next-CSP

High Temperature concentrated solar thermal power plant with particle receiver and direct thermal storage

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Deliverable D1.2

WP1 – Assessment of particle suspensions as heat transfer fluid and storage material

Deliverable D1.2. Report on measurement of particle flow characteristics in long tube

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Symbols

d_B	frontal diameter of bubble, m
$d_{B,max}$	maximum stable bubble size in group A powders
C_{ps}	Specific heat of the particles, J kg^{-1} K^{-1}
D	column diameter, m
d_s	frontal diameter of slug, m
d_{sv}	surface/volume mean diameter of powders, m or µm
f_s	experimental values of slug frequencies, s^{-1}
f_L	value of f_s for deep beds, s^{-1}
G_s	solid upward flux, kg $m^{-2}s^{-1}$
g	gravitational constant, 9.81 m s^{-2}
H	fluidized bed height, m
H_{mf}	bed height at U_{mf}, m
H_{mb}	bed height at U_{mb}, m
H_{os}	Height at onset of slugging, m
h_s	slug height, m
k	coefficient for the slug wake, Eq. (10-a)
N_{or}	Orifice density per unit area of gas distributor, m^{-2}
ΔP	pressure drop, Pa
U	superficial gas velocity, m s^{-1}
U_{mf}	superficial velocity of gas at minimum fluidization, m s^{-1}
U_{mb}	superficial velocity of gas at minimum bubbling, m s^{-1}
U_s	slug velocity, m s^{-1}
W_s	height of fluidized bed between successive slugs, m

Greek symbols

ε_B	fraction of total bed volume occupied by bubbles
ε_{mf}, ε_{mb}	voidage of the bed at U_{mf} and U_{mb}, respectively
ϕ	concentrated solar flux at the receiver, W m^{-2}
ρ_B	bulk density of the fluidized bed, kg m^{-3}
ρ_g, ρ_s	density of the fluidization gas, and absolute particle density, respectively, kg m^{-3}
σ	standard deviation of particle size distribution, m or µm

Abbreviations

I.D.	Internal Diameter, m
UBFB	Upflow Bubbling Fluidized Bed

Introduction and Objectives of the experimental Task 1.2

The solar receiver is the heat exchanger within the solar loop that transfers the concentrated solar radiant heat, emanating from the heliostat field, to the upflow fluidised powder heat transfer/heat storage medium. The solar receiver must internally accommodate the fluidised powder flow process and externally accept the severe radiant heat flux loading. The receiver is part of a complete heat capture, storage and re-use concept where the air-Brayton cycle power generation is the heat-to-electricity part of the project.

The experimental verification needed to examine various aspects:

(i) how is a stable operation of the Upflow Bubling Fluidized Bed (UBFB) receiver affected by the different operation conditions ?

(ii) how do the operation conditions affect the bubble flow in the UBFB, especially in tubes of an increasing length (up to 4 m) ?

(iii) how do the operation conditions affect the particle suspension flow regime in the UBFB ?

(iv) what conclusions can be drawn towards the design and operation of a tall UBFB ?

The report below will address these different issues.

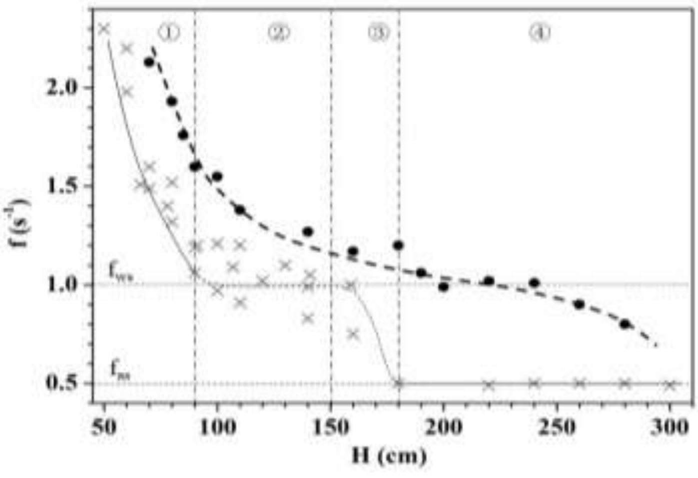
General conclusions of experimental investigations within Task 1.2

The experimental verification needed to examine (i) how is a stable operation of the Upflow Bubling Fluidized Bed (UBFB) receiver affected by the different operation conditions ?; (ii) how do the operation conditions affect the bubble flow in the UBFB, especially in tubes of an increasing length (up to 4m) ?; (iii) how do the operation conditions affect the particle suspension flow regime in the UBFB ?; and (iv) what conclusions can be drawn towards the design and operation of a tall UBFB ?

Section 2 studied the upward flow of particles in an Upflow Bubbling Fluidized Bed (UBFB) for group A powders. For such, the upward solid flux in the tube is proportional with both the applied superficial gas flow rate and the pressure drop exerted at the base of the conveyor tube, and inversely proportional with the tube length. Results are modelled from pressure drop considerations and energy loss equations. The model expression $G_s = \frac{\Delta P}{(U_g - KU_t) + \frac{K^2 gL}{(U_g - KU_t)}}$ can be used for design purposes, with K, the correction factor for hindered settling of the particles, equal to 0.1 for the group A powders tested. The energy efficiency of the system increases with increasing U and G_s, and decreasing particle size and/or density. For SiC, cristobalite and olivine, it is demonstrated that the air velocity required to transport up to 100 kg/m²s of powder is below 0.15 m/s at an inlet pressure slightly exceeding the hydrostatic bed pressure. The model equation was tentatively applied to predict the effects of particle size and tube length. Coarser particles and/or loger tube lenghts impose the use of higher superficial air velocities and higher external pressures, while the transport efficiency decreases considerably. The UBFB concept is ideally suited to deal with A-type powders, with limited particle attrition and tube erosion due to the low gas and solids velocities applied.

Section 3 investigated the gas hydrodynamic regimes in the UBFB, where a gradual transition from a freely bubbling to a slugging regime was experimentally demonstrated. The slugging characteristics were determined from visual observations, pressure drop fluctuations, and high speed camera images.

For the group A powders, it is found that the bed height has no marked effect on the excess gas velocities required to cause a powder to slug. The Stewart and Davidson criterion can be used to determine the excess gas velocity at incipient slugging. The average particle size does not affect slugging. Whereas wall slugging can occur from a bed height of about 0.5 to 0.8 m, at ambient temperature, axi-symmetric slugging occurs higher up the bed, from about 1.5 m upwards. Operation at higher temperatures reduces the delays the slugging phenomenon, occurring at heights in excess of respectively 2 m (wall slugging) and 3 m (axi-symmetric slugs), as illustrated below with reespect to the slug frequencies at 20 °C (×) and 475 °C (•).



The analysis of findings proposes to divide a deep fluidized bed of group A powders, operating at moderate to high excess gas velocities, in four distinct zones, hence stressing the need to combine freely bubbling and slugging modes to the corresponding regions in the bed. This will be further elaborated within Task 1.3.

Section 4 studied the solids flow patters within the UBFB. The particle motion and gross circulation patterns within teh UBFB can be considerd as a combined mode of a plug flow core (as imposed by teh external solid circulation flux), and an important backmixing (along the wall). The fractional tubularity index, τ_p=0.5, corresponds to the hydrodynamics of a 50% reflux along the wall. A cascade of perfectly mixed reactors (CSTR), with a number of reactors, N= 3 to 4, implies that the UBFB upward flow should be divided in 3 to 4 sections, virtually corresponding to the sections defined previously, i.e. a zone of bubble formation, a zone of free bubble growth, a zone of transformation to wall slugging, and ultimately (not always the case) a zone of axi-symmetric slugging. Both sperficial air velocity and imposed solid circulation flux define the combination to be accounted for. This is an important finding towards heat transfer modeling (Task 1.4) and briefly debated hereafter. The bubbling/slugging and particle gulf streaming phenomena moreover affect the mixing within the bed and the temperature increase of the upflowing particles in a 0.05 m I.D. receiver, using group A powders. To tentatively assess this effect, a simulation was performed for a 1 m high receiver, subjected to a concentrated solar flux from the heliostats according to ϕ = 475 kJ/m^{2}s, operated with a G_s solid concentration flux of 50 kg/m^{2}s at a fluidizing velocity of 0.05 m/s (20 ℃). The powder is fed from the storage hopper at 250 °C. Without a solids reflux near the wall (J), only G_s is important for the amount of heat collected, and a particle plug flow can be assumed. If a reflux is accounted for, an iterative procedure is required. This was illustrated by calculating bubble/slug characteristics and particle reflux ratio in every section. The overall balance is fixed by the solar heat input and must be met. The gulfstreaning particles return hot solids to the lower sections in the bed, thus contributing significantly to obtaining a higher receiver exit temperature. This temperature profile is based upon theoretical calculations, but will be experimentally confirmed in Task 1.4.