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EFFECT OF DISTRIBUTOR DESIGN ON SOLIDS CIRCULATION AND GAS BYPASS IN AN INTERNAL CIRCULATING FLUIDIZED BED REACTOR

Xiaotao T. Bi* Terris T. Yang†

*University of British Columbia, xbi@chml.ubc.ca
†Honeywell International, Buffalo, NY

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Terris T. Yang[#] and Hsiaotao T. Bi*
[#]Honeywell International, 20 Peabody St., Buffalo, NY 14210, USA.
*Department of Chemical & Biological Engineering, University of British Columbia, Vancouver B.C. V6T 1Z3 Canada
T: 1-604-822-4408; Fax: 1-604-822-6003; E: xbi@chbe.ubc.ca.

ABSTRACT

The effect of the distributor design on the gas bypass and solids circulation was investigated for the flat, cylindrical and conical gas distributors in a cold model internal circulating fluidized bed to provide design and operating criteria for the future application of ICFB deNO_x reactor. A high gas bypass ratio from the annulus to draft tube and low from the draft tube to annulus were identified for all tested distributors. The solids circulation rates increased with the increase of both annulus and draft tube gas velocities, where the conical distributor exhibited a more flexible and stable operation. The particle size and the reactor configuration exhibited significant effects on the operating characteristics of the hot model ICFB reactor.

INTRODUCTION

In recent years, the selective catalytic reduction of NO_x by hydrocarbons (HC-SCR) has gained extensive attention from academic as well as industrial research groups due to the increasingly stringent emission regulations on NO_x all over the world. As reported, the catalytic activity of most HC-SCR catalysts is severely inhibited by the presence of excess O_2 in the flue gas (1). To mitigate the negative impact of the poisoning components and excess O_2 in the flue gas, a new concept of an integrated NO_x adsorption-reduction process was proposed and reported in our previous paper (1). A fluidized bed reactor with a draft tube, or so called the internal circulating fluidized bed (ICFB) reactor was designed to implement this concept for the flue gas NO_x reduction with the schematic shown in Figure 1, where the annulus was used as the adsorption zone and the draft tube as reduction zone.

The ICFB reactor with different configurations has been studied extensively (2-4). For the proposed ICFB reactor in HC-SCR, the presence of oxygen in the reduction zone (draft tube) is essential but must be controlled within an appropriate range in order to keep the O_2 concentration at a relatively low level (1). On the other hand, gas bypass from the reduction zone to the adsorption zone will cause an increase in the consumption of the reducing agent in the dual-zone reactor, which should be minimized. In addition, the solids circulation rate will be directly linked to the transfer of the adsorbed NO_x from the adsorption zone to the reduction zone and the NO_x reduction in the reaction zone of the reactor.

As reported by Yang and Keairns (5), the gas bypass ratio and solids circulation rate are significantly affected by the type of gas distributor in the operation of ICFB reactor. In order to provide design and operating criteria for the future application of the ICFB reactor in the treatment of the flue gases from stationary combustion processes, a cold model ICFB reactor was constructed to evaluate the effect of several types of gas distributors on the hydrodynamic performance of the ICFB reactor. Meanwhile, a hot model ICFB reactor was built to investigate the effectiveness of the ICFB reactor.

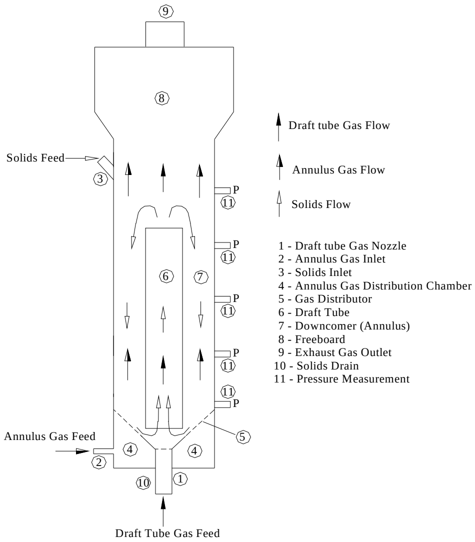


Figure 1. Schematic of the ICFB reactor

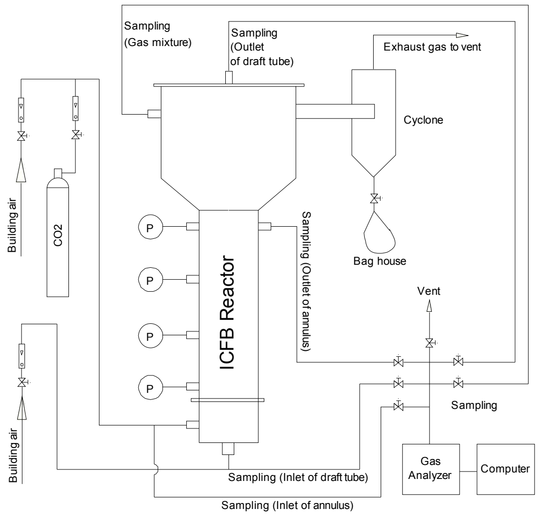


Figure 2. Schematics of the cold model ICFB system

EXPERIMENTAL SECTION

The cold model ICFB system is shown schematically in Figure 2. The geometry of the cold model ICFB unit was developed based on the design criteria described by Yang (6) in order to achieve high solids circulation rate and retain certain degree of gas bypass between the draft tube and the annulus regions. The ICFB reactor unit was made of Plexiglas, with an inner diameter of 102 mm and a length of 1092 mm. A draft tube (50.8 mm I.D., 63.5 mm O.D. and 1016 mm high) was allocated in the center of the column. The bed material used in the experiment was millet with a particle density (ρ_p=837 kg/m^3) and average particle size (d_p=1.1 mm) similar to the Fe/ZSM-5(PUC) catalyst used in the fixed bed experiment (1). The building air was used as the fluidizing gas. Pure CO_2 from Praxair was used as the tracer gas to study the gas bypass.

In the experiment, the building air was injected into the draft tube via the gas nozzle and the gas flow rate was adjusted to have the draft tube region operated at a pneumatic transport condition to carry particles upward to create a continuous circulation of the particles between the annulus and the draft tube. At the same time, the mixture of the building air and the tracer gas was introduced into the annulus or down-comer region through the gas chamber and the annulus gas distributor. The flow rate was controlled to keep the annulus region being operated at the moving bed or minimum fluidization condition. Flow rates in both the draft tube and the annulus were adjusted to investigate the gas bypass between the two regions and the solids circulation from the annulus to the draft tube. Gas compositions at the inlet of the annulus gas chamber, the inlet of the gas nozzle, the outlet of the draft tube, the outlet of the annulus, and the gas mixture in the freeboard region were measured by a Horiba PG-250 flue gas analyzer.

Three types of annulus gas distributors, a flat plate, a cylindrical plate and a conical plate, as shown in Fig. 3, were tested to investigate the hydrodynamic performance of the ICFB reactor. All three perforated distributors had the same opening ratio of 2.1% for easy comparison of the experimental results. The gas nozzle for the flat and conical gas distributor was the same, with 34.9mm I.D. and 38.1mm O.D. To plug the draft tube into the cylindrical distributor and keep the same area ratio of the distributor, the size of the draft tube was reduced to 38.1mm I.D. and 44.5mm O.D in the experiment with the cylindrical gas distributor.

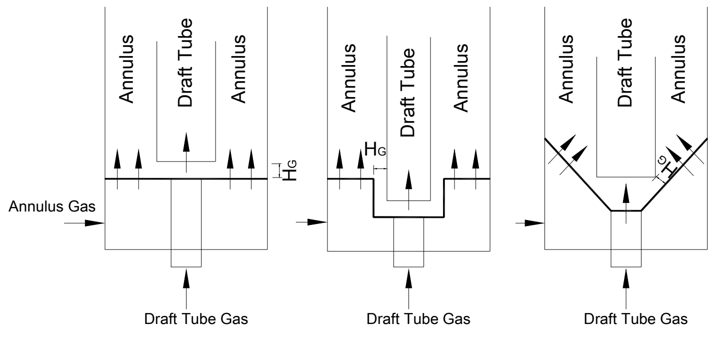


Figure 3. Configuration of gas distributors

At given operating conditions, continuous CO_2 tracer was injected into the inlet gas flow of the annulus. With CO_2 concentrations at the outlet of the draft tube and the annulus, and the inlet of the draft tube and the annulus being analyzed and recorded, the gas bypass between the draft tube and the annulus was evaluated by mass balance method over the CO_2 tracer gas. The solids circulation rate was measured by the visual observation method based on the travel velocity of colored millet particles along the outer wall of the annulus and the assumed packed bed voidage in the annulus region. The effective gap opening (H_G) (as shown in Figure 3) between the draft tube and the gas distributor for the solids circulation was set to 10mm in all cases.

Based on the cold model experimental results, a hot model ICFB reactor with a conical gas distributor was built to investigate the NO_x reduction performance. The gas bypass between the draft tube and the annulus could be evaluated based on O_2 balance instead of CO_2. In the experiment, building air was diluted by pure N_2 to form the annulus gas flow, while pure N_2 was used as the draft tube gas flow. Two kinds of catalysts were investigated in the hot model experiment, i.e., coarse Fe/ZSM-5(PUC) particles with an average particle diameter of 1042 μm and fine Fe/ZSM-5(Albemarle) particles with an average particle diameter of 155 μm.

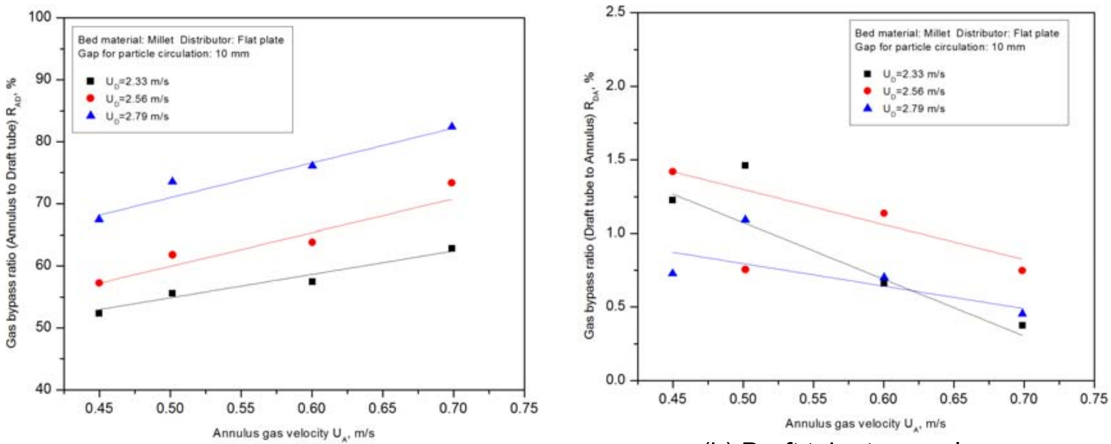
RESULTS AND DISCUSSION

Gas bypass and solids circulation in the cold model experiment

Effects of gas velocities in the annulus (U_A) and the draft tube (U_D) on the gas bypass from both the annulus to the draft tube (R_{AD}) and the draft tube to the annulus (R_{DA}) for all three tested gas distributors in the cold model experiment are shown in Figures 4 to 6.

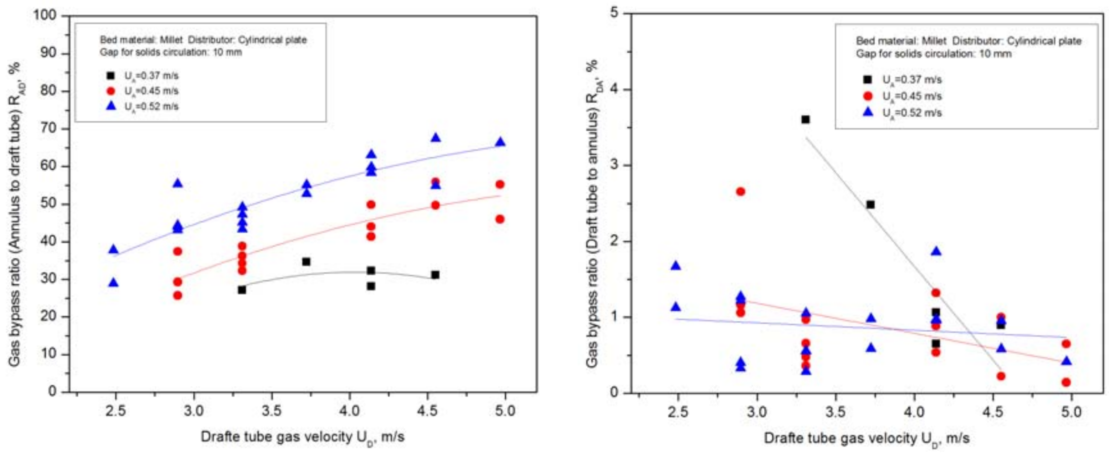
Within the range of tested gas velocities, the ICFB with a flat distributor plate showed more than 50% of gas bypass from the annulus to the draft tube (R_{AD}) (Figure 4(a)), but less than 1.5% from the draft tube to the annulus (R_{DA}) (Figure 4(b)). R_{AD} increased with the increase of both U_A and U_D. Although R_{DA} decreased with the increase of U_A at a given U_D, there was no clear trend with respect to the effect of U_D on the gas bypass at a given U_A (see Figure 4(b)). One should note that R_{DA} values were very small and could be associated with significant measurement errors. It was observed that, because of the high gas bypass from the annulus to the draft tube, insufficient gas was supplied to the annulus. As a result, particles could not be stably circulated if the annulus gas velocity was lower than 0.45 m/s.

For the cylindrical gas distributor, at a low annulus gas velocity (U_A=0.37 m/s), the draft tube gas velocity (U_D) showed less influence on the gas bypass ratio from the annulus to the draft tube (R_{AD}) (Figure 5(a)). However, the increase of U_D decreased the gas bypass from the draft tube to the annulus (R_{DA}) effectively at U_A=0.37 m/s (Figure 5(b)). Further increase of U_A to 0.45 m/s resulted in an increase of R_{AD} by 5%~15%, while R_{DA} dropped to lower than 1.5% in most cases for the U_D range of 3.31 to 4.55 m/s. R_{AD} increased by another 15% with R_{DA} remaining at around 1% when U_A increased from 0.45 to 0.52 m/s.



(a) Annulus to draft tube (b) Draft tube to annulus

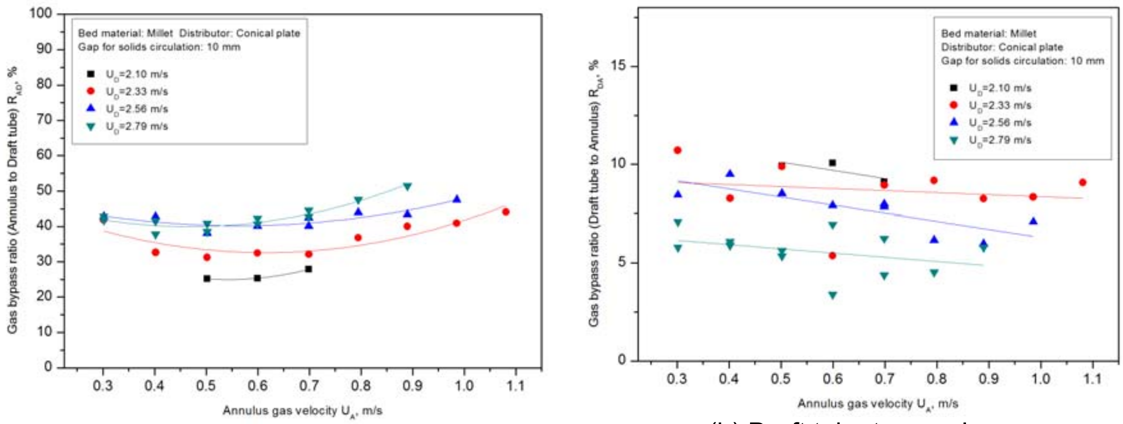
Figure 4. Effect of gas velocities on gas bypass (Flat distributor, H_G=10 mm)



(a) Annulus to draft tube (b) Draft tube to annulus

Figure 5. Effect of gas velocities on gas bypass (Cylindrical distributor, H_G=10 mm)

Although R_{AD} increased with the increase of both U_A (>0.37 m/s) and U_D, when compared with the flat distributor (Figure 4(a)), R_{AD} for the flat distributor was always 20~30% higher than for the cylindrical distributor at given U_A and U_D. The change of the annulus distributor showed no significant influence on R_{DA}, which always remained at a very low level in both cases. It is not surprising to see the significant decrease of R_{AD} in Figure 5(a) in comparison to Figure 4(a) in view of the fact that the use of a smaller size draft tube for the cylindrical distributor led to an increase of the annulus cross-sectional area from 4940 to 6556 mm^2, and a corresponding decrease of the draft tube cross-sectional area from 2027 to 1140 mm^2.



(a) Annulus to draft tube (b) Draft tube to annulus

Figure 6. Effect of gas velocities on gas bypass (Conical distributor, H_G=10 mm)

For the conical gas distributor, as seen in Figure 6(a), the increase of U_D increased the gas bypass ratio from the annulus to the draft tube, but not as significantly as the flat and cylindrical distributors. For a given U_D, U_A showed less influence on R_{AD}, with R_{AD} ranging from 20 to 50% over the tested range of gas velocities. Relatively high values of R_{DA} were observed using the conical distributor, ranging from 5~10%, as shown in Figure 6(b). R_{DA} remained almost constant with the variation of U_A at a given U_D, but decreased with increasing U_D at a given U_A.

Effects of gas velocities on the solids circulation rate (W_s) are shown in Figures 7 to 9 for flat, cylindrical and conical distributor, respectively. For the flat distributor (Figure 7), W_s increased with increasing annulus gas velocity (U_A) at a given U_D. Meanwhile, the same tendency was observed for the influence of U_D at a given U_A. However, U_A clearly showed more influence on W_s than U_D. For the cylindrical distributor (Figure 8), at a given U_A, W_s increased with the increase of U_D. For a given U_D, lower W_s was observed at U_A=0.37 m/s. Further increase of U_A beyond 0.45 m/s showed less influence on W_s indicating that W_s was mainly affected by U_D. This trend is different from the flat distributor where W_s was more sensitive to U_A than to U_D (see Figure 7). Moreover, the cylindrical distributor exhibited much higher W_s than the flat one. For example, at U_A=0.52 m/s and U_D=3.26 m/s, W_s was 105 $kg/m^2.s$ and 49 $kg/m^2.s$ for the cylindrical and the flat distributor, respectively. The cylindrical distributor exhibited lower gas bypass from the annulus to the draft tube and relatively higher solids circulation rate than the flat distributor, at given U_A and U_D, as shown in Figure 8. However, as observed in the experiment, constrained by the shape of the cylindrical distributor, the particles could not be circulated at low draft tube gas velocities, which limited the possible operation window of the gas flow rate.

With the conical distributor, W_s increased with increasing the annulus gas velocity (U_A) at a given draft tube gas velocity (U_D), as shown in Figure 10. When U_A reached a certain level, i.e. >0.90 m/s, further increase in U_A had only little influence on W_s. Meanwhile, the same tendency was observed for the influence of U_D at a given U_A. However, the increase of U_A clearly showed more influence on W_s than that of U_D. As observed in the experiment, the conical distributor showed a more flexible and stable operation than the flat and cylindrical distributor in a wide range of velocities for both U_A and U_D.

Since the solids circulation rate was mainly influenced by both U_A and U_D for the conical distributor, and there existed uncertainties on the actual gas velocities inside the draft tube and the annulus because of the gas bypass between the annulus and the draft tube, an overall gas velocity (U), which is defined as the total gas flow rate divided by the total cross-sectional area of the draft tube and the annulus, is introduced here to evaluate its impact on W_s. As shown in Figure 10, W_s increased with the increase of U, and could be well fitted by a 2nd order polynomial equation with most of the data points falling into an error range of ±20%. The same effect of the overall gas velocity on the solids circulation rate was also observed for the ICFB with a cylindrical distributor plate which is not shown here. However, for the flat distributor, the data showed a great scattering with poor correlation between U and W_S.

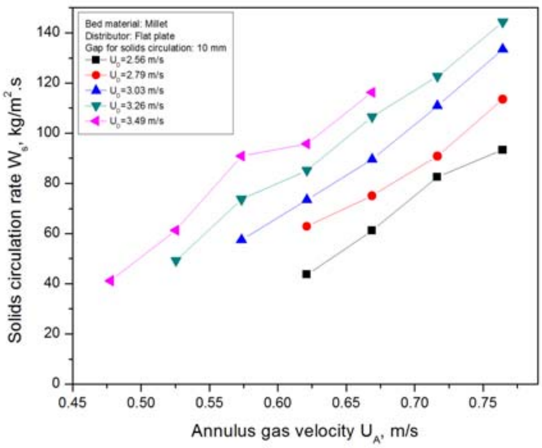


Figure 7. Effect of gas velocities on solids circulation rate (Flat distributor)

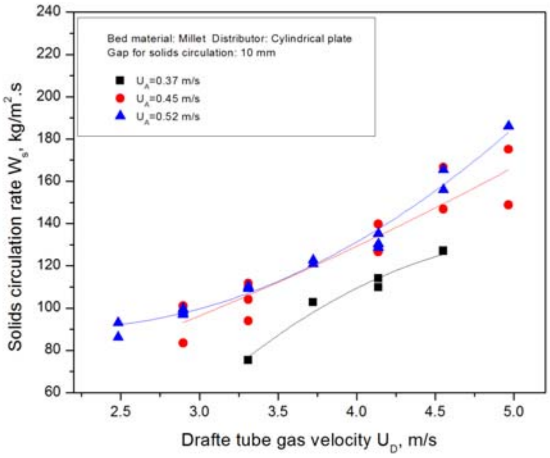


Figure 8. Effect of gas velocities on solids circulation rate (Cylindrical distributor)

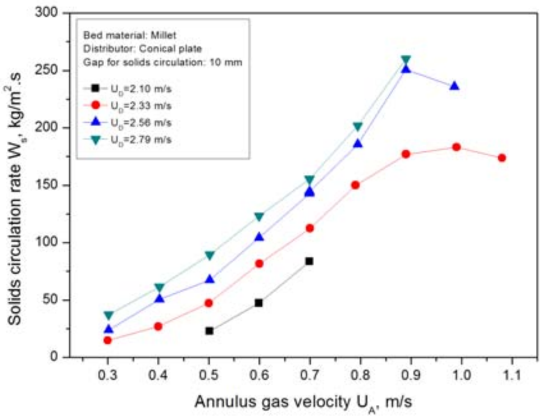


Figure 9. Effect of gas velocities on solids circulation rate (Conical distributor)

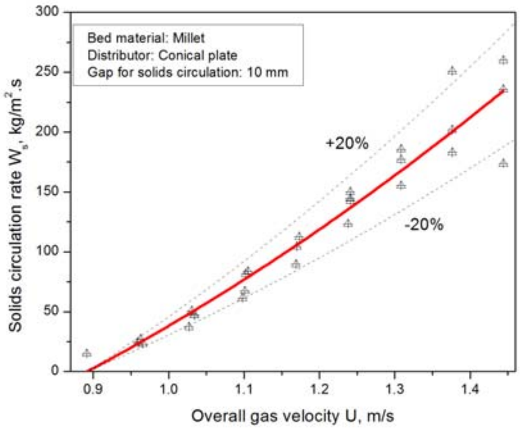


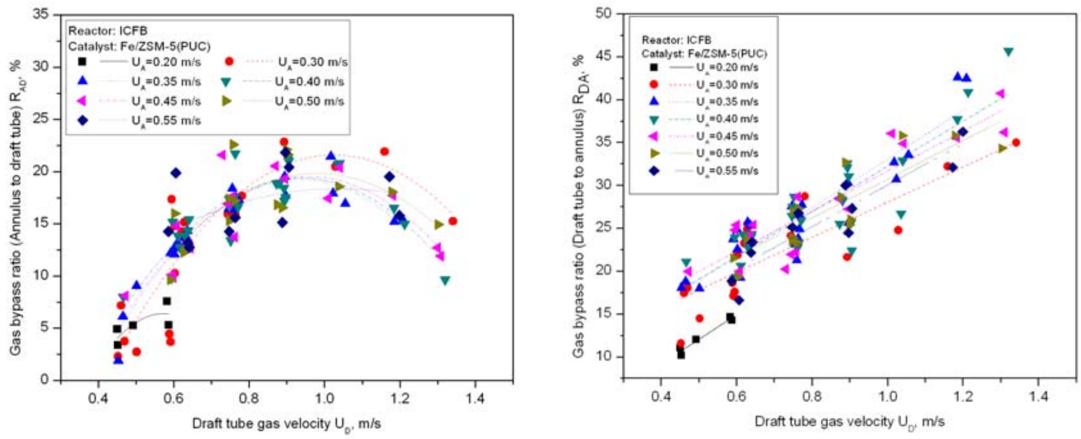
Figure 10. Effect of overall gas velocity on solids circulation with conical distributor

Gas bypass in the hot model experiment

In the cold model experiment, the conical distributor plate exhibited high solids circulation rate, high gas bypass from the draft tube to the annulus and relatively low gas bypassing from the annulus to the draft tube compared to the flat and cylindrical distributor plates. Moreover, the conical distributor plate showed flexible and stable operation within wide ranges of gas velocities for both U_A and U_D. As a result, the conical distributor plate was selected as the annulus gas distributor for the hot model ICFB reactor. To further reduce gas bypass from the annulus to the draft tube, the perforated holes were aligned in parallel to the draft tube or the column wall in the hot model unit instead of in perpendicular to the surface of the conical distributor in the cold model unit.

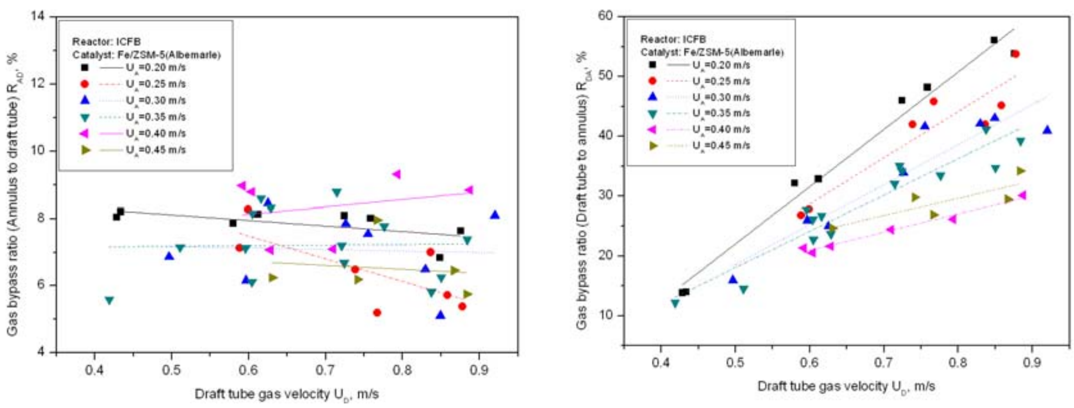
Effects of gas velocities on gas bypass for coarse Fe/ZSM-5(PUC) catalyst in the hot model ICFB reactor are shown in Figure 11. In the range of velocities investigated, the gas bypass from the draft tube to the annulus (R_{DA}) was always higher than that from the annulus to the draft tube (R_{AD}) at given U_A and U_D. For cases with $U_A \geq 0.3$ m/s, with the increase of U_D from 0.45 to 1.30 m/s, R_{AD} increased from 3~7% to a peak value of 17~18% at U_D=0.9~1.1 m/s, then decreased to 10~13% (Figure 11(a)) with further increase in U_D, while R_{DA} increased monotonically from 18% to 40% (Figure 11(b)) with the increase in U_D. For U_A=0.20 m/s, as U_D increased from 0.45 to 0.59 m/s, R_{DA} increased from 11% to 14%, while R_{AD} increased from 4% to 6%. Compared to the effect of U_D, it seemed that U_A had less influence on both R_{AD} and R_{DA}. Furthermore, for a given U_D, there was no clear relationship between U_A and R_{AD} because of the scattering of data.

In comparison with the cold model results, the change of the opening direction of perforated holes on the annulus gas distributor has been demonstrated to be successful in reducing the gas bypass from the annulus to the draft tube. At the same time, R_{DA} was enhanced, which is beneficial for the HC-SCR of NO_x in the adsorption zone.



(a) Annulus to draft tube (b) Draft tube to annulus

Figure 11. Effect of gas velocities on gas bypass (Fe/ZSM-5(PUC), T=350±10°C)



(a) Annulus to draft tube (b) Draft tube to annulus

Figure 12. Effect of gas velocities on gas bypass (Fe/ZSM-5(Albemarle), T=355±15°C)

Unlike Fe/ZSM-5(PUC), the change of both U_A and U_D had almost no effect on the gas bypass from the annulus to the draft tube (R_{AD}) for fine Fe/ZSM-5(Albemarle) particles, which fluctuated in the range of 5~9% as shown in Figure 12(a). This feature could be useful for controlling the O_2 concentration to a desired constant level when the draft tube region is used as the reduction zone. For all cases in Figure 12(b), with the increase of U_D at a given

U_A, the gas bypass ratio from the draft tube to the annulus (R_{DA}) was higher than using Fe/ZSM-5(PUC) (Figure 11(b)), but following a similar trend. As U_A increased, R_{DA} decreased. At U_D=0.45 m/s, the decrease of R_{DA} was not significant, remaining at a level around 14%. With U_D increased from 0.60 to 0.90 m/s, R_{DA} decreased quickly with the increase in U_A. In the gas velocity range of the current experiment, a higher U_A and a lower U_D are preferred in order to control R_{DA} to a relatively low level. The reactor would not work properly if U_D<0.40 m/s and U_A>0.45 m/s.

CONCLUSIONS

The hydrodynamic performance of an ICFB cold model unit was investigated using three types of annulus gas distributors. All distributors showed very low gas bypass from the draft tube to the annulus but high gas bypass at the reverse direction. The increase of both U_A and U_D could enhance R_{AD} for the flat and cylindrical distributor. The increase of U_D increased R_{AD} while the change of U_A showed less effect on R_{AD} for the conical distributor, but the effect of U_D was not as significant as that for the flat and cylindrical distributors. Both U_A and U_D showed marginal effect on R_{DA} for all three distributors. The solids circulation rate (W_s) increased with the increase of both U_A and U_D in all cases, which was found to be well correlated with the combined effect of U_A and U_D for the conical and cylindrical distributors. As observed in the experiment, both the flat and cylindrical distributors showed relatively narrow window of operating gas velocities, while the conical distributor exhibited flexible and stable operation in a wide range of velocities for both U_A and U_D.

Particle size exhibited significant effect on the gas bypass in the hot model experiment. R_{DA} increased with the increase of U_D, and R_{DA} was always higher than R_{AD} for both coarse Fe/ZSM-5(PUC) and fine Fe/ZSM-5(Albemarle) catalysts. At given U_A and U_D, the fine Fe/ZSM-5(Albemarle) gained higher R_{DA} but lower R_{AD} than the coarse Fe/ZSM-5(PUC). The gas bypass ratio of Fe/ZSM-5(PUC) from the annulus to draft tube (R_{AD}) reached a maximum value when the draft tube gas velocity (U_D) was 0.9~1.0 m/s in this study. The change in the direction of perforated holes on the conical distributor in the hot unit reduced the gas bypass from the annulus to the draft tube, but enhanced the gas bypass from the draft tube to the annulus, meaning that the reactor configuration could have a significant impact on the operating characteristics of the ICFB reactor. Further detailed investigation is needed in order to fully understand the hydrodynamics of the ICFB reactor.

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