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Hydrodynamic Behaviour of Solid Transport for a Closed Loop Circulating Fluidized Bed with Secondary Air Injection

Jonghoon Kim†

Nuclear Fuel Cycle Research Group, Korea Atomic Energy Research Institute, 150 Dukjin-dong, Yousung-gu, Taejon 305-353, Korea

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Abstract−The aim of this work was to study the mechanism of solid circulation in a Circulating Fluidized Bed pilot as a function of secondary air flow rate. A rectangular column of 7 m height equipped with a U type siphon was used for this purpose. The results obtained showed that the solid circulating phenomenon depends on different limiting steps like feeding step (dense bed), siphon circulating capacity and suspension saturation capacity.

Key words: Circulating Fluidized Bed, Hydrodynamics, Solid Flow Rate, Secondary Air Injection

INTRODUCTION

There are actually very few existing theories concerning the solid flow rate in a closed loop CFB (Circulating Fluidized Beds). By <Closed Loop> we mean that solid circulating rate is free and can be only cut flow rate measurements. While in an <Open Loop> configuration, an intermediate hopper is used to control the solid feed rate. CFB reactors used in coal combustion processes are generally of <Closed Loop> type.

These reactors always have a secondary air feed, introduced some meters above the fluidization grid, in order to control the combustion quality and reduce NO_x production. However, the division of total air flow to primary and secondary air, affects the flow structure at the lower level of the reactor. Few workers have studied the effect of secondary air on the flow structure [Wang et al., 1991; Arena et al., 1993; Cho et al., 1994].

In a previous work [Aguillon et al., 1995], we discussed the hydrodynamic behaviour of open loop circulating fluidized beds with secondary air injection. We concluded that in this case the rate of secondary air injection (compared to total air) modifies slightly the flow pattern at the stabilized region (above 3 m height) of the CFB.

In the present work, however, we show that for <Closed Loop> CFB the distribution of air feed at primary or secondary position strongly affects the flow properties and the solid circulating flow.

EXPERIMENTAL

Fig. 1 shows the CFB unit used in this work. The pilot unit has been described in detail for the open loop CFB [Aguillon et al., 1995]. We recall here some general aspects of the set-up after changing the circulating system from an open loop to closed loop CFB.

The column has a rectangular 0.286×0.176 m cross section and is 7 m high. The solid flow rate is measured separately in a solid return line. The column is equipped with Plexiglas windows and 36 pressure taps. Gas and solid are separated by a primary charged cyclone, a secondary standard cyclone and a set of filters. Solid particles are fed through a standpipe with a siphon for controlling the flow rate. In addition to the geometrical similarity between the pilot and CFB combustors, we use cracking catalyst (mean particle size of 68 microns and density of 1,100 kg/m^3) at ambient temperature to operate at similar Archimedes numbers and similar solid concentrations. The fluidization air can be distributed between the primary or the secondary air injections. The industrial operating conditions correpond to 2/3rds of the total air to the secondary air injection

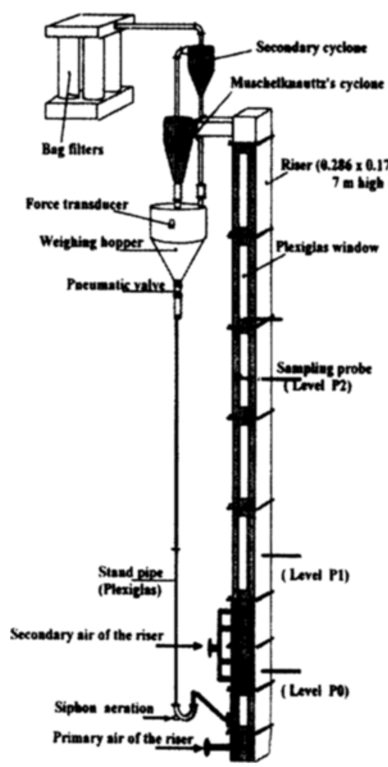

Fig. 1. The circulating fluidized bed pilot.

†To whom correspondence should be addressed.
E-mail: njhkim2@nanum.kaeri.re.kr

and only 1/3rd to the primary air injection.

A siphon is used in the return line in order to establish the pressure drop between the bottom of the fluidized bed and the air exit at cyclone level. The siphon is found to be a limiting step for high fluidized velocities.

Solid circulating flow rate is measured by means of an external weighted hopper. Note that this measurement technique needs the external line to be cut. However, the variation of hopper weight remains linear during 10 to 15 seconds (before the column concentration begins to decrease), where the slope of changing weight gives the solid flow rate. The measurement error is found to be less than 10%. The only problem with this technique is that after each measurement, the pilot needs about 15 minutes to regain the stationary operating conditions.

Local solid concentration and particle velocities are measured by means of <Optical Fibers> at three different levels (P0, P1 and P2 on Fig. 1). These measurements give useful information about the structure of the solid flow and allow us develop some of our hypothesis presented in this work. However, to avoid being too long, these results are not discussed here and will be presented in future.

RESULTS AND DISCUSSION

Among different variables of the system, the gas velocity 'Ug' (total air flow/column cross section), secondary air/total air ratio 'SA/TA' and solid inventory 'M' are chosen as initial variables, and the effect of their variation on the solid circulating rate and on the solid concentration in the column is studied. Solid local and mean velocities are measured as well in the column. However, we will limit here our discussion to the first three variables.

Fig. 2 shows the variation of solid circulating flow rate and solid mean concentration as a function of air velocity in the column. From this figure, it can be seen that for low gas velocities, both variables increase linearly, then there is a stagnation zone (circulating rate decreases even slightly), then they increase again.

The solid flow seems to be regular at the first zone (probably because of pressure fluctuation in the column). At higher velocities the flow structure changes again and it becomes regular again. This third zone, however, could not be fully studied because of gas velocity limitation.

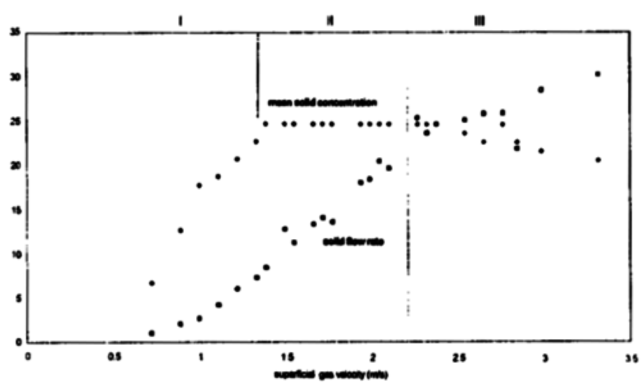

Fig. 2. Variation of solid circulating flow rate and solid mean concentration as a function of gas flow rate, with M=27 kg and SA/TA=0.

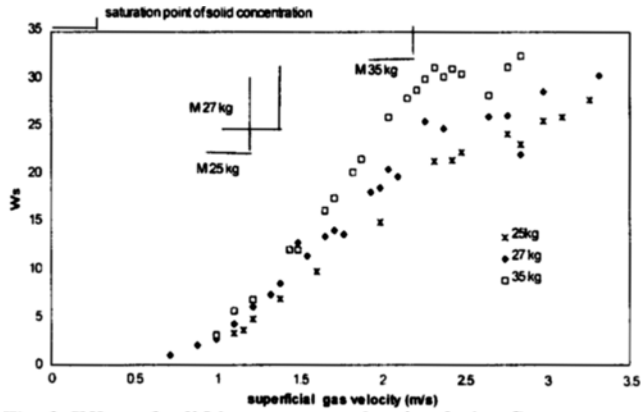

Fig. 3. Effect of solid inventory on the circulating flow rate.

Similar results are obtained at lower solid inventory. These results are shown in Fig. 3, where we note that the circulating flow rate is higher solid inventories. Note that the global form of the curve is independent of the solid inventory and similar zones can be defined again on these curves. The transition velocities are the same in all cases (2.3 m/s and 3 m/s respectively) between zone I-zone II and zone II-zone III.

As we mentioned at the beginning of this paper, the main goal of this work was to define the effect of secondary air on the circulating flow rate. Fig. 4 shows the variation of solid circulating flow rate as a function of gas velocity at different SA/TA ratios.

Fig. 4 is an important diagram that is obtained from different series of measurements. Note that the solid flow rate is null if all of the air is injected into the secondary level (SA/TA=100%) and values at SA/TA=0 are a part of results already shown on Fig. 2.

It can be seen from this diagram that putting air to the secondary level (rather than primary level) causes a decrease in the circulating flow rate. This means that the main controlling step of solid transport in the column is at the dense to dilute bed transport.

At very low velocities, a slight distribution of air at secondary level seems to improve the circulating rate, probably because it prevents some clusters ejected from dense to dilute bed to fall down.

Finally, to verify the role of secondary air at constant primary air feed (which means that the lower dense bed feeds the

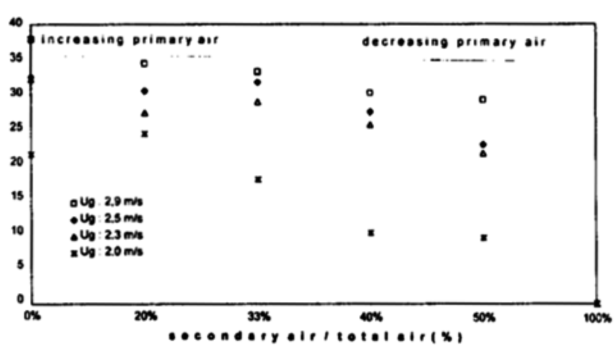

Fig. 4. Effect of secondary air on solid flow rate (M=27 kg).

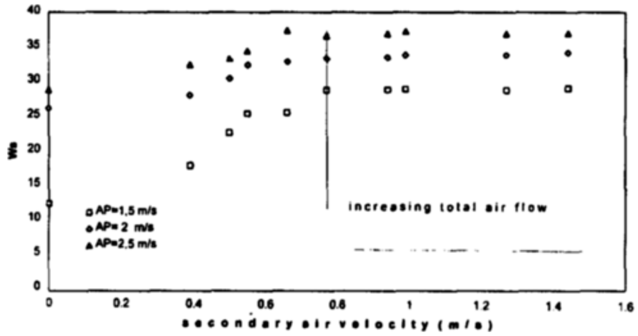

Fig. 5. Solid flow rate as a function of secondary air at different primary air.

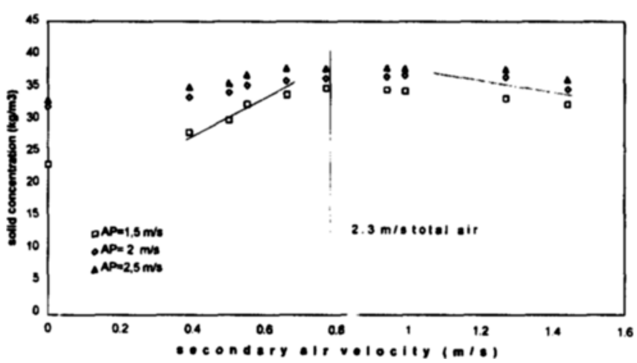

Fig. 6. Solid mean concentration in column as a function of secondary air injection and at different primary air.

upper dilute bed by a constant rate of solid cluster), solid flow and sold concentration are measured as functions of additional secondary air.

These results are shown in Figs. 5 and 6. The results in Fig. 5 show that solid flow rate increases and reaches a limit value as the secondary air increases (this is independent of the primary air flow rate varying from 1.5 to 2.5 m/s). Solid concentration, however, increases first, with the rise in secondary air, then decreases slightly for higher values of secondary air.

The analysis of the above results lets us consider that the lower dense bed behaves as a solid feeder to the upper dilute bed. As some solid clusters fall down (especially near the wall), a secondary air feed prevents some clusters from falling back into the dense bed and gradually improves the solid transfer between two parts. Nevertheless, the final value of solid flow rate cannot overpass the upward solid flow produced by the lower bed. Again for solid concentration, it increases in the first part of the diagram (Fig. 5), then decreases because the solid flow rate becomes constant, but the solid mean velocity continues to increase because of increasing gas velocity (we remember that the secondary air is fed in addition to the primary air so that the total air flow increases).

CONCLUSION

The aim of the present work is to explain the mechanism of solid transport through closed loop Circulating Fluidized Beds. In the results obtained, we can conclude that the lower part of the bed behaves as a feeder to the upper part. Meanwhile, the upper part of the bed (the dilute bed) has a limited capacity in solid concentration and then discharges a part of the solid fed by the lower part in the column. Fig. 7 shows very well the mechanism of solid transport in a closed loop CFB. Firstly, the solid flow rate is only controlled by the primary air that imposes the main solid (upward) flow F^+.

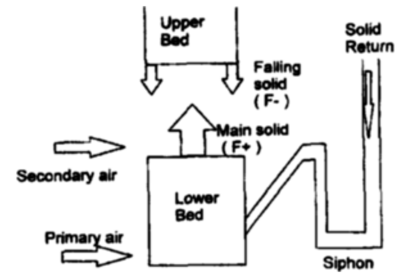

Fig. 7. Mechanism of solid transport in a closed loop CFB with secondary air feed.

The secondary part of air can only affect the downward solid flow F^- that decreases with a rise in secondary air.

The definition of an empirical correlation, giving solid flow rate as a function of other variables doesn't seem to be useful for these complicated systems. This rule must be defined by writing a complete set of force balance equations that will be the subject of a future publication.

NOMENCLATURE

F^+ : upward solid flow from lower to upper bed [kg/s·m^2]
F^- : downward solid flow from upper to lower bed [kg/s·m^2]
M : solid inventory in the column [kg]
PA : primary air flow rate [m/s]
SA : secondary air flow rate [m/s]
TA : total air flow rate [m/s]
Ug : mean gas velocity [m/s]
Ws : solid flow rate [kg/s·m^2]

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