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Particle motion and heat transfer in an upward-flowing dense particle suspension: Application in solar receivers

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HIGHLIGHTS

- Particle trajectories are determined within a dense upward-moving fluidised bed.
- Particle-to-wall heat transfer coefficients have been measured experimentally.
- Heat transfer coefficients are in the range 180–320 W/m^2 K.
- Particle residence times at the wall were found to be distributed according to a log-normal distribution.
- Experimentally-obtained heat transfer coefficients were found to be in good agreement with prior predictions.

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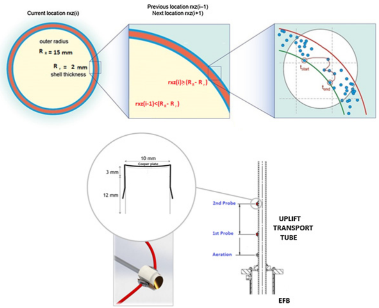
GRAPHICAL ABSTRACT



ABSTRACT

Concentrated solar power (CSP) plants conventionally make use of molten salt as the heat transfer medium, which transfers heat between the solar receiver and a steam turbine power circuit. A new approach uses particles of a heat-resistant particulate medium in the form of many dense upward-moving fluidised beds contained within an array of vertical tubes within the solar receiver. In most dense gas–solid fluidisation systems, particle circulation is induced by bubble motion and is the primary cause of particle convective heat transfer, which is the major contributing mechanism to overall heat transfer. The current work describes experiments designed to investigate the relationship between this solids convection and the heat transfer coefficient between the bed and the tube wall, which is shown to depend on the local particle concentration and their rate of renewal at the wall. Experiments were performed using 65 μm silicon carbide particles in a tube of diameter 30 mm, replicating the conditions used in the real application. Solids motion and time-averaged solids concentration were measured using Positron Emission Particle Tracking (PEPT) and local heat transfer coefficients measured using small probes which employ electrical resistance heating and thermocouple temperature measurement. Results show that, as for other types of bubbling beds, the heat transfer coefficient first increases as the gas flow rate increases (because the rate of particle renewal at the wall increases), before passing through a maximum and decreasing again as the reducing local solids concentration at the wall becomes the dominant effect. Measured heat transfer coefficients are compared with theoretical approaches by Mickley and Fairbanks packet model and Thring correlation. The close correspondence between heat transfer coefficient and solids movement is here demonstrated by PEPT for the first time in a dense upward-moving fluidised bed.

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Nomenclature

PEPT	Positron Emission Particle Tracking
DPS	Dense particle suspension
CSP	Concentrated solar power
HTF	Heat transfer fluid
DiFB	Dispenser Fluidised Bed
k_e^o	effective radial thermal conductivity, W/m·K
C_p	solid heat capacity, J/kg·K
U_{mf}	minimum fluidising velocity, m/s
U_{mb}	minimum bubbling velocity, m/s
ε_{mf}	minimum fluidisation velocity associated void fraction, m/s
ρ_p	particle density, kg/m^3
U_{ae}	aeration velocity, m/s
U_o	optimum fluidising velocity, m/s
h	heat-transfer coefficient, W/m^2·K
d_p	particle size, 10^{-6} m
q	power supplied to the heater, W
S_{pr}	surface area of the probe, m^2
R_{pr}	resistance of the probe, Ω
I	electrical current, A
T_b	dense phase suspension temperature, °C
T_s	surface temperature of the heater, °C
R_R	uplift transport tube radius, 10^{-3} m
R_r	shell thickness, 10^{-3} m
$r_{xz}(i)$	current tracer location
$r_{xz}(i-1)$	previous tracer location
$r_{xz}(i+1)$	next tracer location
τ	wall contact time, s
ϕ	wall region, 10^{-3} m
t_r	residence time of the emulsion packet at the heat transfer surface, s

1. Introduction

Concentrated Solar Power (CSP) plants have received recent attention as an alternative to photovoltaics. In CSP, solar radiation is focused using diverse mirror or lens configurations onto a **solar receiver** where it raises the temperature of a **heat transfer fluid** (HTF), which is in turn used to generate steam that powers a turbine-generator to produce electricity (Flamant et al., 2013).

The classical **heat transfer and thermal storage fluids** are synthetic **oils and molten salts**. Oils have limitations since they are stable only up to 400 °C and present significant safety issues due to their flammability. Although the use of **molten salts** improves performance it is far from optimal since they are restricted to operating temperatures below 550 °C and they suffer from corrosion problems at high temperatures which significantly increases maintenance costs. In addition molten-salt systems are affected by freezing problems if the salt temperature drops too low, and therefore require high parasitic power consumption to prevent this.

Liquid metals present potential alternative heat transfer media, since some are relatively stable at high temperatures and typically offer good thermal properties. Their use is limited by inherent **safety risks**, since they will combust in contact with air and their large hydration energy results in a vigorous exothermic reaction with water. Moreover, liquid metals interact with structural materials at high temperature (Pacio and Wetzel, 2013).

The purpose of this research is to evaluate a further alternative: the use of **small particles suspended in gas in the form** of a **dense upward-flowing fluidised bed**. The stirring effect induced by the gas bubbles within the bed results in relatively uniform axial and radial temperature distribution in the dense phase and good heat transfer from the walls.

The term **dense suspension** here means an overall phase concentration of particles comparable to that encountered in conventional fluidised beds (≥25%). **Dense particle suspensions** offer the possibility of operation at elevated temperatures which is fundamental for achieving higher **heat transfer rates** which are essential in order to achieve economically attractive plant designs. Operation is favoured if the solid particles selected have a large **thermal conductivity** and high **heat capacity,** which would enable the additional benefit of **thermal storage**. Similarly, operational aspects such as safety and corrosion risk are minimised and the power consumption for pumping is small compared with the alternatives.

Fluidisation offers excellent **heat transfer** between the particles and the wall, because the **particle motion** within the bed

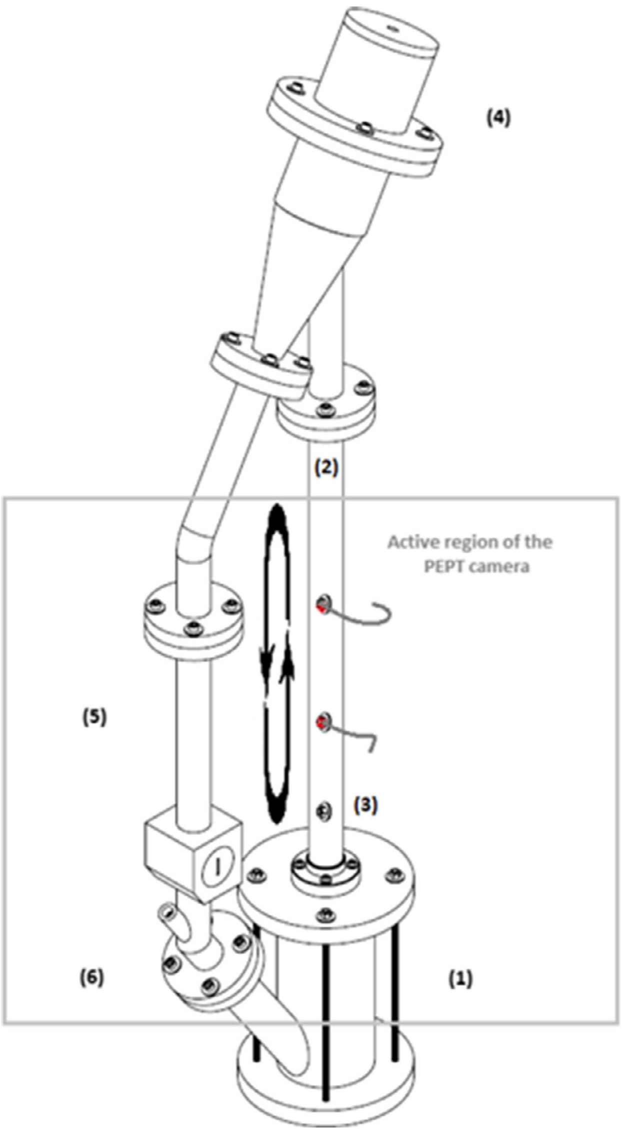

Fig. 1. Schematic diagram of the experimental set-up.