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Fluidization behavior in a circulating slugging fluidized bed reactor. Part II: Plug characteristics

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Abstract

In the transporting square nosed slugging fluidization regime ($0.4 < u_0 < 1.0\,\mathrm{m/s}$) a bed of polyethylene powder with a low density ($\rho = 900\,\mathrm{kg/m^3}$) and a large particle size distribution ($70 < d_p < 1600\,\mu\mathrm{m}$) was operated in two circulating fluidized bed systems (riser diameters 0.044 and 0.105 m). A relation was derived for the plug velocity as a function of the gas velocity, solids flux, riser diameter, particle size range and particle and powder properties. The influence of the plug length on the plug velocity, the raining rate of solids onto and from the plugs and the influence of the particle size range on the plug velocity is accounted for.

Keywords: Slugging; Powders; Polymerization reactor; Plug velocity; Plug length Particle raining; Circulating bed

1. Introduction

In Part I of this work (Van Putten et al., 2004), it was explained that measurements on the hydrodynamics in a riser of a circulating fluidized bed reactor for olefin polymerization operated in the slugging regime (Weickert, 2000) were done to understand and describe the slugging fluidization regime. In part I, the research was concentrated on the overall solids mixing expressed in the residence time and residence time distribution of solids in the riser of the circulating fluidized bed as well as segregation of particles of different size and raining of particles through slugs. In this part measurements on the hydrodynamics, the characteristics of plugs are done to further understand and interpret the overall solids mixing mechanisms in the slugging fluidization in terms of plug length and plug velocity and eventually be able to describe heat transfer in a model.

The fluidized bed reactor is operated in the square nosed slugging regime. With the polymer powder used in the current research square nosed slugging is observed. Square nosed slugging can occur with powders like coarse powders (group D powders). In contrast to round nosed slugging, in square nosed slugging particles do not flow along the side of the slug downward to mix up in the wake under the slug. In square nosed slugging particles rain down through the slug over the whole area of the slug. The velocities of slugs are influenced partly by the raining of particles through the slugs.

Square nosed slugging is studied only limited and further research is necessary for understanding and eventually modeling of the slugging behavior. The particles are both the catalyst and the product. Because the polymerization reaction is very exothermic, reaction temperatures can become very high. Heat is produced in the polymer particles in which catalyst is distributed. With fresh particles heat production is high and heat removal is difficult. The catalysts used in the polymerization process will be deactivated at higher temperatures, causing a lower production. Also the polymer can melt because of the higher temperatures, causing quality problems in the polymer and operational problems. Therefore, understanding of the plug characteristics is important; they are essential for correct description of local reaction rates and heat transfer to the wall.

1.1. Plug velocity

In the slugging fluidization regime the gas slugs have velocities close to the gas velocity and will push the packets of solids or plugs above them up with about the same velocity. In square nosed slugging fluidization solids rain down from the plugs

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through the slugs on top of the plugs below them. This movement causes an oscillating velocity of solids in the riser. The actual velocity of solids in the riser column is therefore sometimes much higher and sometimes much lower than can be expected from the residence time of the solids and the length of the column.

Much attention is devoted to slug velocity in literature, but the interest of the current research is on the particles and thus on the plugs above the slugs as is explained in part I. The relations to describe the slug velocities can, however, also be used in the understanding of the mechanisms responsible for the velocities of the plugs. The plugs move through the column with about the same velocities as the slugs that push up the plugs. Therefore, the same relations might apply for the plugs although the basis for the expressions is different, as will be shown.

Most work done on the description of the slug velocity is focused on the velocity of round nosed slugs or wall slugs. Some research focused on slugs in liquid, for instance Ormiston et al. (1965). Round nosed slugs were further studied by Stewart and Davidson (1967), Kehoe and Davidson (1970), Baeyens and Geldart (1974), Fan et al. (1983) and Lee et al. (2002). The expressions for slugs in liquid were also applied to slugs in fluidized beds of particles. However, for understanding of the slugging phenomena an overview of work on the velocity round nosed slugs is given.

Ormiston et al. (1965) gave an overview of workers who studied air slugs in water and defined the slug velocity to be

$$u_{sl} = k_2\sqrt{gD} \tag{1}$$

with k_2 having various values around 0.35. This is the velocity of the slugs relative to the fluidized medium. This expression could be derived from analysis of streamlines around the nose of the slug, as was done by Davies and Taylor (1950) and Stewart and Davidson (1967).

For continuously generated slugs rising through a stagnant fluidized medium, the often used general description for the slug velocity reads:

$$u_{sl} = k_1(u_0 - u_{mf}) + k_2\sqrt{gD}. \tag{2}$$

With $k_1 = 1.2$ (Davidson and Harrison, 1963) and $k_2 = 0.361$ as found by Ormiston et al. (1965) and Layzer (1955). More recently, Fan et al. (1983) derived an expression for k_1. They found in their model I:

$$k_1 = 2.43\left(\frac{\overline{d_p}}{D}\right)^{-0.5}\left(\frac{\rho_s}{1000\rho_g}\right)^{-4.2} \tag{3}$$

by defining a dimensionless particle size and a dimensionless particle density. They suggested however that the slug rise velocity was not dependent on the volume of the slug. In their model II they assume that the behavior of slugs is influenced mostly by the characteristics of the column wall and is affected only slightly by the particle properties and the column size. This is not in agreement with the expression for k_1 in their model I. Lee and Kim (1989) followed this derivation but found a slightly different expression for k_1, based on a fit of experimental results.

Lee et al. (2002) found that the rise velocity of slugs was dependent on the bed height due to slug coalescence. They work with powders that cause square nosed slugging and report, in accordance with findings of Noordergraaf et al. (1987), that the velocity of square nosed slugs is lower than the superficial gas velocity. The slope of slug rise velocities, expressed in the constant k_1 for particles causing square nosed slugging is also lower than for beds with round nosed slugging.

1.2. Plug length

To further understand and describe the movement of solids in the riser, it is necessary to study the plug characteristics such as the plug length; the length of a plug will influence its velocity as will be shown. In most research, more emphasis is put on the study of slugs than on the study of plugs. In fluidization research the slug length is well studied, whereas the plug length received less attention.

Kehoe and Davidson (1973) derived an equation for the slug length based on pressure fluctuations in an ideally slugging (single slug) fluidized bed

$$\frac{L_{sl}}{D} - 0.495\left(\frac{L_{sl}}{D}\right)^{1/2}\left[1 + \frac{u_0 - u_{mf}}{0.35\sqrt{gD}}\right] + 0.061 - (T - 0.061)\left[\frac{u_0 - u_{mf}}{0.35\sqrt{gD}}\right] = 0. \tag{4}$$

For large particle systems the slug length is given by De Luca et al. (1992)

$$\frac{L_{sl}}{\sqrt{DH_{mf}}} = 2.09\frac{u_0 - u_{mf}}{\sqrt{gD}} - 0.37. \tag{5}$$

The angle of internal friction (φ) determines the maximum plug length possible (Gibilaro, 2001):

$$\tan\varphi = \frac{L_{max}}{D}. \tag{6}$$

This relation, however, is only of interest for single-slug systems. In multi slug systems this maximum plug length is never reached because of the contact forces between plugs and raining of particles. An average plug and slug length has to be used in multi-slug systems.

In this work, it will be shown that the slug or plug velocity in square nosed slugging is described as a function of the slug or plug length. New results on plug velocity and plug length are presented.

1.3. Raining of solids

For the measurement of the raining rate the bed height is used as a measure for the plug length. A minimal amount of solids in the riser will however not be pushed up by the slug. This is the part of the bed that would be the dense bubbling zone at the bottom of the riser, where bubbles did not yet grow large enough to become slugs. So the plug length can be calculated from the used bed height and the height of the dense bed of solids at the bottom of the riser.

Table 1
Overview of vertical positions of detector array in the 105 mm riser experiments for measuring plug velocity and plug length. Heights above distributor plate

Vertical position of array in riser	Lowest detector (m)	Highest detector (m)	Length of array (m)	Distance between detectors (m)
Upper zone	1.810	2.795	0.985	0.003177
Lower zone	0.695	1.795	1.100	0.003548

The calculation of the height of the dense part of the bed might however not be very accurate. Only few authors have given an expression for the height of the dense bed. De Luca et al. (1992) gave an expression

$$H_{bf} = 68.6\frac{(rD)^{1.235}}{(u_0 - u_{mf})^{1.37}} \tag{7}$$

when the ratio between the bubble and bed diameter, r, is larger than 0.5 and when the bed height is higher than the limiting bed height H_L defined by:

$$H_L = 60D^{0.175}. \tag{8}$$

In this work, attention is devoted to the actual velocity of solids in the riser. This velocity is necessary for description of the heat transfer in the riser column. Heat transfer in plugs and slugs is different. Therefore the plug length and plug velocity are crucial for the product properties.

2. Experimental

Two types of experiments were carried out. The first type of experiments was used for different studies. Gas velocity, solids flux, riser diameter and particle size range were varied. With the data from the detectors (part I) the plug velocity and the plug length could be measured. The length of a plug can change during the lifetime of a plug and this can be followed in the measured data.

The second type of experiments was used to study raining of particles through slugs. The growing height of the dense bottom zone of the powder bed was measured. The dense zone grew because of particles raining onto the dense zone. The gas velocity was varied. From the measurements the raining rate as function of gas velocity could be determined.

2.1. Determination of plug characteristics

Two set ups (set up A and set up B) with the same configuration were used, as are described in part I. With the detectors described in part I and analysis of the measurement data from the detectors plug velocities and plug lengths could be determined. In the 105 mm riser the array of detectors needed to be elongated (Table 1) as compared to the 44 mm riser to be able to measure the larger plug lengths (Table 2). The polyethylene powder as was described in Part I was used.

Table 2
Overview of vertical positions of detector array in the 44 mm riser experiments for measuring plug velocity and plug length. Heights above distributor plate

Vertical position of array in riser	Lowest detector (m)	Highest detector (m)	Length of array (m)	Distance between detectors (m)
Upper zone	2.452	3.126	0.674	0.00217
Middle zone	1.295	1.915	0.620	0.00220
Lower zone	0.750	1.406	0.656	0.00212

2.2. Raining of solids

A standpipe was created by altering set up B as described in Part I. In the standpipe the growth of the height of the dense bottom zone of the bed was measured with detectors. This growth of the height of the dense bottom zone is a measure for the raining rate. The raining rate is expressed in meters of powder bed growth.

3. Results

3.1. Plug velocity

Different gas velocities were applied, with polymer beds of different particle size ranges. Influence of gas velocity on the plug velocity could be determined. Experiments were done in two different set-ups with risers with different diameters so that influence of riser diameter could be determined as well.

3.2. Influence of the gas velocity

Velocities of plugs, the dense phase packets of solids on top of gas slugs, were measured as a function of gas velocity, solids flux through the riser, riser diameter and height in the riser column.

The plug velocity is given as a function of $(u - u_{mf})$, in accordance with representation in literature (Fig. 1). The plug velocity seems to have a linear dependency on the gas velocity. The diameter of the riser does not have a profound influence on the plug velocity but more on the evolution of the plug velocity with increasing riser diameter. The plug rise velocities increase less with increasing gas velocity in the larger diameter than in the smaller diameter. The plug velocities are lower when measured at a higher position in the riser. This is most visible in the smaller diameter riser.

3.3. Influence of the particle size

The different particle size fractions were fluidized separately to determine influence of the average particle size on the velocity of the plugs. The particle size fractions were fluidized in both the 44 mm and the 105 mm riser. Results (Fig. 2) show that the particle size range has a profound influence on the plug rise velocities.

For larger particle diameters the plug velocities are lower at a given gas velocity. For the different ranges this trend is

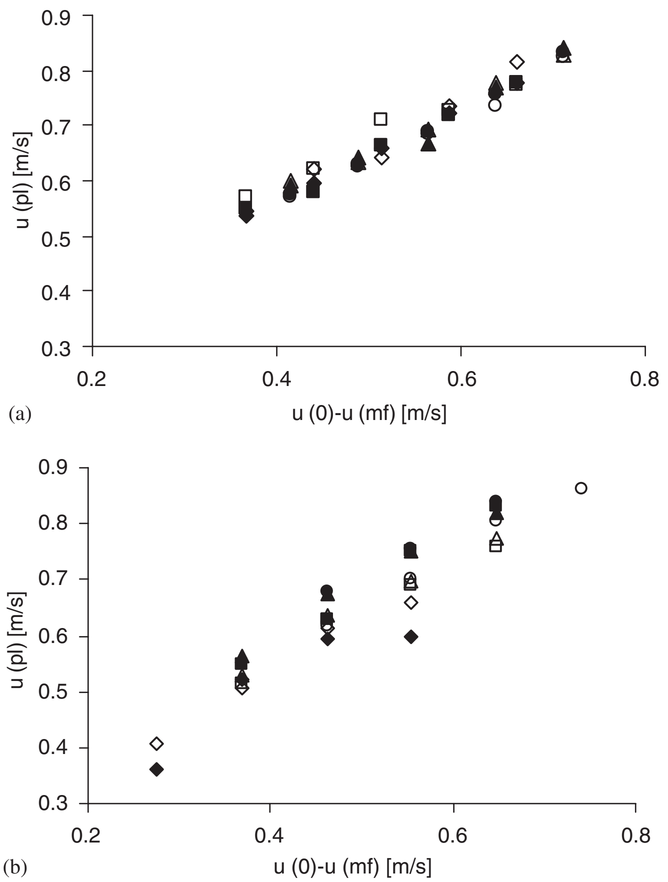

Fig. 1. (a) Plug velocity vs excess gas velocity in upper and lower zone of 105 mm diameter riser. Comparison of plug velocities at different solids fluxes. Upper zone: ♦: $G_s = 2.9\,\mathrm{kg/m^2\,s}$; ■: $G_s = 3.48\,\mathrm{kg/m^2\,s}$; ▲: $G_s = 5.84\,\mathrm{kg/m^2\,s}$; •: $G_s = 6.45\,\mathrm{kg/m^2\,s}$; lower zone: ◊: $G_s = 3.37\,\mathrm{kg/m^2\,s}$; □: $G_s = 4.14\,\mathrm{kg/m^2\,s}$; △: $G_s = 7.38\,\mathrm{kg/m^2\,s}$; ◯: $G_s = 8.08\,\mathrm{kg/m^2\,s}$, (b) plug velocity vs excess gas velocity in upper and lower zone of 44 mm diameter riser. Comparison of plug velocities at different solids fluxes. ♦: $G_s = 3.27\,\mathrm{kg/m^2\,s}$; ■: $G_s = 5.45\,\mathrm{kg/m^2\,s}$; ▲: $G_s = 8.3\,\mathrm{kg/m^2\,s}$; ×: $G_s = 10.52\,\mathrm{kg/m^2\,s}$; upper zone: solid symbols, lower zone: open symbols.

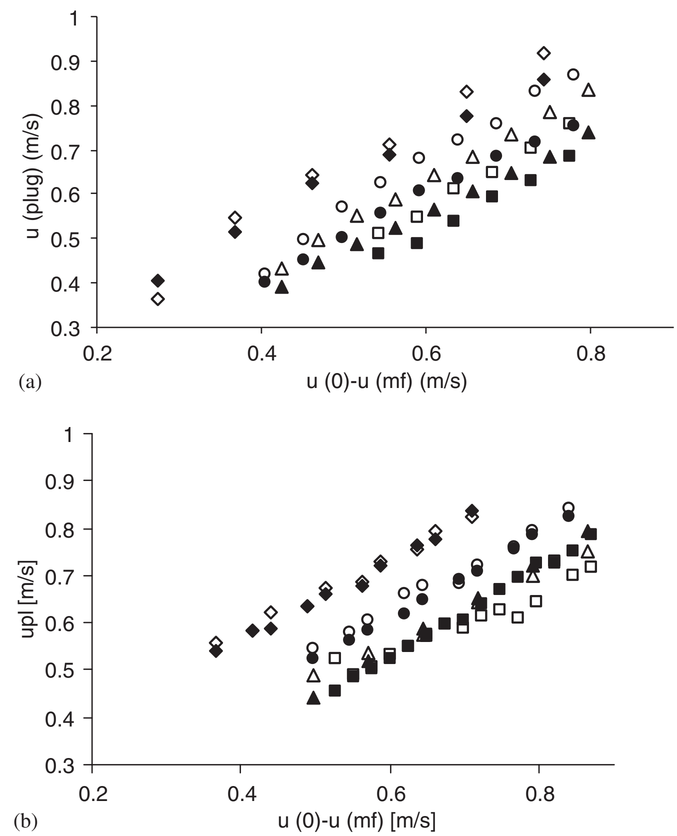

Fig. 2. (a) Plug velocity vs excess gas velocity. Plug velocities in upper and lower zone of 44 mm diameter riser (245–313 cm above distribution plate) and (75–141 cm above distribution plate). ♦: 'total' powder; •: $420\,\mu\mathrm{m} < d_p < 800\,\mu\mathrm{m}$; ▲: $800\,\mu\mathrm{m} < d_p < 1200\,\mu\mathrm{m}$; ■: $d_p > 1200\,\mu\mathrm{m}$. Upper zone: solids symbols, lower zone: open symbols, (b) plug velocity vs excess gas velocity. Plug velocities in upper and lower zone of 105 mm diameter riser (181–279 cm above distribution plate) and (69–179 cm above distribution plate). ♦: 'total' powder; •: $420\,\mu\mathrm{m} < d_p < 800\,\mu\mathrm{m}$; ▲: $800\,\mu\mathrm{m} < d_p < 1200\,\mu\mathrm{m}$; ■: $d_p > 1200\,\mu\mathrm{m}$. Upper zone: solids symbols, lower zone: open symbols.

clearly visible. However the 'total' powder shows significantly larger plug velocities although the average particle diameter is smaller than for the 'large' particle range.

The trends in the plug velocities for the different particle size ranges are the same for both riser diameters, although in the 105 mm riser almost no distinction can be made between the plug velocities of the 'average' size fraction and the 'large' size fraction.

3.4. Plug length

The plug lengths were measured for different gas velocities and different particle size ranges in both the 44 mm riser and the 105 mm riser. Results are shown in Fig. 3. The plug lengths given are average plug lengths of a number of measurements.

As can be seen, the height at which the plug length is measured is of influence on the results. This can be explained from the slugging fluidization itself. At lower height in the bed the plugs are still being formed, resulting in rather short plugs. In the middle zone of the riser plugs are increasing and decreasing in length because of raining of solids onto and from them. They are completely developed, having a large average length. In the upper zone of the riser the plugs only loose solids because of raining and are, therefore, shorter again than in the middle zone.

The plug length in the middle zone is most important, since only the middle zone will increase when scaling up whereas the lower zone and the upper zone will remain the same. Exit effects affect the upper zone of the riser and the lower zone is affected by the creation of plugs from the dense bottom zone of the powder bed. Only the riser diameter has influence on the heights of these zones.

The solids flux does not have a large influence on the length of the plugs in the lower and upper zones of both risers: the results for the measurements with different solids fluxes are approximately the same. But the solids flux causes a spread in plug length in the middle zone, where raining onto and from the plugs takes place. The plug length is largest at the lowest solids flux and is smallest at the highest solids flux. The trend in plug length seems to be linear with the solids flux (Fig. 4).

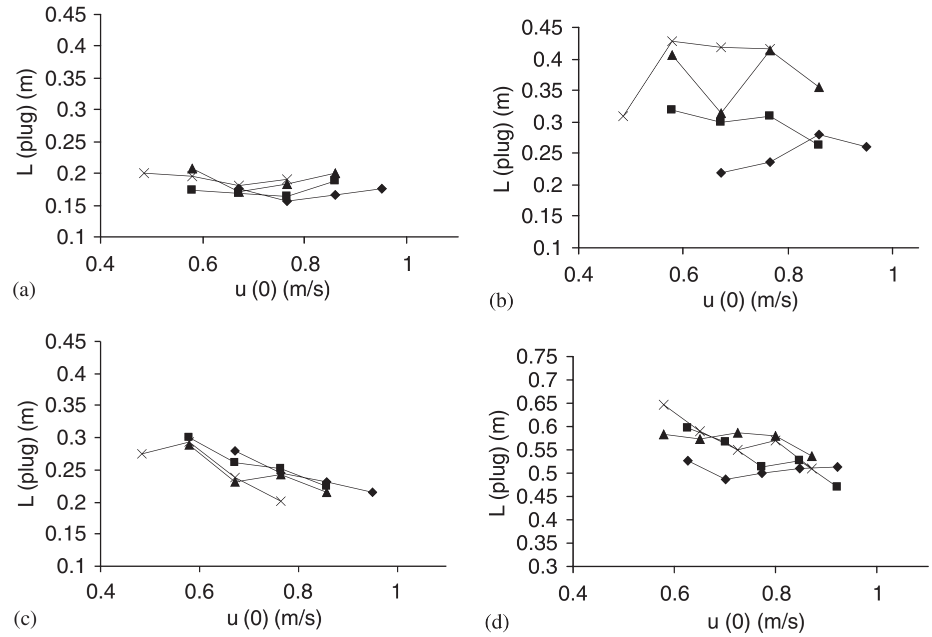

Fig. 3. (a) Plug length vs gas velocity, in lower part of 44 mm riser (75–141 cm above distribution plate), 'total' particle size distribution. ♦: $G_s = 10.52\,kg/m^2\,s$; ■: $G_s = 8.3\,kg/m^2\,s$; ▲: $G_s = 5.45\,kg/m^2\,s$; ×: $G_s = 3.27\,kg/m^2\,s$, (b) plug length vs gas velocity, in middle part of 44 mm riser (129–191 cm above distribution plate), 'total' particle size distribution. ♦: $G_s = 10.52\,kg/m^2\,s$; ■: $G_s = 8.3\,kg/m^2\,s$; ▲: $G_s = 5.45\,kg/m^2\,s$; ×: $G_s = 3.27\,kg/m^2\,s$, (c) plug length vs gas velocity, in upper part of 105 mm riser (245–313 cm above distribution plate), 'total' particle size distribution. ♦: $G_s = 10.52\,kg/m^2\,s$; ■: $G_s = 8.3\,kg/m^2\,s$; ▲: $G_s = 5.45\,kg/m^2\,s$; ×: $G_s = 3.27\,kg/m^2\,s$, (d) plug length vs gas velocity, in lower part of 105 mm riser (70–180 cm above distribution plate), 'total' particle size distribution. ♦: $G_s = 6.45\,kg/m^2\,s$; ■: $G_s = 5.84\,kg/m^2\,s$; ▲: $G_s = 3.48\,kg/m^2\,s$; ×: $G_s = 2.9\,kg/m^2\,s$.

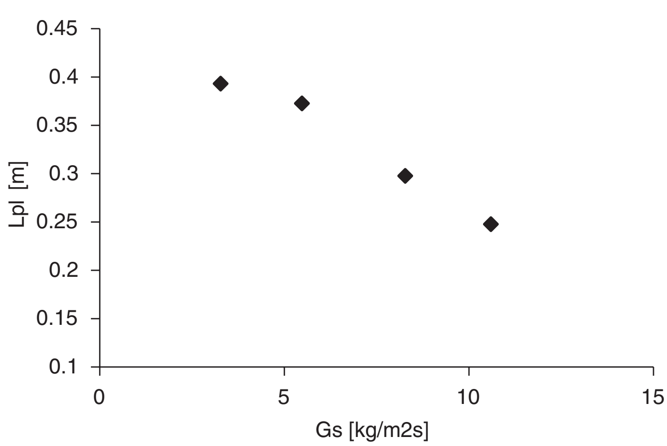

Fig. 4. Plug length in middle zone of 44 mm diameter riser (129–191 cm above distribution plate) as function of the solids flux. Average plug length calculated for different solids fluxes.

The results however show a fairly large scatter. Also this dependency is not found in the results for the lower and the upper part of the riser.

In the results for the 105 mm diameter riser a dependency on the solids flux was found. A specific middle zone was not measured. The lower and upper zones were large enough to occupy the whole riser zone.

When looking at the results of the plug lengths measured in the 105 mm diameter riser, it is clear that the larger diameter causes larger plugs to appear. The aspect ratio of the plugs in the lower part of the 105 mm diameter riser is roughly 5.2 whereas the aspect ratio for the plugs in the upper zone of the 44 mm diameter riser is 4.5. The plug lengths in the 105 mm riser are measured relatively lower than in the 44 mm riser, what means that the plugs were expected to be smaller: the trend in plug length versus height in the bed shows smaller plugs lower in the riser. When measurements higher in the 105 mm riser would have been possible, it is expected that even larger plugs would be found.

The gas velocity has a limited influence on the length of the plugs. The plug length is shorter at higher gas velocities, what is expressed most in the middle and upper zone of the 44 mm riser and in the 105 mm riser. The results for the middle zone of the 44 mm riser are scattered and a dependency is hard to determine. Still, for understanding a dependency is determined.

3.5. Solids raining rate

Raining rates were measured at different solids loadings of the standpipe, expressed as bed height. The larger the bed height is the larger the plugs will be that are pushed up. For accurate description of the plug length the height of the dense bottom zone of the bed is calculated. This height is only 5.5 cm in the 105 mm riser according to the calculations. This, is however, not the case in the raining experiments where the dense bed is much higher than that. It is assumed therefore, that the plug length can be taken in the calculation for the raining rate since the packet of solids pushed up by the pulse will have approximately the same length as a normal plug.

In part I raining rates were measured for a combination of bed height, pulse gas velocity and pulse length. From the results of all experiments, no correlation between the raining rate and the gas velocity could be found. Also, no correlation between raining rate and pulse length was found, so the raining rate was concluded to be independent of the pulse length. However, a linear dependency of the raining rate on the bed height was found.

4. Discussion

4.1. Influence of the gas velocity

Gas velocity has a large influence on the plug velocity, as can be expected. However, the plug velocities are not the same as the gas velocities. Some of the gas 'slips' through the plugs. When relations from literature are used to describe the measured plug velocity, it is clear that these relations do not apply. When Eq. (2) is fitted to the results for the middle zone in the 44 mm riser for all particle size ranges, it is clear that k_1 and k_2 do not have the same values as mentioned in literature (Table 3).

Velocities of plugs are described in literature with the same expressions as are developed for the velocities of slugs. However, the basis for the development of these expressions is different from the nature of the plugs and can therefore not be expected to describe the velocity of the plugs. The basis for the description of the slug velocity was found by analysis of streamlines around the noses of the slugs, but in the case of plugs in the square nosed slugging regime no streamlines are present in the fluidum. In fact in the square nosed slugging regime the fluidum does not flow around the slug, but particles fall through it so the relations for round nosed slugs will in principle not apply for square nosed slugs.

It seems that the value of k_1 is dependent on the position in the riser and on the riser diameter. The values for k_1 with the 105 mm riser diameter are lower than the values with the 44 mm riser. However, the trend in the values of k_1 and k_2 suggest a rotation: when the value of k_1 increases, the value of k_2 decreases. This suggests an influence of possibly one parameter in both constants. To be able to use the influence of different parameters in modeling, a new mathematical description for the plug velocity was derived.

A new relation was derived. The plug velocity is generally the same as the gas velocity, but with some adjustments. The basis for the plug velocity is given by Eq. (2) in that the first term accounts for the direct influence of the gas velocity on the plug, and that the second term is the result of a force balance around the plug in the fluidum.

In the force balance, the plug is described as a cylinder, its volume being calculated as $V = \pi D^2/4 \cdot L_{\mathrm{pl}}$. The derivation of the force balance around a plug is

$$\sum F = -F_g + F_b + F_{\mathrm{fr},g} - F_{\mathrm{fr},w}. \tag{9}$$

All forces from gravity, buoyancy and friction from the gas with the particles are taken into account. The friction with the wall is assumed to be negligible compared to the friction between the particles and the friction between the particles and the gas.

$$\sum F = -\rho_b g \frac{\pi}{4} D^2 L_{\mathrm{pl}} + \rho_g g \frac{\pi}{4} D^2 L_{\mathrm{pl}} + \frac{1}{2} \rho_b u_0^2 \frac{\pi}{4} D^2 c_f \tag{10}$$

with

$$c_f \tfrac{1}{2} \rho_b u_0^2 = \rho_b g L_{\mathrm{pl}} - \rho_g g L_{\mathrm{pl}}. \tag{11}$$

Table 3
Fit of Eq. (2) to results of middle zone 44 mm riser and upper zone 105 mm riser

Riser diameter (mm)	Zone in the riser	Particle size range (μm)	k_1 (dimensionless)	k_2 (dimensionless)
44	Lower	$70 < d_p < 1600$	0.95	0.24
44	Lower	$420 < d_p < 800$	0.94	0.05
44	Lower	$800 < d_p < 1200$	0.90	0.03
44	Lower	$d_p > 1200$	0.96	−0.10
44	Middle	$70 < d_p < 1600$	0.95	0.21
44	Middle	$420 < d_p < 800$	1.12	−0.3
44	Middle	$800 < d_p < 1200$	0.96	−0.25
44	Middle	$d_p > 1200$	1.04	−0.38
44	Upper	$70 < d_p < 1600$	1.13	0.14
44	Upper	$420 < d_p < 800$	1.17	−0.04
44	Upper	$800 < d_p < 1200$	1.05	0.00
44	Upper	$d_p > 1200$	1.07	0.12
105	Lower	$70 < d_p < 1600$	0.78	0.26
105	Lower	$420 < d_p < 800$	0.84	0.13
105	Lower	$800 < d_p < 1200$	0.72	0.12
105	Lower	$d_p > 1200$	0.66	0.14
105	Upper	$70 < d_p < 1600$	0.85	0.22
105	Upper	$420 < d_p < 800$	0.89	0.08
105	Upper	$800 < d_p < 1200$	0.95	−0.02
105	Upper	$d_p > 1200$	0.95	−0.05

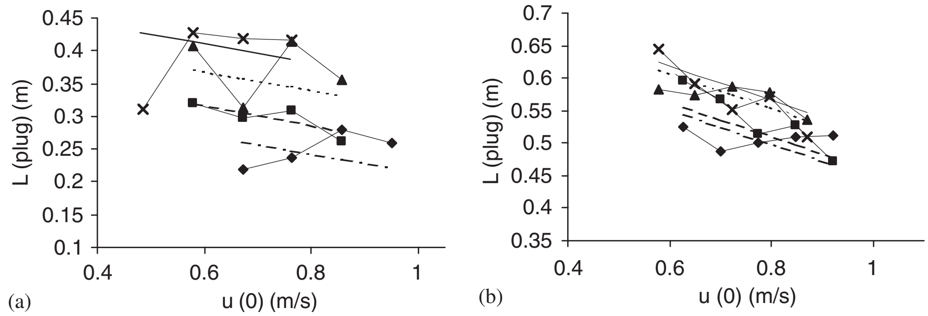

Fig. 5. (a). Plug velocity vs gas velocity, 44 mm diameter riser, middle zone. Fit of Eq. (14) to results. ♦: $G_s = 10.52\,\text{kg/m}^2\,\text{s}$, — – —: fit; ■: $G_s = 8.3\,\text{kg/m}^2\,\text{s}$, — —: fit; ▲: $G_s = 5.45\,\text{kg/m}^2\,\text{s}$, – –: fit; ×: $G_s = 3.27\,\text{kg/m}^2\,\text{s}$, —: fit, (b) plug velocity vs gas velocity, 105 mm diameter riser, lower zone. Fit of Eq. (14) to results. ♦: $G_s = 6.45\,\text{kg/m}^2\,\text{s}$, — – —: fit; ■: $G_s = 5.84\,\text{kg/m}^2\,\text{s}$, — —: fit; ▲: $G_s = 3.48\,\text{kg/m}^2\,\text{s}$, – –: fit; ×: $G_s = 2.9\,\text{kg/m}^2\,\text{s}$, —: fit.

This results in the following relation for the plug velocity relative to the fluidum

$$u_{\text{pl,rel}} = \sqrt{2\frac{\rho_b - \rho_g}{c_f \rho_b}} \cdot \sqrt{g L_{\text{pl}}}. \tag{12}$$

As can be seen not the diameter of the column is of influence on the relative plug velocity, but the length of a plug. The term $\sqrt{2(\rho_b - \rho_g)/c_f \rho_b}$ in Eq. (12) is the same as the constant k_2 in Eq. (2). This means that a relation for the description of the plug length is needed.

With an expression for length of a plug the velocity of the plug relative to the fluidum can be calculated. The absolute plug velocity however is calculated with one more contribution: the apparent plug velocity due to raining of solids onto and from the plugs. Raining of solids takes place through the slugs and makes plugs grow and shrink, but raining of solids also increases the visual plug velocity. In fact, the absolute plug velocity is calculated as

$$u_{\text{pl}} = k_1(u_0 - u_{mf}) + \sqrt{2\frac{\rho_b - \rho_g}{c_f \rho_b}} \cdot \sqrt{g L_{\text{pl}}} + u_{\text{pl},r}. \tag{13}$$

The structure is roughly the same as of Eq. (2), but the calculation of the various contributions to the plug velocity is different.

4.2. Influence of the plug length

The plug length is measured for different gas velocities and different particle size ranges in both the 44 mm riser and the 105 mm riser. Results are shown in Fig. 5. The plug lengths given are average plug lengths of a number of measurements.

As can be seen, the height at which the plug length is measured is of influence on the results. This can be explained from the slugging fluidization itself. At lower height in the bed the plugs are still being formed, resulting in rather short plugs. In the middle zone of the riser plugs are increasing and decreasing in length because of raining of solids onto and from them. They are completely developed, having a large average length. In the upper zone of the riser the plugs only loose solids because of raining and are therefore shorter again than in the middle zone. The plug length in the middle zone is most important, since only the middle zone will increase when scaling up whereas the lower zone and the upper zone will remain the same. Only the riser diameter has influence on the heights of these zones.

When all influences are summarized and put together, a relation for the plug length is found that is dependent on the gas velocity, the riser diameter and the solids flux and is most valid for the middle zone. The solids flux is of influence only on the abscissas. When comparing this with the relation found by De Luca et al. (1992) there are a few differences. The dependency of the plug length with the riser diameter is quite different. Also the influence of solids flux is not taken into account. It is possible that these differences occur because De Luca et al. described slug length whereas in this work the plug length is described. The relation of Kehoe and Davidson (1973) also deviates from the results found here. The general form of the relation found here is

$$L_{\text{pl}} = -a_l \cdot D^{b_l} \cdot u_0 - c_l \cdot G_s + d_l \cdot D^{e_l}. \tag{14}$$

Comparison with experimental data from the middle zone of the 44 mm diameter riser and the 105 mm diameter riser gives:

$$L_{\text{pl}} = -1.2 \cdot D^{0.68} \cdot u_0 - 0.019 \cdot G_s + 2.3 \cdot \sqrt{D}. \tag{15}$$

A fit of this relation with experimental data is given in Fig. 5.

4.3. Solids raining rate

In part I an explanation was given for the increase in raining rate with an increase in bed height. In this work the results of the measurements are used. As an example the expression for the length of a plug (Eq. (14)) is used. Although the actual length of the 'plug' in the raining rate measurements may be different, the trend of the plug velocity with the raining rate will be visualized. The contribution of the raining rate to the plug velocity will then be

$$u_{\text{pl},r} = 0.021 L_{\text{pl}} + 0.0234. \tag{16}$$

When this contribution to the plug velocity is compared to the other contributions in Eq. (13) it is clear that this contribution

Table 4
Results of fit of linear equation to experimental results for plug velocity

Riser diameter (mm)	Zone	Particle size range (μm)	a (dimensionless)	b (dimensionless)	$u(d_p)$ (dimensionless)
44	Lower	$70 < d_p < 1600$	0.9395	0.16	−0.053
44	Lower	$420 < d_p < 800$		0.03	0.077
44	Lower	$800 < d_p < 1200$		−0.01	0.117
44	Lower	$d_p > 1200$		−0.05	0.157
44	Middle	$70 < d_p < 1600$	1.01	0.107	0
44	Middle	$420 < d_p < 800$		−0.13	0.237
44	Middle	$800 < d_p < 1200$		−0.19	0.297
44	Middle	$d_p > 1200$		−0.25	0.357
44	Upper	$70 < d_p < 1600$	1.14	0.092	0.063
44	Upper	$420 < d_p < 800$		−0.01	0.165
44	Upper	$800 < d_p < 1200$		−0.06	0.215
44	Upper	$d_p > 1200$		−0.12	0.275
105	Lower	$70 < d_p < 1600$	0.745	0.28	−0.173
105	Lower	$420 < d_p < 800$		0.185	−0.078
105	Lower	$800 < d_p < 1200$		0.11	−0.003
105	Lower	$d_p > 1200$		0.075	0.032
105	Upper	$70 < d_p < 1600$	0.83	0.18	−0.073
105	Upper	$420 < d_p < 800$		0.055	0.052
105	Upper	$800 < d_p < 1200$		−0.01	0.117
105	Upper	$d_p > 1200$		−0.025	0.132

is only very small. Nonetheless, this influence from the raining of particles should be taken into account for the sake of completeness.

4.4. Influence of the particle size

In the derivation of the plug velocity the influence of the particle size was not taken into account. Measurements however have shown that the particle size has a profound influence on the plug velocity.

When the plug velocities for the different particle size ranges are fitted with a simple linear $y = ax + b$ equation, with x the gas velocity and y the plug velocity, values for a are found that are not equal to 1 (Table 4). The plug length L_{pl}, however, is a function of the gas velocity. When k_1 in Eq. (13) is set to 1, the deviation from 1 is caused by the term for the plug length L_{pl}. Values for b are found by addition of all contributions in Eq. (13) except the $u_0 - u_{mf}$ term.

Comparison of the results in Fig. 2 with the simplified equation shows that the influence in particle size is represented in the force balance term by the bulk density in the calculation for k_2. But the plug velocity is also shifted to higher or lower values by the particle size ranges without a change in the trend in plug velocity with the gas velocity. This means that an additional term must be applied to describe the influence of particle size range.

The height at which the plug velocity measurements were done has influence on the values for a and b, but this influence is averaged for all measurements. When the system would be scaled up, the middle zone would become more important. However, the values for the 105 mm riser are more consistent with values for the lower and upper zone of the 44 mm riser. The influence of $u(d_p)$ will not change in character when other values are chosen, the structure stays the same. Therefore, the values for the equation for $u(d_p)$ are chosen to fit most of the experimental data. Also the diameter of the riser has influence on the values of a and b. The riser diameter is used in the calculation of L_{pl} and that causes this influence.

It is clear that the particle size range almost has no influence on the slope of the line, but largely influences the abscissas. This means that the influence of particle size range contributes to the value of b. So b can be calculated with

$$b = \sqrt{2\frac{\rho_b - \rho_g}{c_f \rho_b}} \cdot \sqrt{g L_{\mathrm{pl}}} + u_{\mathrm{pl},r} + u_{d_p}. \tag{17}$$

A possible explanation for the influence of the particle size range is the friction of the gas with the particles in a plug. When the particles are smaller, the friction may be larger, causing a larger velocity of the plug. However, the powder with the whole particle size range (the 'total' powder) has an even larger velocity. Therefore, another explanation is that not so much the particle size determines the plug velocity, but more the bulk density of the powder. The 'total' powder has the highest bulk density of all powders and also gives the highest value of b. The powder with particle size $> 1200\,\mu$m has the lowest value of b and also the lowest bulk density. Then $u(d_p)$ becomes

$$u_{d_p} = a \cdot \rho_b + c. \tag{18}$$

The value of c is calculated and is the value for b minus all contributions other than that of $u(d_p)$. The average value is taken and corrected for the value for the 'total' powder; for a a slope of 0.0043 is taken. The result is

$$u_{d_p} = 0.0043 \cdot \rho_b - 2.26. \tag{19}$$

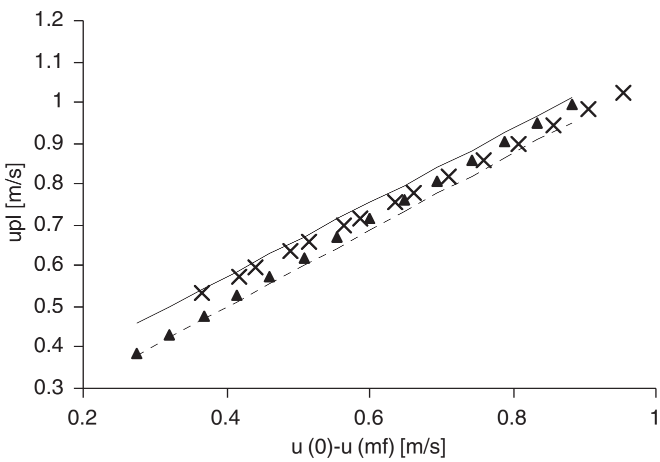

Fig. 6. Fit of Eq. (19) to results of plug velocity. ×: plug velocity 105 mm averaged for 'total' powder; ▲: plug velocity 44 mm middle zone for 'total' powder; —: model for 105 mm riser diameter; - - - -: model for 44 mm riser diameter.

4.5. Plug velocity

Summarizing the above mentioned influences, the resulting expression for the plug velocity becomes

$$u_{\mathrm{pl}} = (u_0 - u_{mf}) + \sqrt{2\frac{\rho_b - \rho_g}{c_f \rho_b}} \cdot \sqrt{g L_{\mathrm{pl}}} + 0.021 L_{\mathrm{pl}} + 0.0043\rho_b - 2.24. \tag{20}$$

A fit of this equation through the experiments is shown in Fig. 6. For c_f a value of 85 was chosen. This value can be calculated when the Reynolds number of the powder is known but was used as a fit parameter in this study. The fit of the model through the experimental values is quite good, although a fairly large amount of scattering was shown in the experimental results. This could lead to large uncertainties in Eq. (19), and a fit would be worse. The relation for the plug velocity was found by mechanistic evaluation of the factors influencing the plug velocity. Although uncertainties in the experimental results remain, Eq. (19) should be valid in a broad range of applications. However, for different powders the constants in the equation need to be re-evaluated.

Eq. (19) is valid for the square nosed slugging regime (gas velocities between $0.28 < ug < 0.95\,\mathrm{m/s}$) and was found by analysis of measurements with a polymer powder (density $\rho_{\mathrm{pol}} = 900\,\mathrm{kg/m^3}$ and $423 < \rho_b < 474\,\mathrm{kg/m^3}$) with a broad particle size distribution ($70 < d_p < 1600\,\mu\mathrm{m}$).

5. Conclusion

A relation was derived for the plug velocity in a bed of polymer powder with a low density and a large particle size distribution. Influences of gas velocity, solids flux, riser diameter, particle size range and particle and powder properties were measured and quantified for their influence on the plug velocity.

Existing relations for the calculation of slug velocity were found not to apply to the powder used in the experiments. Also the derivation of the expression for the slug velocity was different in nature. A new relation for the description of the plug velocity relative to the fluidum was derived and all influences of system properties were added. The resulting equation for the plug velocity fits well with the experimental results and can be used to describe the plug velocity in a fluidized bed operated in the square nosed slugging regime in a broad range of applications.

Notation

a_l	constant in equation for plug length, s/m^{b_l}
a, b, c, d	constants, dimensionless
b_l	constant in equation for plug length, dimensionless
c_l	constant in equation for plug length, $\mathrm{m^3\,s/kg}$
c_f	friction coefficient, dimensionless
d_l	constant in equation for plug length, $1/m^{(e_l-1)}$
d_p	particle diameter, m
D	riser diameter, m
e_l	constant in equation for plug length, dimensionless
F_g	gravity force, N
F_b	buoyancy force, N
$F_{\mathrm{fr},g}$	friction force due to gas, N
$F_{\mathrm{fr},w}$	friction force due to wall, N
g	acceleration of gravity, $\mathrm{m/s^2}$
G_s	solids flux, $\mathrm{kg/m^2\,s}$
H_{mf}	bed height at minimum fluidization, m
H_{bf}	height of a freely bubbling zone in a fluidized bed, m
H_L	limiting bed height where coalescence is complete and a stable plug length is achieved, m
k_1, k_2	constants, dimensionless
$L_{\max}$	maximum slug length, m
L_{pl}	plug length, m
L_{sl}	slug length, m
r	ratio between bubble and column diameter, dimensionless
T	plug length/bed diameter, dimensionless
u_0	gas velocity, m/s
u_{mf}	minimum fluidization velocity, m/s
u_{pl}	plug velocity, m/s
$u_{\mathrm{pl},r}$	contribution to plug velocity due to raining of particles, m/s
u_{sl}	slug velocity, m/s
u_{d_p}	contribution to plug velocity due to particle size, m/s

Greek letters

ρ_b	bulk density of powder, $\mathrm{kg/m^3}$
ρ_g	gas density, $\mathrm{kg/m^3}$
ρ_s	solids density, $\mathrm{kg/m^3}$
φ	angle of internal friction, dimensionless

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