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ABSTRACT

Bubbles bursting at the surface of a BFB project particles into the freeboard. Coarser particles fall back, the solids loading declines with height in the freeboard, and fines are ultimately carried over. The height of declining solids loading is the TDH, measured in this research by Positron Emission Particle Tracking, and modeled from a balance of forces on ejected particles. Model predictions and PEPT-data are in good agreement. Empirical equations overestimate the TDH.

INTRODUCTION

Bubbles bursting at the surface of the BFB bed project particles into the freeboard. Depending on their terminal velocities (U_t) and the gas velocity (U), particles are carried up the freeboard to various heights. The solids loading (kg solids/m^3 gas) will decline with height. The region within which the solids loading falls is called TDH. Coarse particles, even with $U_t > U$, are flung upwards by the bursting bubbles and then fall back. Above the height they reach, only fines, i.e. particles with $U_t < U$, are found. The concentration of fines further decreases with height and eventually reaches a constant value. The projection height of the coarse particles is called the splash height or TDH(C). The height above which the fines concentration remains nearly constant is called TDH(F). The definition of a coarse or fine particle will depend upon its U_t and upon U. U_t can be calculated according to Geldart [1].

The TDH and the solids loading in the freeboard influence the entrainment rate and the rate of internal circulation of solids (Geldart et al. [2]), the heat transfer to surfaces in splash zone and freeboard (George and Grace, [3]), and the progress of reactions in the freeboard (Baeyens and Van Puyvelde [4]). The TDH has been studied by measuring the entrainment rate in batch or semi-continuous experiments at various velocities for different positions of the gas off take (e.g. Chan and Knowlton [5], Schuurmans [6]); by visually observing the height above which no downward moving coarse particles are observed (Sciazko et al. [7]); by particle sampling (Fournol et al. [8]); or from the curve of the pressure drop profile versus height in the freeboard (Geldart et al.[9], Smolders and Baeyens [10]).

The present paper reports results of real time particle trajectories as measured by Positron Emission Particle Tracking (PEPT).

EMPIRICAL TDH EQUATIONS

Several empirical equations to predict TDH have been presented in literature and are cited in Table 1 with their dominant parameters.

Authors	Dominant parameters	Comments
Soroko et al. [11]	Settled bed height (H_s) Particle Re and Ar numbers	Only valid for TDH(C) $H_s < 0.5$ m, d_p 0.7-2.5 mm
Amitin et al. [12]	Superficial gas velocity (U)	TDH(F)
Fournol et al. [8]	Superficial gas velocity (U)	TDH(F), for FCC powder
Horio et al. [13]	Diameter of bubble at bed surface (d_{Bo})	TDH(F)
Wen et al. [14]	From entrainment rates	TDH(F), for D < 0.6 m
Pemberton et al. [15]	Bubble velocity (U_B) and d_{Bo}; U, ρ_g and μ; d_p and ρ_p	TDH(F)
Hamdullahpur et al. [16]	Bubble diameter (d_{Bo})	TDH(F)
Zenz [17]	Graph as function of ($U - U_{mb}$) and d_{Bo}	TDH
Baron et al. [18]	Bubble velocity (U_B)	TDH(F), U_B calculated from Werther [19]
Smolders and Baeyens [10]	Bubble diameter (d_{Bo}) and excess gas velocity ($U - U_{mf}$)	TDH(F)

Table 1: Empirical correlations to predict the TDH

The TDH can thus be predicted when calculating d_{Bo} using e.g. Darton's equation [20], and U_B according to e.g. Werther [19]. For a 90 µm sand in a 0.5m deep bed of 1m I.D at U = 0.4 m/s, predictions vary from 0.55 m [10], to 0.7 m [17, 18], to approx. 1.8 m [13, 14, 15, 16], and 2.2 m [12]. The predicted TDH-values differ significantly. Similar differences are predicted for different bed materials and operating conditions. There is an obvious need to better predict TDH-values.

EXPERIMENTAL SET-UP, PROCEDURE AND ILLUSTRATION OF RESULTS

PEPT is a technique to track a fast moving particle in opaque vessels. It has been extensively applied for obtaining dynamic information of powder flow in a very wide variety of processes. ^{18}F is prepared and is incorporated into the tracer by an anion-substitution surface adsorption procedure (Fan et al. [21, 22]). The tracer is located by triangulation of a number of detected annihilation events, and this ~ every 4 ms, thus providing trajectory and velocity information. The bulk bed material was rounded sand (120 µm, 2260 kg/m³) and rounded sand particles of 150, 250, 330, 390, 460 and 550 µm were labelled, as well as alumina (135 µm) and coal (390 µm), each having a density of 1600 kg/m³. A fluidized bed of 0.16 m I.D. with porous plate distributor (high ΔP) was used, for static bed heights of 0.25, 0.35 and 0.45 m.

The superficial gas velocity was varied between 0.029 and 0.352 m/s, mostly in the freely bubbling regime.

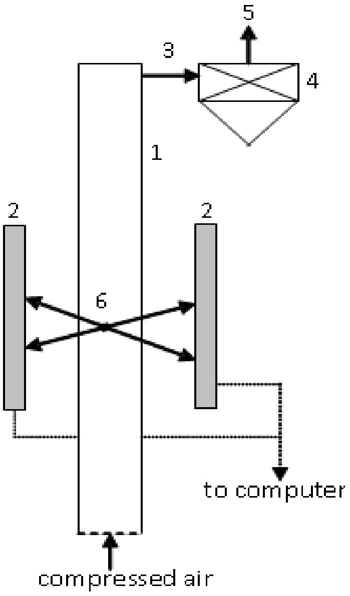

Fig. 1. Experimental set-up with (1) BFB; (2) γ-ray cameras; (3) vent, to (4) filter and (5) atmosphere; (6) tracer.

The detectors, each 0.47 m wide and 0.59 m high, were positioned between 5 to 65 cm above the static bed height, thus allowing for bed expansion. The principle of the experimental layout is shown in Fig. 1. The tracer particles were introduced with the bed material. The exhaust of the rig was connected to a bag filter. The obtained data, an extensive list of consecutive particle locations in three dimensions, determined the instantaneous velocity as well as the location of the particle in the freeboard. Since the PEPT-experiments lasted for several hours at each combined operating condition, tracer motions were seen in large numbers, each time with an upward and a downward movement. Occasionally, tracer was seen to be re-entrained during its movement by a second erupting bubble.

Operating air velocity and particle size play important roles. The height of projection increases with increasing superficial air flow rate, with decreasing particle size. The TDH-values within given operating conditions show a wide range of values due to the distribution of bubble sizes and velocities and the possible coalescence of 2 bubbles prior to erupting at the surface. Data were hence analysed statistically, and given below with a value obtained at 50 % and 99 % of the cumulative TDH curve respectively. Some of the data are illustrated in Tables 1a and 1b.

d_p 135 µm		d_p 390 µm	
TDH_{50}	TDH_{99}	TDH_{50}	TDH_{99}
0.125	0.241	0.037	0.071
0.166	0.304	0.084	0.154
0.255	0.477	0.254	0.416
0.375	0.609	0.306	0.576
0.394	0.646	0.34	OR
0.515	OR	0.382	OR
TDH_o 0.035		0.024	

**TDH_o: minimum TDH measured at lowest velocity*
**OR: Outside range of camera*

Table 1a: TDH (in meters) of alumina and coal

U, (m/s)	d_p 150µm		d_p of 320µm		d_p of 460µm		d_p of 550µm	
	TDH_{50}	TDH_{99}	TDH_{50}	TDH_{99}	TDH_{50}	TDH_{99}	TDH_{50}	TDH_{99}
0.023	0.091	0.156	0.127	0.186	0.131	0.167	0.146	0.223
0.069	0.152	0.278	0.145	0.24	0.139	0.291	0.194	0.275
0.105	0.185	0.369	0.158	0.312	0.145	0.312	0.162	0.308
0.182	0.364	0.582	0.206	0.44	0.185	0.462	0.185	0.375
0.242	0.382	0.642	0.235	0.515	0.226	0.526	0.224	0.452
0.351	0.455	OR	0.307	0.612	0.295	0.611	0.266	OR
TDH_o	0.027		0.046		0.034		0.041	

**TDH_o: minimum TDH measured at lowest velocity*
**OR: Outside range of camera*

Table 1b: TDH (in metres) of sand particles

MODELING APPROACH TO PREDICT TDH

The fundamental model equations were adapted from Do et al. [23] and transformed to make a distinction between fine and coarse particles. Consider an individual particle of size d_p and density ρ_p, projected into the freeboard by a bursting bubble rising with velocity U_B. The superficial gas velocity in the freeboard is U. The instantaneous particle velocity is v. In a dilute particle flow, without collisions and associated momentum transfer, a balance of forces yields:

$$\rho_p \frac{\pi d_p^3}{6} \frac{dv}{dt} = -\left(\rho_p - \rho_g\right) g \frac{\pi d_p^3}{6} \pm C_D \frac{\pi d_p^2}{4} \frac{1}{2} \rho_g \left(U - v\right)^2 \qquad (1)$$

The ’-’ -sign applies to the region where v > U; the ‘+’ -sign to the zone where U > v. Introducing the slip velocity, $v_{r,}$, and group-constants a and b:

$v_r = U – v$; $a = (\rho_p – \rho_g)g/ \rho_p$ and $b = 3 \rho_g C_D /(4 \rho_p d_p)$

$$\frac{dv_r}{dt} = a - b\, v_r \left|v_r\right| \qquad (2)$$

Where, $\frac{dv_r}{dt} = a + b\, v_r^2 \quad v_r < 0$ (3a) or, $\frac{dv_r}{dt} = a - b\, v_r^2 \quad v_r > 0$ (3b)

The equation was solved for an initial boundary condition corresponds with $v_{r(t=0)}=U-U_B$. Therefore, the height that a particle reaches can be calculated from:

$$\frac{dh}{dt} = v = U - v_r \qquad (4)$$

C_D, the drag coefficient is itself a function of the instantaneous velocity and can be calculated over the whole velocity range by equation (5a) below (Do et al. [23]):

$$C_D = \frac{24}{Re}\left(1 + 0.15\, Re^{0.687}\right) + \frac{0.42}{1 + 42500\, Re^{-1.16}} \qquad (5a)$$

With $Re = \frac{d_p \left(U - v\right) \rho_p}{\mu}$ (5b)

Smolders et al. [10] previously demonstrated that only particles with $U_t \leq U_B$ will be ejected, thus fixing the maximum particle size, $d_{p,max}$ ejected by the bubbles:

$$\text{For } U_t = U_B \quad \text{and} \quad U_t = \sqrt{\frac{4}{3}\frac{(\rho_p - \rho_g)\, d_{p,max}\, g}{\rho_g\, C_D}} \tag{6}$$

For reasons of simplicity it is assumed that the freeboard is not tapered i.e. that a single value of the superficial gas velocity U can be used throughout the freeboard height and is equal to the superficial velocity in the fluidised bed itself ($\Omega_B = \Omega_{FB}$).

The bulk bed sand being a Geldart-B powder, the bubble diameter d_B is calculated from Darton et al. [20], whereas the bubble velocity is calculated by the procedure of Werther [19].The operation was mostly freely bubbling (according to the Yagi and Muchi criterion [24]), except at high air velocities in the 45 cm deep bed.

The solution of differential equations (3a) and (3b) with conditions of t=0 at $v_r = v_{r0}$ and $t=t_i$ at $v_r = v_{ri}$ is as follows:

$$v_r < 0 \qquad t_i = \frac{1}{\sqrt{ab}}\left[\mathrm{Arctg}\left(\sqrt{\frac{b}{a}}\, v_{ri}\right) - \mathrm{Arctg}\left(\sqrt{\frac{b}{a}}\, v_{r0}\right)\right] \tag{7a}$$

$$v_r > 0 \qquad t_i = \frac{-1}{2\sqrt{ab}} \ln\left[\frac{\left(\sqrt{\frac{a}{b}} - v_{ri}\right)\left(\sqrt{\frac{a}{b}} + v_{r0}\right)}{\left(\sqrt{\frac{a}{b}} + v_{ri}\right)\left(\sqrt{\frac{a}{b}} - v_{r0}\right)}\right] \tag{7b}$$

Since the drag coefficient C_D is a function of v_r, a stepwise calculation needs to be used whereby Δv is calculated in steps of e.g. 0.01 m/s. The corresponding C_D and each corresponding value of t_i are calculated. The path length is calculated by:

$$h_i = v_i t_i = (U - v_{ri})\, t_i \tag{8}$$

When the particle reaches its final velocity, all h_i are summed to calculate the total path covered by the particles. According to the difference between their terminal velocity and respective bubble or superficial gas velocity, we can classify the particles in three groups:

$U_t > U_B$: these particles are not ejected and need not be considered in TDH.

As shown in Figure 2(a), when $U < U_t < U_B$, particles leave the bed at the bubble velocity U_B. At first the particle velocity exceeds the gas velocity ($v_r<0$), and the particle is decelerated by gravity and drag. When its velocity becomes smaller than the gas velocity ($v_r>0$), it is still decelerated by gravity, whilst the gas now tries to accelerate it. Finally, the particle velocity becomes zero ($v_r=U$) and its direction of motion is reversed: the particle falls back into the bed. It is evident that in the deceleration zone, both regimes of v_r will occur since initially v will exceed U, but after deceleration, U will exceed v. Hence both formulae (7a) and (7b) will be used to calculate the total value of time t.

Fig 2(b) applies to the case when $U>U_t$. These particles are also projected at the bubble velocity U_B. The particle velocity exceeds the gas velocity ($v_r<0$) and the particle is decelerated by gravity and drag. When its velocity becomes smaller than the gas velocity ($v_r>0$), it is still decelerated by gravity, whilst the gas tries to accelerate it. When v_r equals the terminal velocity U_t of the particle, the system is in equilibrium and the particle will be carried through the freeboard at this constant velocity ($U-U_t$).

According to the definition of TDH(C), one can reasonably assume that this TDH(C) corresponds with the maximum height reached by those coarse particles with $U_t=U_b$. Similarly, the height at which a particle with $U_t=U$ reaches its final velocity ($v_r=U_t$ or $v=0$) is called the TDH(F).

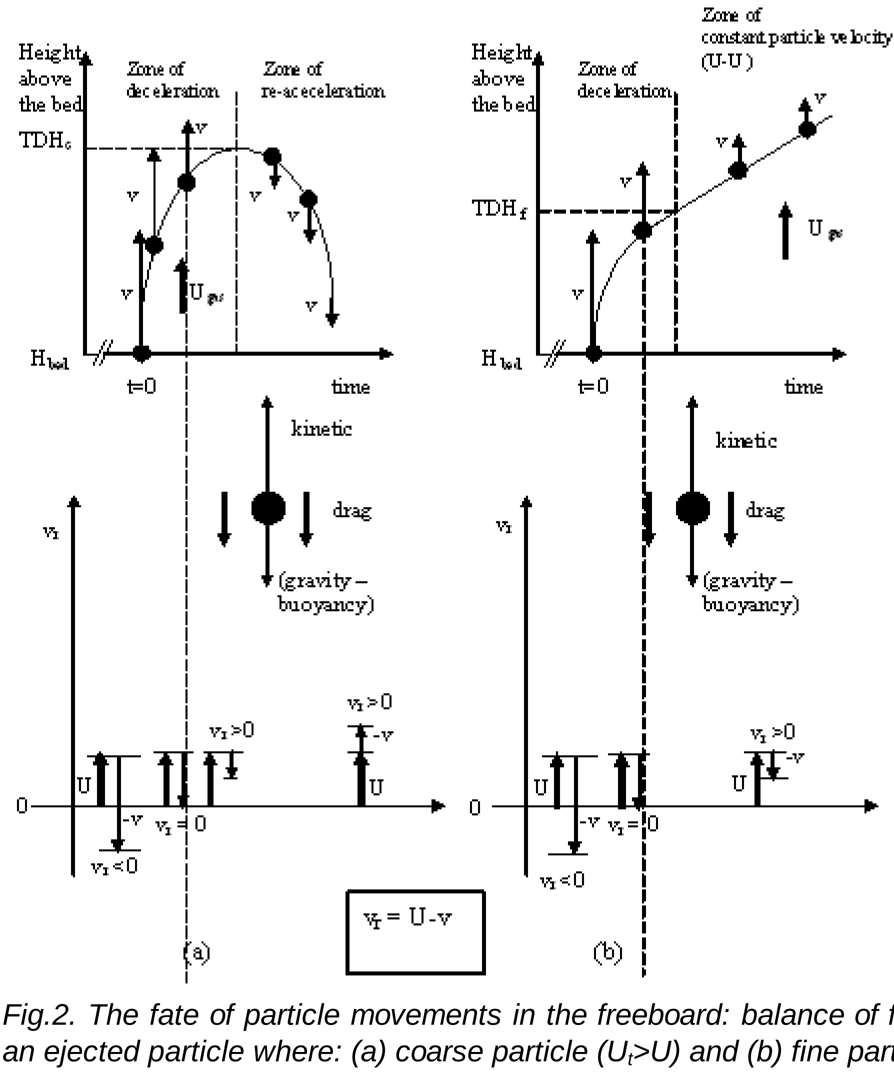

Fig.2. The fate of particle movements in the freeboard: balance of forces acting on an ejected particle where: (a) coarse particle ($U_t>U$) and (b) fine particle ($U_t \leq U$)

DISCUSSION

The TDH_{50}-values of Tables 1 are in fair agreement with empirical predictions of Smolders and Baeyens [10] and Zenz [17]. Other empirical equations considerably overestimate TDH.

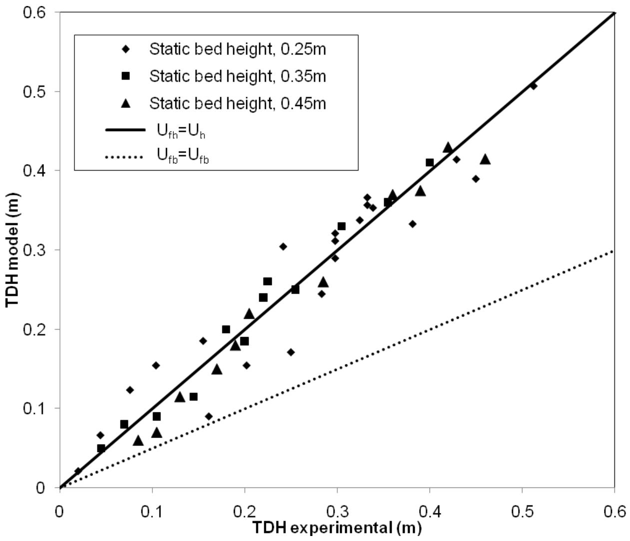

Fig.3. Comparing TDH model with TDH experimental

Figure 3 summarises all experimental TDH_{50}-data in comparison with model predictions. A good agreement is obtained, provided the air velocity throughout the particle jetting zone is taken as U_B.

Since TDH_{99} is about twice TDH_{50}, probably due to the effect of coalescing bubbles near the bed surface, the TDH_{99}-value is only predicted by the model when using a bubble eruption diameter (and associated velocity) corresponding to about 1.5 d_{Bo}

CONCLUSIONS

PEPT gives a clear picture of the TDH for coarse and fine particles. Model predictions improve understanding the fundamentals of particle projections and the TDH, with a different behavior of coarse and light particles. The use of the model predictions for industrial applications will be dealt with during the presentation.

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NOTATIONS

d_{Bo}	Diameter of bubbles at the bed surface [m]
h, H_s	Height and settled bed height, respectively [m]
Re	Reynolds number, as defined by Eqn. 5(b) [-]
TDH(C)	Transport disengagement height for coarse particles, [m]
TDH(F)	Transport disengagement height for fine particles, [m]
t	Time, [s]
U_{mf}, U_t	Minimum fluidization velocity and terminal velocity of particles, respectively [m s^{-1}]

U	Superficial air velocity, [m s^{-1}]
U_B	Velocity of erupting bubbles, [m s^{-1}]
U_{fb}	Velocity of air in the freeboard, [m s^{-1}]
v_r	Slip velocity, [m s^{-1}]
v	Velocity of particles, [m s^{-1}]
ρ_g, ρ_p	Density of air and of particles, respectively [kg m^{-3}]
d_p	Diameter of particles, [m]

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