flow. Apart from the aperture section, the slip velocity was found to be negligible in the receiver cavity, as is evident from the comparison of the fluid and particles' velocity profiles.

The findings of this investigation could potentially provide insights into the industrial application of FBSR, where the particles damage the glass window of the receiver during long-term operation.

Declarations

I certify that this work contains no material which 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 citation has been made in the text. In addition, I certify that no part of this work will, in the future, be used in a submission for any other degree or diploma in any university or other tertiary institution without the prior approval of the University of Adelaide and where applicable.

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Nomenclature

Greek letters

α	volume fraction
β	constant for RNG *k*-*ε* turbulence model
δw	streamline displacement due to the presence of Pitot tube
Δ	incremental change
ϵ	displacement correction factor
ε	dissipation rate
η_0	constant for RNG k-ε turbulence model
μ	dynamic viscosity
μ_t	turbulent viscosity
ρ_g	gas density
ρ_p	particle density
$\bar{\bar{\sigma}}$	Reynolds stress tensor
τ_f	fluid time scale
τ_p	particle aerodynamic response time

Romans

a_r	radial acceleration
A_{in}	receiver inlet area
A_{out}	receiver outlet area
a_t	tangential acceleration
C_c	Cunningham correction factor
C_D	coefficient of drag
D	diameter of the pipe
d_a	diameter of the aperture
d_p	particle diameter
$\bar{d}_p$	mean particle diameter
d_r	diameter of the receiver
e	exponential e

F_B	buoyancy force
F_d	drag force
F_i^{Brown}	Brownian force
F_G	gravitational force
F_r	radial force
$F_{Saff\ lift}$	Saffman lift force
F_t	tangential force
g	gravitational acceleration
G_i^{mp}	Gaussian number
k	turbulent kinetic energy
k_b	Stefan-Boltzmann constant
k_{gs}	momentum transfer coefficient between gas and solid phases
l	length of the receiver
L	characteristics length of the flow
m	mass of the particle
$\dot{m}_{cpc}$	mass flow in the CPC
$\dot{m}_{in}$	inlet mass flow to the receiver
n	spread parameter
P_s	static pressure
P_t	total pressure
R	additional strain rate
Re	Reynolds number
Re_p	particle Reynolds number
S_k	Stokes number
S_0	spectral intensity
T	temperature
U	characteristic velocity of the flow
u_g	gas velocity
u_{mf}	minimum fluidisation velocity
u_p	particle velocity
v_x	radial velocity
v_y	axial velocity
v_z	tangential velocity

x	radial distance from the centre of the receiver
x_i, x_y, x_z	Cartesian coordinate system
Y_d	cumulative fraction

Superscripts

$\rightarrow$	vector quantity
$(\bar{\ })$	averaged or mean
$\cdot$	derivative with respect to time

Subscripts

g	gas phase
gp	gas particle
p	particle phase
t	tangential or total

Acronyms

BFB	Bubbling Fluidised Bed
BP	British Petroleum
CFB	Circulating Fluidised Bed
CFD	Computational Fluid Dynamics
CPC	Compound Parabolic Concentrator
CSP	Concentrated Solar Power
DAQ	Data Acquisition
DNS	Direct Numerical Simulation
DPM	Discrete Particle Model
FBSR	Fluidised Bed Solar Receiver
GNF	Granular Flow Model
HTF	Heat Transfer Fluid
ICFB	Internally Circulating Fluidised Bed
IEA	International Energy Agency
IISR	Indirectly Irradiated Solar Receiver

LFR	Linear Fresnel Reflector
MTOE	Million Tonnes of Oil Equivalent
PDE	Partial Differential Equations
RANS	Reynolds Averaged Navier-Stokes equations
RNG	Renormalised Group Theory
SPSR	Solid Particle Solar Receiver
TFI	Turbulent Flow Instrumentation
WJ	Without Jet