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THE SOLIDS FLOW IN THE RISER OF A CFB VIEWED BY POSITRON EMISSION PARTICLE TRACKING (PEPT)

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ABSTRACT

The PEPT study of the riser of a CFB determines (i) the acceleration length and time, (ii) the upwards and downwards velocities; (ii) the population densities; (iii) the flow pattern at the riser bottom; and (iv) the existence of different flow regimes for associated operating conditions of gas flow rate (U) and solids circulation flux (G).

INTRODUCTION

The fundamental study of a CFB riser started with Yerushalmi and Cankurt (1): the fast fluidisation regime exists at gas velocities (U) in excess of the transport velocity (U_{TR}), with a decreasing solids concentration from the bottom to the top of the riser and high particle slip velocities as a result of cluster formation. The term fast fluidisation has been used for completely different regimes, hence an unambiguous definition of the fluidisation modes in the riser is needed. PEPT tracking elucidates the occurring regimes via the real-time study of particle motion.
Most investigators have accepted that U_{TR} identifies the start of the fast fluidisation regime, although U_{TR} is not always defined in the same way (Smolders et al., 3). PEPT work by Van de Velden et al. (4) pointed out that U_{TR} can best be predicted using the equation of Bi and Grace (5).

Rhodes and Geldart (2) explained the solids hold-up profiles in a low (U, G)-range by an entrainment model, with accumulation of solids at the bottom of the riser (a bubbling/turbulent fluidised bed, BTFB). There remains controversy about the distinction of regimes within the riser flow, i.e. core-annulus with or without BTFB, dilute pneumatic conveying and fully developed dense suspension upflow.

In-line with Rhodes and Geldart, some researchers noticed that the axial solids hold-up profile of the riser has an inflection point separating a dense phase at the bottom from a dilute phase at the top. This is commonly referred to as the S-profile and reported by Li et al. (6), Kwauk et al. (7), Rhodes and Geldart (2), Kato et al. (9), Mori et al. (9), Van de Velden et al. (10). For some time, this was thought to be universal and necessary for the CFB regime. However, recent literature has shown an exponential profile of solids hold-up with no dense bed, but with an acceleration zone at the bottom of the riser. These exponential profiles are characteristic of other riser transport modes i.e. dilute pneumatic conveying or dense suspension upflow, as reported by Bai et al.(11, 12), Hartge et al. (13), Li et al. (6), Berutti et al. (14), and Van de Velden et al. (4). Initial studies were mostly performed at low superficial gas velocities (≤ 10 m/s) and low solids circulation fluxes (G ≤ 100 kg/m²s), and therefore relevant for gas-solid reactions only. Gas-catalytic CFB reactors operate at higher velocities and/or circulation rates (Van de Velden et al., 4).

EXPERIMENTAL SET-UP AND PROCEDURE

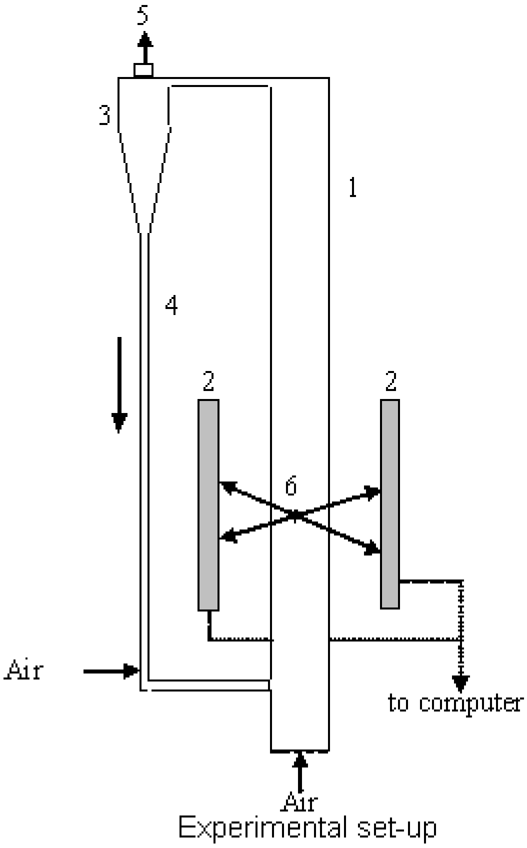


Fig. 1. Experimental set-up: 1) CFB-riser 2) γ-ray cameras; 3) high-efficiency cyclone; 4) downcomer and L-valve; 5) vent, to filter and atmosphere; 6) tracer

By changing the position of the γ-ray cameras, various parts of the CFB can be studied, i.e. near the distributor and L-valve discharge; within the fully developed zone; near the exit; in the cyclone and/or downcomer.

PEPT studies of the solids motion were performed in different risers, all with abrupt exit, of dimensions 0.046, 0.09 and 0.16 m I.D. and of respective heights 2 and 4 m. Air from a compressor was fed to the riser while the recycle solids enter the column via the L-valve. The air velocity was determined from rotameter readings. The bulk solids (bed material) used were rounded sand with a mean diameter of 100-120 µm and a particle density of 2260 kg/m³. The experimental layout is shown in Fig. 1 where U was varied between 1 and 10 m/s and G, between 25 and 622 kg/m²s.

As tracer, a sand particle, of size equal to the average size of the bulk bed material, was labelled with the ^{18}F-isotope (Fan et al., 15) The compressor was started so that the air flow could be set to the required value of the superficial gas velocity. The L-valve was thereafter activated to start the solids circulation. Geiger counters were used to check the tracer circulation and to determine the solid circulation rate so that it could be adjusted to the desired value. The experiment was initiated when the system had stabilised and the tracer coordinates were recorded for about 20 minutes. The experiment could be stopped by turning off the L-valve and the air supply.

Positrons emitted from the tracer annihilate with electrons to produce back-to-back γ-rays. The rays were detected by a pair of γ -ray detectors, each with an active surface area of 0.47 by 0.59 m. Successive detections of γ-rays enable the tracer particle position to be found by triangulation. An extensive list of consecutive particle locations (~1 position every 4 ms) enables the determination of the instantaneous velocity and position. In doing so, an average velocity vector plot and an occupancy plot were obtained. Two sections of the riser were viewed, i.e. (i) around the entry point of solids from the L-valve and the base of the riser, (ii) and at a riser height of between 1.0 and 1.6 m.

RESULTS AND DISCUSSION

Particle Motion and Occupancy Plots in the Fully Developed Riser Flow mode

The result of each experiment is a long list of three dimensional coordinates, as a function of time. Fig. 2 illustrates a typical particle movement in the fully developed zone of the riser. Between successive points, the distance travelled (ΔY) within a given time interval (Δt) can be calculated. It can also be seen that, at the specific conditions used, the tracer sometimes moves upwards and downwards, with the thicker bands representing more rapid successive upwards and downwards motion. The blanks between successive recordings correspond to the time interval spent by the particle in the rest of the riser and in the external recycle loop (where it was followed by Geiger counters only).

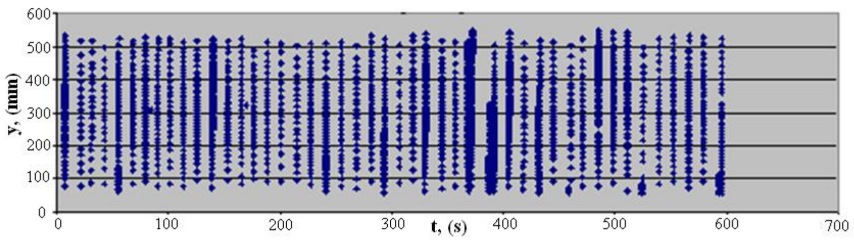


Fig.2. Illustration of the axial (vertical) component of the tracer movement at U of 2.55 m s^{-1} and G of 77.5 kg m^{-2} s^{-1} within the geometric limits of the detectors

The occurrence of core-annulus flow (up and down) and dominant core flow (up only) is strongly dependent upon parameters U and G, as demonstrated in Fig. 3. Results will further be used to determine the extent of different operating modes.

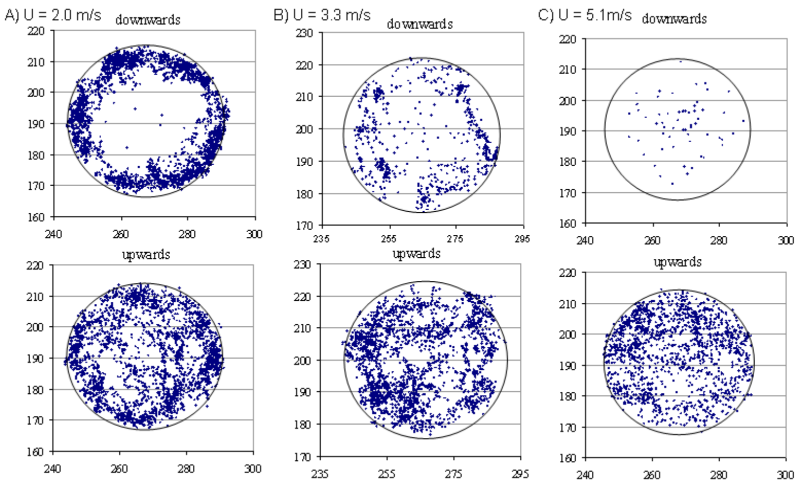


Fig. 3. Cross-sectional view of particle motion in the riser: downwards (top) and upwards (bottom) at solids circulation rate of 260 kg/m²s (Van de Velden et al.,[4]).

Particle Motion at the Bottom of the Riser

The acceleration length and time are nearly constant as can be observed in Fig. 4 and Fig. 5, at 0.2 to 0.4m and an average of 0.21s respectively, independent of U and G (Chan et al., 16). The acceleration length can be modelled fairly accurately, using a C_D-factor of approximately 3.2.

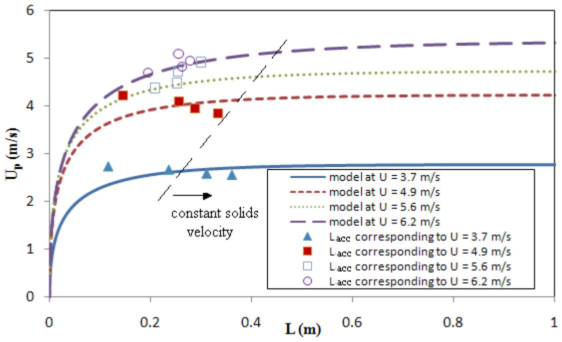


Fig. *4. Experimental acceleration length and model prediction using C_D ~3.2 and a slip factor of 1.3*

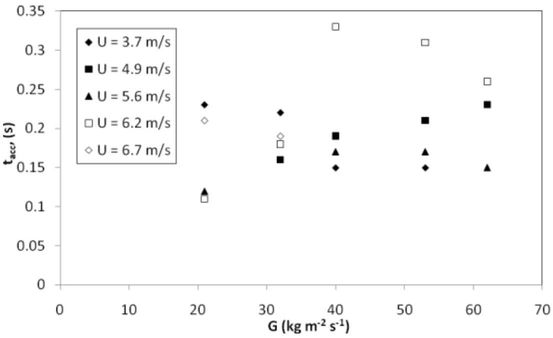
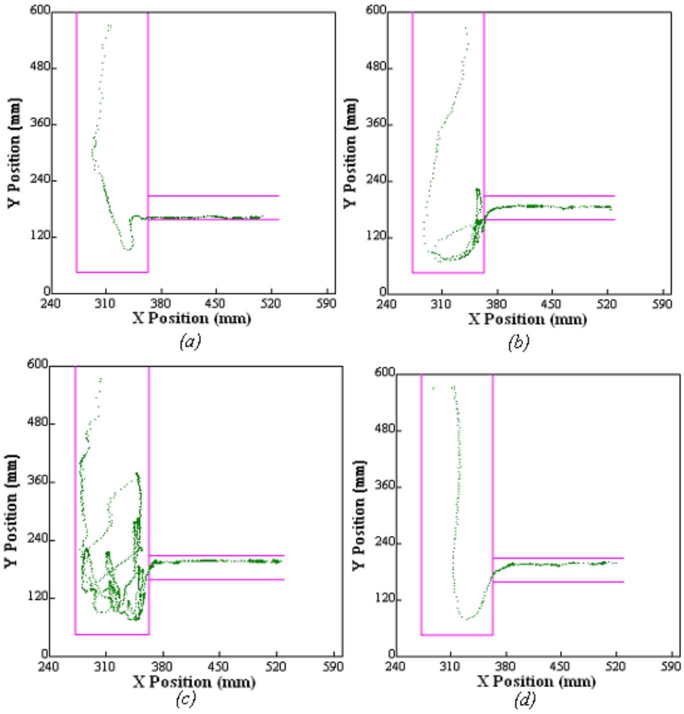


Fig. 5. PEPT observation of acceleration time at various operating G and U

To examine the extent of the acceleration zone and the possible occurrence of a bottom BTFB, the bottom section of the riser was separately viewed in the various riser geometries. The solids movement mode differs completely with operating regimes, as depicted in Fig.6.



These regimes differ:

(i) at low G-values (< ~10 to 20 kg/m²s) the tracer particle is seen to descend to below the solids entry level from the L-valve, where after, it is accelerated and conveyed up the riser at a nearly constant velocity;

(ii) at intermediate values of G and/or U, a BTFB is formed at the bottom of the bed;

(iii) at very high G-values, and $U - U_{TR} > 3$ m/s, no BTFB is seen and acceleration proceeds in a similar manner as in regime (i). Clearly, the existence of a BTFB is confined to a specific range of U,G operating values.

Fig.6. PEPT view of the bottom of the riser, at $U\text{-}U_{TR}$ = 2.1 m/s, for G (kg/m^{2}s) = (a)5.5; (b)20.1 (c)55.5 (d)210

The views of Fig.3, taken along the riser height between 1m to 1.6m, demonstrate either a core-annulus or a dominant core flow of the tracer as a function of U and G. The earlier papers by Van de Velden et al. (4, 10) reported a difference in slip velocity when operating in these two flow modes, with measured particle velocities in the core-annulus flow being lower than the expected theoretical value ($U/\varepsilon - U_t$), which was attributed to cluster formation.

A full analysis of over 150 sets of PEPT-data, together with literature data, all within a range of gas velocities and solids circulation fluxes between 2 and 12m s^{-1} and 5 to 622 kg m^{-2} s^{-1} respectively, enabled us to distinguish between different operating modes of the CFB riser. Individual data points are not indicated but reference to previous illustrations of Figures 3 and 6 are given. Depending on the values of U and G, different operating modes can be distinguished as shown in Figure 7. U_{TR} is calculated according to the equation of Bi and Grace (5). Although the equation determines U_{TR}, a certain margin of U and/or G is required to move into a fully developed riser flow mode, especially at lower values of U and higher values of G.

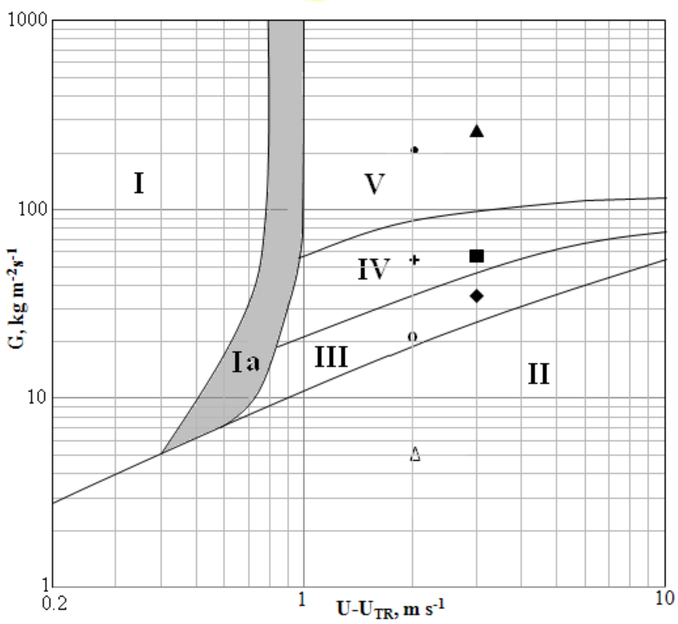


Fig.7. Modes of operation of a CFB riser, expressed as G vs $U-U_{tr}$ depending on
Zone I: bubbling/ turbulent fluidised bed, incompletely developed riser flow
Zone II: dilute pneumatic conveying
Zone III: core-annulus flow
Zone IV: core-annulus flow, BTFB at the bottom
Zone V: fully developed Dense Suspension Up-flow (DSU)
Zone Ia: uncertainty
Δ, o, +, •, correspond respectively to data (a), (b), (c) and (d) in Fig. 6.
◆, ■, ▲ corresponds to data (I), (II) and (III) in Fig. 8.

The region of ‘uncertainty’ corresponds to a (U,G)- domain where some literature cites a fully developed riser flow, whereas other researchers still notice a TFBoperating mode. The regime of dilute flow extends over the whole (U, G) range from low U and low G, to higher U and moderate G values. The commonly discussed core-annulus flow occurs within the (U, G) combinations of Zone III and IV, whereas higher G and/or U values lead to a dense suspension upflow of the solids (Zone V). The selection of the operating condition is of importance when considering the regime to be used for gas-solid or gas-catalytic reactions: whereas the solids residence time is well defined and approximately constant in Zones II and V (favourable for gas-catalytic reactions), it is less uniform and larger in Zones III and IV, thus more appropriate for gas-solid reactions. The difference in operating mode can also be seen when PEPT-data are statistically transformed into the velocity distribution curves of the solids, as discussed below.

Solids Mixing

A core-annulus flow exhibits more mixing than dilute flow or DSU. The velocity profile of solids should therefore show a wider range of velocity distributions than in dilute flow or DSU, which should exhibit a narrower range of velocity distribution closely resembling plug flow behaviour. The span of the velocity, S, can help to define the extent of the deviations of the real solids flow behaviour to that of ideal plug flow.

$$S = \frac{R_{0.9} - R_{0.1}}{R_{0.5}}$$

with S defined as the ratio, R, of the particle velocity to the average particle velocity for a cumulative fraction of 10, 50 and 90%.

For ideal plug flow, S would be 0 since $R_{0.1} = R_{0.5} = R_{0.9}$. Larger values of *S* mean more mixing, deviating away from ideal plug flow behaviour. The degree of mixing as indicated by the S values in Fig. 8 also correctly corresponds to the phase diagram of Fig. 7. The data points from Fig. 8 are retrofitted onto Fig. 7. At U of 5.4 m s^{-1} and G of 57 kg m^{-2} s^{-1}, the S value is the largest corresponding to operation in core-annulus flow with a BTFB at the bottom, showing the highest degree of mixing. At lower or higher G value, the distribution curve shows a more pronounced ‘plug’ flow appearance corresponding to dilute flow and DSU respectively. This statistical analysis of PEPT-velocity data is ongoing and will give a further quantitative distinction between the regimes. As can be seen in Fig. 7, it is expected that Zones II, III, IV and V will converge at very high $U-U_{TR}$ into a 2 regime operation, either dilute flow or DSU.

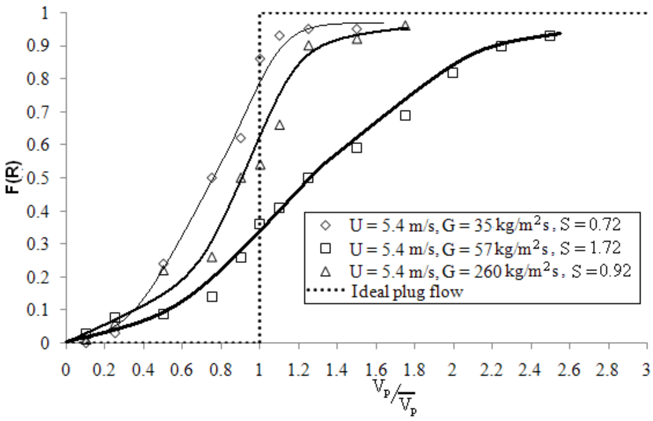


Fig. 8: Solids flow behaviour in the riser at U - 5.4 m s^{-1} but increasing G from 35 kg $m^{-2}s^{-1}$ to 260 $m^{-2}s^{-1}$

CONCLUSIONS

The solids residence time in the riser of a CFB is determined by the particle movement within the riser. Previous studies have mainly focused upon risers operating at lower values of the solids circulation flux, and have distinguished mainly between an S-type and exponential solids hold-up profile in the riser. The present paper used Particle Emission Positron Tracking of a radioactively labelled single particle. The movement of the tracer was monitored in "real time" and determined (i) acceleration length and time, nearly constant at approximately 0.2-0.4m and 0.21s respectively, independent of U and G (ii) the particle upwards and downwards velocities; (ii) the population densities of these particles in the cross sectional area of the riser; (iii) the solids flow pattern at the bottom of the riser and L-valve recycle; (iv) the existence of 5 different operating solids hold-up regimes in the riser and the (U,G) conditions whereby these different regimes prevail; (v) the convergence of the regimes into dilute flow and DSU at very high $U-U_{TR}$. To operate in a dominant core flow mode, as preferred for reactions where a strict control of the residence time is needed, operation in either dilute flow or dense suspension upflow is required. To operate in a core-annulus mode, possibly with a BTFB at the bottom of the riser, G-values < 100 kg/m²s need to be applied. Dilute flow is observed at a combination of G-values between 5 and 50kg m^{-2} s^{-1}, depending on the operating velocity, U.

NOTATION

G	solids circulation flux [kg/m²s]
t	time [s]
$R_{0.1}$, $R_{0.5}$, $R_{0.9}$	particle velocity ratio of 0.1, 0.5 and 0.9 respectively [-]
€	voidage in the riser [-]
S	span [-]
U	superficial gas velocity in the riser [m/s]
U_{TR}	transport velocity (onset of fast fluidization) [m/s]
U_t	terminal velocity of the particle [m/s]
V_p	Upward particle velocity [m/s]
$\overline{V_p}$	average upward particle velocity [m/s]
X,Y,Z	3D-position of the tracer as viewed by PEPT [m]

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REFERENCES

1. Yerushalmi, J. and Cankurt, N.T., Further studies of the regimes of fluidization, Powder Technol., 24 (1979), pp. 187-205
2. Rhodes, M., Geldart, D., The upward flow of gas/solid suspensions, part I: A model for the CFB incorporating dual level entry into the riser, Chem. Eng. Res. Des., 67 (1989), pp. 20-29

3. Smolders, K. and Baeyens, J., Gas fluidized beds operating at high velocities: critical review of occurring regimes, Powder Technology, 119 (2001), pp. 269-291
4. Van de Velden, M., Baeyens J., Seville J.P.K. and Fan X.: The solids flow in the riser of a CFB viewed by Positron Emission Particle Tracking (PEPT), Powder Technology, 183 (2008), p. 290-296
5. Bi, H.T., Grace, J.R., Flow regime diagrams for gas-solid fluidization and upward transport, International Journal Multiphase Flow 21 (1995), pp. 1229-1236
6. Li, J., Tung, Y., Kwauk, M., Axial voidage profiles in fast fluidized beds in different operating regimes, In : CFB Technology II, Basu,P., Large, J.F. (Eds), Pergamon Press (1988), pp. 193-203
7. Kwauk, M., Wang, N., Li, Y., Chan, B., Shen, Z., Fast fluidization at ICM, In: CFB Technology I, Basu, P., (Ed), Pergamon Press (1986), pp. 33-62
8. Kato, K.H., Shibasaki, H., Tamura, K., Arita, S., Wang, C., Takarada, T., Particle hold-up in a fast fluidized bed, J.Chem.Eng.Japan, 22 (1989), pp. 130-136
9. Mori, S., Kato, K., Kobayashi, E., Liu, D., Hasatani, M, Matsuda, H., Hattori, M., Hirama, T., Takeuchi, H., Effect of apparatus design on hydrodynamics of CFB, AIChE Symp.Series, 289 (1992), pp. 17-25
10. Van de Velden, M., Baeyens J., Dougan B. and McMurdo A.: Investigation of operational parameters for an industrial CFB combustor of coal, biomass and sludge, China Particuology, 5(4), (2007-b), pp. 247-254.
11. Bai, R.D., Jin, Y., Yu, Z.Q., Zhu, J.X., The axial distribution of the cross-sectionally averaged voidage in fast fluidized beds, Powder Technology, 71 (1992), pp. 51-58
12. Bai, R.D., Jin, Y., Yu, Z., Flow regimes in circulating fluidized beds, Chem.Eng.Technol ., 16 (1995), pp. 307-313
13. Hartge, E.U., Rensner,D., Werther,J., Solids concentration and velocity patters in circulating fluidized beds, In: CFB Technology II, Basu,P., Large, J.F. (Eds), Pergamon Press (1988), pp. 165-180
14. Berutti, F., Chaouki, J., Godfroy, L., T.S. Pugsley, G.S. Patience, Hydrodynamics of circulating fluidized-bed risers - A review, Can. J. Chem. Eng. 73 (1995), pp. 579-602
15. Fan, X., Parker, D.J., Smith, M.D., Enhancing F-18 uptake in a single particle for positron emission particle tracking through modification of solid surface chemistry, Nucl. Instr. and Meth. A 558 (2006), pp. 542-546.
16. Chan, C.W., Seville, J., Yang, Z. and Baeyens, J., Particle motion in the CFB riser with special emphasis on PEPT imaging of the bottom section, Powder Technology, 196 (2009), pp. 318-325