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FLUID DYNAMIC EFFECTS OF RING-TYPE INTERNALS IN A DUAL CIRCULATING FLUIDIZED BED SYSTEM

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ABSTRACT

Intensified gas-solids contact in the fuel reactor of chemical looping combustion systems can be a key issue for achieving the necessary gas-phase conversion rates. Wedge-shaped rings were designed and installed in the fuel reactor of a cold flow model for fluid dynamic testing. These internals are meant to reduce the typical radial and axial solids concentration non-uniformity. It is shown, that more solids are present in the upper regions of the riser when internals are used. Additionally, increase of the solids elutriation rate from the riser was found.

INTRODUCTION

Dual Circulating Fluidized Bed System

The general idea of dual fluidized bed (DFB) reactor systems is to expose two different gas streams to a circulating stream of solids transporting chemical species and often also heat. The use of loop seals avoids direct contact between the two main gas streams. Chemical looping processes in particular require high gas–solid interaction and sufficient contact time in both reactors.

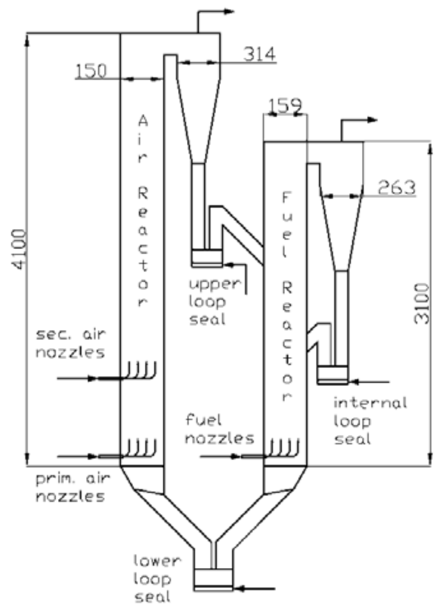

Figure 1: Sketch of the 120kW DCFB pilot unit.

The unit (Figure 1) has been designed as dual circulating fluidized bed system with the solids elutriated from a primary circulating fluidized bed reactor (air reactor, AR) separated in a cyclone and fed to a secondary CFB reactor (fuel reactor, FR) passing first through a loop seal (upper loop seal, ULS). The particles from the fuel reactor are fed back into the fuel reactor itself after separation in a second cyclone provided with a loop seal too (internal loop seal, ILS). The global solids circuit is closed via a loop seal in the lower part of the reactors (lower loop seal, LLS) that constitutes a hydraulic communication of the reactor inventories.

In this design, only the air reactor entrainment is responsible for the global solids circulation between the two reactors, while the fuel reactor can be optimized in order to reach maximum fuel conversion. An excellent gas-solids contact is especially required in the fuel reactor to prevent undesirable presence of unconverted fuel in flue gas (1) (2).

Application of Internals

Introduction of internals has been studied for decades in slow velocity fluidized beds, several types of internals are reported in literature already; rings, perforated plates, tubes, etcetera, an initial classification of internals and their effects was done by Harrison and Grace (3). Whereas, for circulating fluidized beds (CFB) some pioneering efforts have been completed (summaries can be found in Lim et al. 1995 (4) and Zhu et al. 1997 (5)).

The principal objective of internals installation is the improvement of gas-solids contact; it has been indicated that walls with baffles reduce the typical radial solids concentration non-uniformities by removing the particles flowing down near the wall (annulus region) and bringing them to the core, where reaction by contact with the gas is possible. They can likely also minimize solids back-mixing along the riser while preserving overall solids inventory. Even a series of baffles might divide a fluidized column in a multilayer fast fluidized bed that alternates dense and dilute zones.

Above all, wall baffles in the form of flat rings have been of special interest when it comes to internals in CFB and their effects on the gas-solids flow characteristics were well described by Bu and Zhu in (6). They also concluded that elimination of sharp edges in the baffles would be practical to reduce erosion. Likewise, the observed accumulation of particles in the corner formed between flat rings and the wall, particularly important at low velocities and small opening percentage of the ring, can be avoided by using wedged profile rings.

Optimal sizing of the baffles has been found to be decisive since they can affect the pressure drop, on one hand, by scraping the down-flowing solids at the wall and deflecting them into the core region where they can be quickly entrained upwards, and on the other hand, by creating extra resistance to the gas-solids up-flowing stream. "When the rings are only in the annulus region, the first mechanism would dominate, but when the rings extend into the core region, the second mechanism would become more and more significant" (6).

For this particular dual circulating fluidized bed system, given that, the global circulation rate is governed by the primary reactor fluidization and that the secondary reactor (where the internals need to be installed) is a counter-current reactor, effect of the rings introduction must be seen from an additional point of view. It is, the internals not only intensify the contact between the phases and promote a denser core, but also prolong the time needed for the particles to reach the bottom of the reactor and hence increase their availability for reaction in this section of the system. Additionally, it is important to notice that the investigated unit represents a system of freely circulating CFBs where the total inventory is constant and the solids fluxes in the risers result as a consequence of inner fluid dynamics.

Rings Design

The rings were designed with a wedge shape section and an aperture ratio of 60% (Figure 2). The wedge form of the rings can likely be applied in refractory-lined hot systems and have the advantages of reducing the impact of erosion and of eliminating any dead area above the internal. This shape is expected to influence the flow structure of particles and gas by both, promoting the change of direction in particles flow and by creating a narrowed length for the flow of gas.

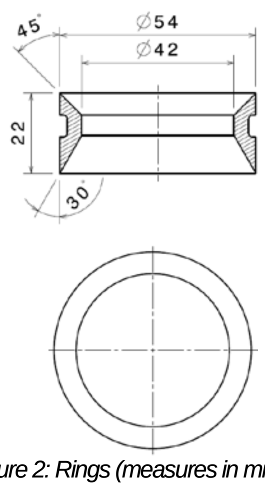

Figure 2: Rings (measures in mm).

EXPERIMENTAL

Cold Model

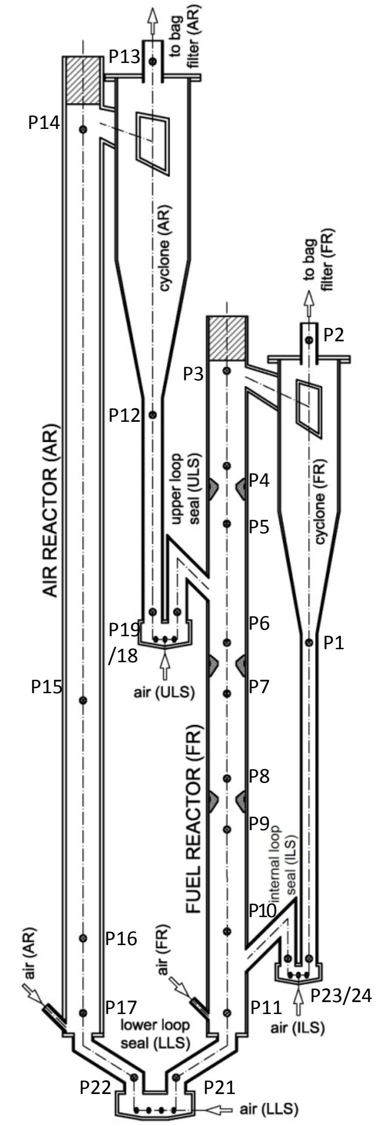

Figure 3: Sketch of the cold flow model including rings.

The present study was carried out in a cold flow model previously designed and built for the fluid dynamic analysis of a 120 kW chemical looping pilot rig for gaseous fuels. The model is a 3:1 scale of the hot unit and was dimensioned based on data of the hot facility and according to Glicksman criteria (7); these principles allow the transformation of the results from the model to the pilot plant conditions. A basic fluid dynamic description of the system was previously carried out, in which influence of main parameters, namely fluidization velocities and inventory, were characterized (8).

Figure 3 presents the configuration of the experimental rig. The most important parameters are listed for both, hot and cold units in Table 1. Compressed air was used as the fluidization agent for all fluidization points. The air flows were regulated by means of several rotameters and fed to the different fluidization points, namely, primary and secondary air injection of both, air and fuel reactors, as well as upper, lower and internal loop seals. Bronze powder, with a mean diameter of 64 µm was selected as the bed material. Elutriated particles from each reactor are separated by independent cyclones and each stream passes through a filter before leaving the unit.

Parameter	Dimension	AR_H	FR_H	AR_C	FR_C
η_G	Pa·s	$4.7\cdot10^{-5}$	$4.1\cdot10^{-5}$	$1.79\cdot10^{-5}$	$1.79\cdot10^{-5}$
ρ_G	$kg\cdot m^{-3}$	0.316	0.288	1.22	1.22
U	$m\cdot s^{-1}$	7.32	2.08	4.25	1.21
ρ_P	$kg\cdot m^{-3}$	3200	3200	8730	8730
d_P	µm	161	161	64	64
Φ	-	0.99	0.99	1.00	1.00
D	mm	150	159	50	54

Table 1: Main fluid dynamic parameters in hot (H) and cold (C) units.

Three identical rings (Figure 2) were inserted in the secondary reactor of the cold flow model at the positions indicated in Figure 3. Different operating conditions were tested in order to determine the effect of the internals on pressure profiles of the system as well as on global and internal solids circulation rates.

Pressure was recorded at 9 positions along the height of the secondary reactor. Circulation rates were calculated based on the accumulation velocities of particles measured in each of the downcomers after interruption of fluidization gas flow in the corresponding loop seal; ULS for global circulation rate and ILS for internal circulation rate.

RESULTS AND DISCUSSION

Inherent Pressure Drop of the Unit with Rings

Pressure along the empty unit was measured under several aeration velocities. Pressure pro files are presented in Figure 4. The pressure drop expected to appear in the places were rings were installed, was very slight or even nonexistent. This supports the statement that for the type of rings and the aeration velocities used here, the influence of the rings on the pressure profiles due to extra resistance to the up-flowing gas stream might be low.

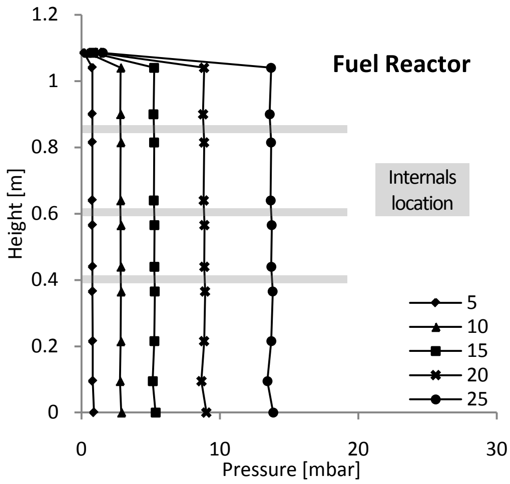

Figure 4: Pressure profile of FR with no bed material for variation of fluidization between 5 and 25Nm^3/h.

Effect of Internals on Pressure Profiles

Figure 5 presents a comparison of pressure profiles for the unit with and without internals at standard operating conditions, 30Nm³/h in AR and 10Nm³/h in FR. This profile is especially interesting since it exhibits a comparable total pressure drop in FR with and without rings. Here it can be seen that pressure profiles of AR are hardly altered after installation of rings. In the FR, a notable increment in pressure is seen for the profiles with rings, particularly in the lower part of the column; while in the top, pressures appear to be very similar for both profiles. It can be said then, that for a similar total pressure drop along the FR (which would also mean, similar total particles hold up), pressure drop, and hence particles, are redistributed upwards in the column.

A relatively larger pressure drop is observed across ring positions than along the length between them, the effect is more important as lower is the ring located, it is, as more concentrated is the bed. Since, no important pressure drop was found to be caused by the presence of the rings themselves (Figure 4), this pressure drop would be then due to accumulation of particles visually observed in the regions right above the rings. This tendency has been also found by Jiang et al. 1991 (9) and Zhu et al. 1997 (5). The observation that the pressure drop occurs across the ring while solids density is high above it, could be explained by the obvious

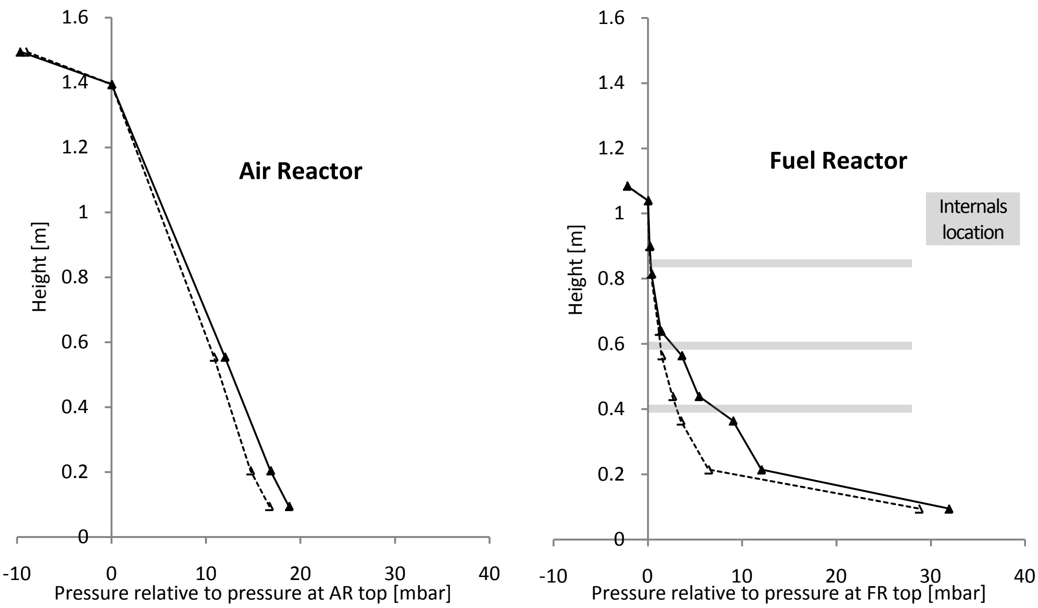

Figure 5: Pressure profiles for operation at 10Nm^3/h in FR and 30Nm^3/h in AR; with (solid line) and without (dotted line) rings. 4kg inventory, 1.0 Nm^3/h fluidization in LLS, 1.0Nm^3/h fluidization ULS and 0.6Nm^3/h fluidization in ILS.

acceleration of the solids in the area of the ring. The acceleration phenomena cause a deviation of the pressure profile and solids concentration in the vicinity of the internals. Zhu et al 1997 (5) described a detailed flow structure around the internals as follows: "particles have the tendency to form a relatively dense region above the rings under high solids circulation rates, the hold-up of this relatively dense region increases with the solid circulation rate and decreases with the distance from the ring, this hold-up region is besides, denser at lower gas velocities. The tendency to form a dense region depends also on the open area, a wider ring with relative smaller open area provides, more "protected" space for the solids to form a dense region".

Experiments in the modified model were performed varying systematically AR and FR fluidization gas flow rates. Figure 6 shows pressure profiles of the unit with and without rings for a fluidization gas rate of 30Nm³/h in AR and variation of fluidization rate in FR. In general, some effects of variation of FR fluidization gas flow rate on the pressure of the unit are preserved whether the rings are installed or not; namely:

- Pressure profile of FR is erected as the fluidization gas flow is increased, since higher fluidization velocities carry higher amounts of particles to upper sections of the reactor.
- Neither the pressure in AR nor in LLS undergo important modifications due changes in FR fluidization gas flow as long as the latter is kept in lower values. Strong fluidization in FR (see profile for 15Nm³/h) leads to accumulation of particles in ILS-downcomer and consequent decrease of pressure in LLS as well as in both reactors. The effect is intensified if the AR fluidization velocity in reduced (Figure 7).

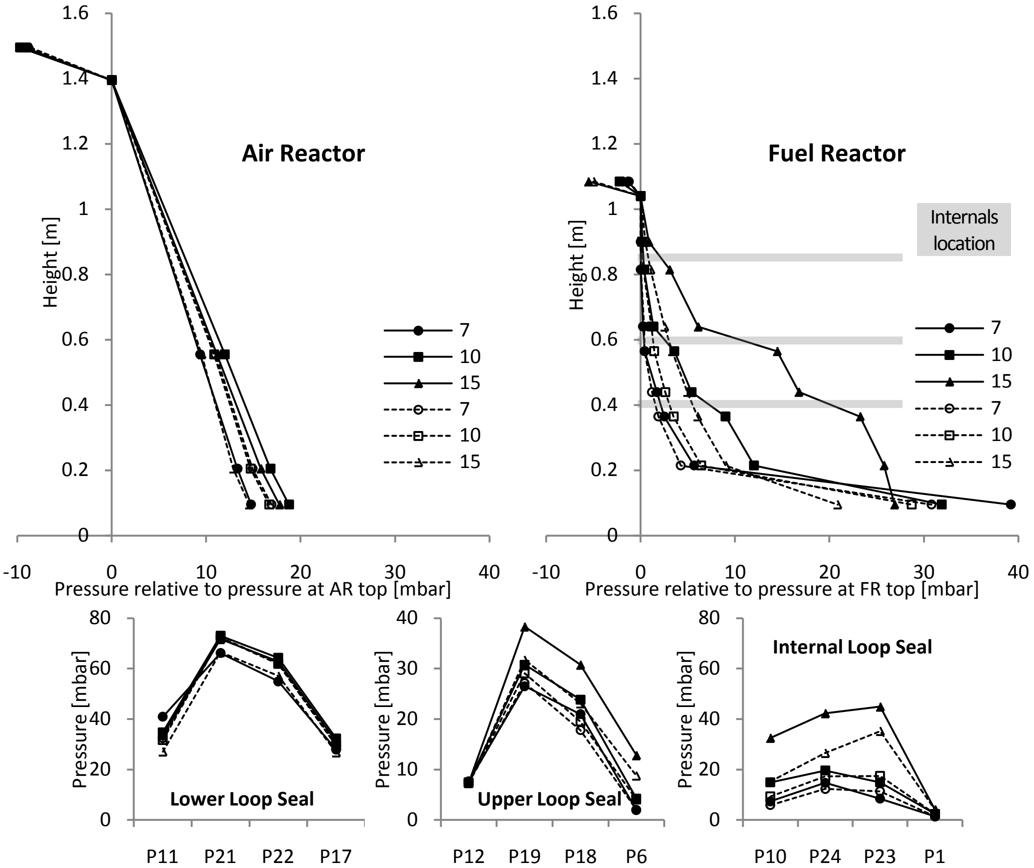

Figure 6: Pressure profiles for operation at 30Nm³/h constant in AR and variation between 7 and 15Nm³/h in FR. 4kg inventory, 1.0Nm³/h in LLS,1.0Nm³/h in ULS and 0.6Nm³/h in ILS. With rings: solid lines, without rings: dotted lines.

- Pressures of ULS and ILS are increased with the increment of FR fluidization gas flow, in the first case, as a consequence of the increased pressure in the discharge branch, and in the second due to increment of elutriation from FR.

However, the increase of pressure in FR due to the presence of rings has an interesting influence on the ILS, since a higher pressure difference needs to be overcome. Especially at low FR fluidization gas low rates (with very low circulation rates), ILS does not reach a desirable operation state, and for high FR fluidization gas flow rates, where enough circulation occurs, pressures in ILS are higher for the unit with rings. Pressure profiles prove as well, the increment of total pressure difference in the FR for every set of conditions, caused by the installation of rings; which indicates a general increment of hold up in this reactor.

Figure 7 presents a comparison of pressure profiles for the unit with and without rings at $20Nm^3/h$ in AR and variation of FR fluidization velocity. Comparing with Figure 6, where the AR fluidization gas flow and thus the solids circulation between AR and FR was higher; it can be seen that even preserving the tendencies valid for the unit without rings with changes in AR fluidization velocity (it is, redistribution of pressure drop in the AR riser and increment of pressure in ULS), the presence of the rings makes the FR more sensitive to changes in the AR fluidization gas rate. In Figure 8, pressure profiles for different inventories are shown for the unit with internals, the expected increments in pressure drop due to increased inventory are observed in both reactors.

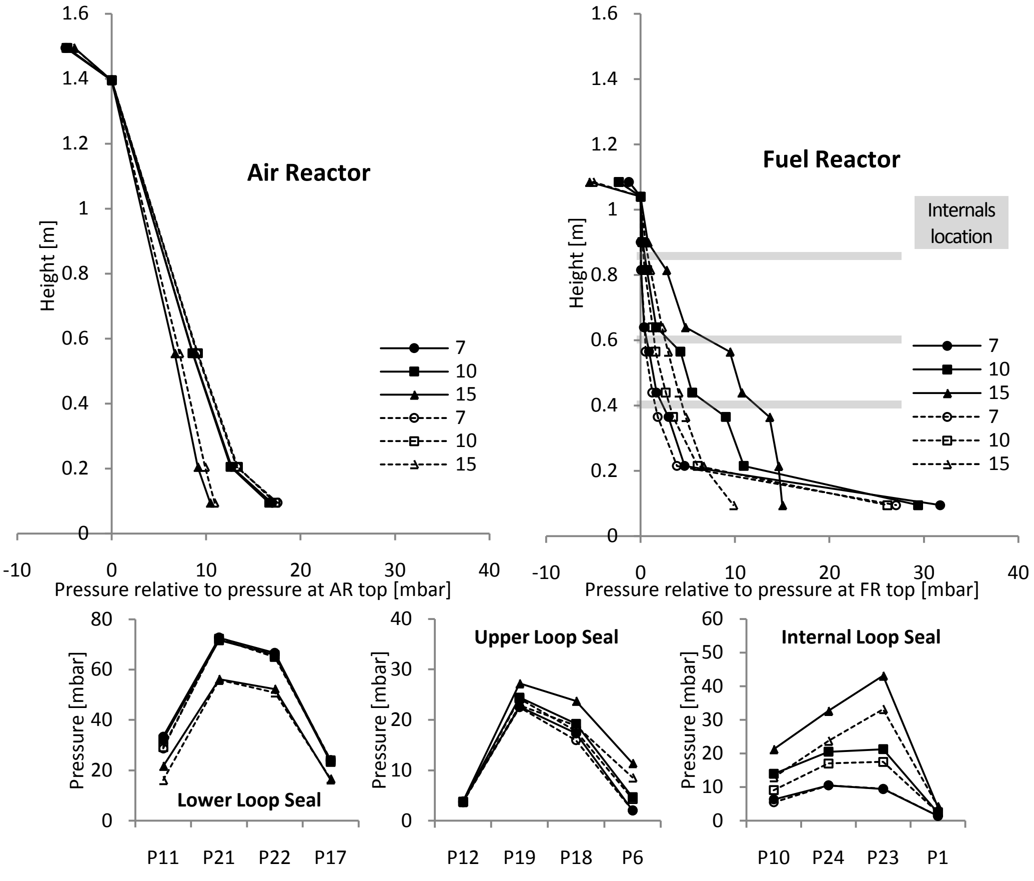

Figure 7: Pressure profiles for operation at $20Nm^3/h$ constant in AR and variation between 7 and $15Nm^3/h$ in FR. 4kg inventory, 1.0 Nm^3/h in LLS, $1.0Nm^3/h$ in ULS and $0.6Nm^3/h$ in ILS. With rings: solid lines, without rings: dotted lines.

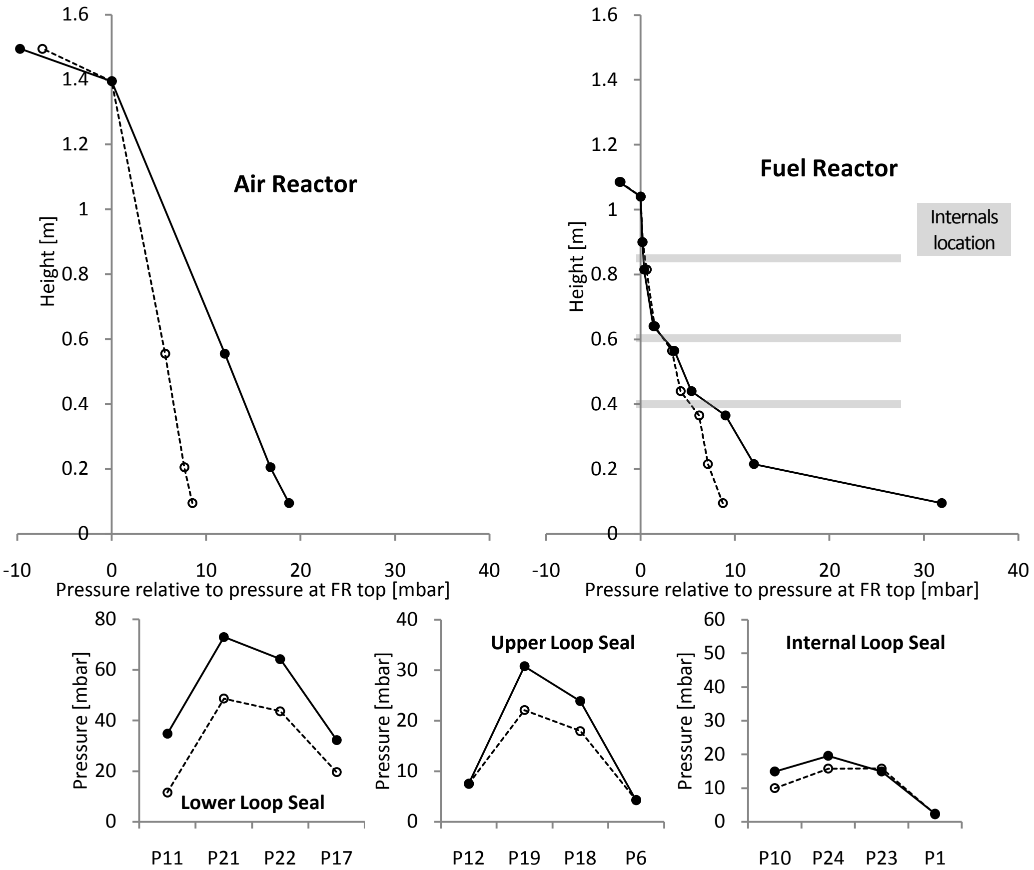

Figure 8: Pressure profiles operation (with rings) at 10Nm^3/h in FR and 30Nm^3/h in AR for variation of inventory between 3kg (dotted line) and 4kg (solid line). 1.0 Nm^3/h in LLS, 1.0Nm^3/h in ULS and 0.6Nm^3/h in ILS.

Effect of Internals on Circulation Rates

Given the increased pressures in both ULS and ILS after installation of rings, global and internal circulation rates are expected to be raised. This can be confirmed in Figure 9, the increments are proportional to the fluidization rates, it is, larger differences appear for higher fluidization gas flow rates. However, at 15Nm^3/h of fluidization gas flow in FR, the increase of the internal circulation rate and the accumulation of material in FR-downcomer reduce dramatically the concentration of particles in the rest of the system (as already seen in the profiles) and

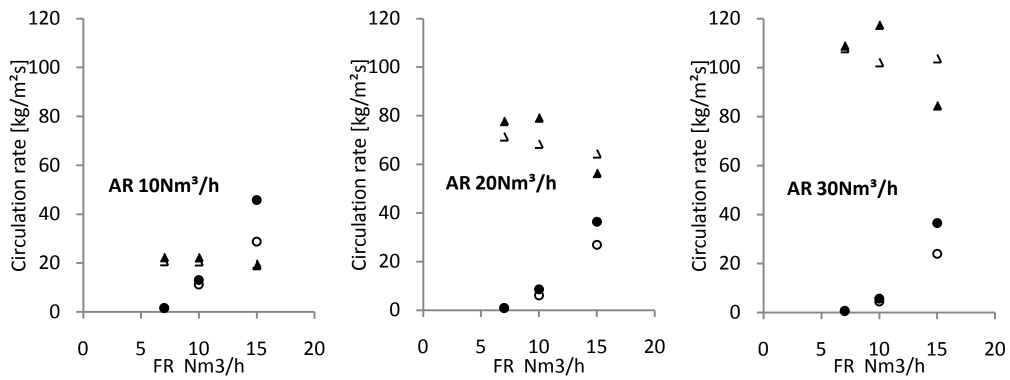

Figure 9: Global circ. rate (triangles Δ) and internal circ. rate (circles O) with variation of FR fluidization for different values of AR fluidization. Comparison between operation with (solid markers) and without (empty markers) rings in FR. 4kg total inventory.

hence the global circulation rate. The balance between global and internal circulation rates should be thus better considered in the unit with internals. It must be additionally indicated that at stronger fluidization rate in FR, high elutriation was observed.

CONCLUSION

The designed rings with wedge-shaped section installed in the secondary reactor of a DCFB cold flow model were found to be effective on increasing the inventory in this section and improving the contact between solid and gas phases by reducing the typical radial solids concentration non-uniformities. After comparison of pressure profiles and circulation rates between the unit with and without rings it can be affirmed that the pressure in the FR has been increased and redistributed after installation of rings; total pressure drop is also increased, meaning an increment in total hold up in this reactor. Particularly high pressure drops are observed across the sections were rings were installed, which can be attributed to the reacceleration of particles in these segments after the bed material is scrapped from the wall and directed to the core zone by effect of the rings. Slightly higher internal circulation rate as well as the corresponding pressure increase in ILS was observed in the unit with rings. Additionally, the influence of the aperture ratio of rings will be studied in further work.

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NOTATION

AR	Air Reactor	Fr	Froude Number, [-]	ULS	Upper Loop Seal
Ar	Archimedes Number, [-]	g	grav. acceleration, [m·s^{-2}]	$\dot{V}$	normal vol. flow, [Nm^3·s^{-1}]
D	inner riser diameter, [m]	ILS	Internal Loop Seal	Φ	mean sphericity of part., [-]
d_P	mean particle diameter, [m]	LLS	Lower Loop Seal	η	dynamic viscosity, [Pa·s]
DCFB	dual circulating fluidized bed	Re_P	particle Reynolds N., [-]	ρ	density, [kg·m^{-3}]
FR	Fuel Reactor	U	superficial gas velocity,[m·s^{-1}]		

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