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The study of solid circulation rate in a compartmented fluidized bed gasifier (CFBG)

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Abstract. Biomass waste has been abundantly available in Malaysia since the booming of palm oil industry. In order to tackle this issue, gasification is seen a promising technology to convert waste into energy. In view of the heat requirement for endothermic gasification reaction as well as the complex design and operation of multiple fluidized beds, compartmented fluidized bed gasifier (CFBG) with the combustor and the gasifier as separate compartments is proposed. As such, solid circulation rate (SCR) is one of the essential parameters for steady gasification and combustion to be realized in their respective compartments. Experimental and numerical studies (CFD) on the effect of static bed height, main bed aeration, riser aeration and v-valve aeration on SCR have been conducted in a cold-flow CFBG model with only river sand as the fluidizing medium. At lower operating range, the numerical simulations under-predict the SCR as compared to that of the experimental results. Also, it predicts slightly different trends over the range. On the other hand, at higher operating range, the numerical simulations are able to capture those trends as observed in the experimental results at the lower operating range. Overall, the numerical results compare reasonably well with that of the experimental works.

1. Introduction

In 2012, Malaysia, the world's second largest producer [1], produced 18.79 million tonnes of crude palm oil on roughly 5,000,000 hectares (19,000 m^2) of land [2, 3]. An annual production of over 4 million tonnes of oil palm shell solid wastes [4, 5] is reported. Gasification is considered to be promising technologies for converting biomass waste into energy. The gasification of solid wastes with steam can efficiently convert 97% of the feedstock into syngas, however it is highly endothermic. To meet its energy demand, a possible solution is to have a separate combustor which burns biomass and interconnects it with the gasifier by transfer lines for heat exchange purpose. However, this type of configuration often complicates the design and operation of the system.

As such, a single compartmented vessel is introduced to improve the conventional design. Compartmented fluidized bed gasifier (CFBG) is a unique compartmented reactor which consists of two reactors, namely the combustor and the gasifier, partitioned at a ratio of 65:35, based on the heating requirement during thermochemical operation. Solids are circulated internally between

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compartments via a set of non-mechanical valves and risers. Solid circulation rate (SCR) is hence one of the essential parameters for steady gasification and combustion to be realized in their respective compartments.

Several lab-scale cold-flow experimental works had been carried out to study the SCR. Sathiyamoorthy and Rudolph [6] proposed an empirical correlation for SCR based on the different gas flow rates at main bed, V-valve and riser, with a constant depending on the V-valve inlet diameter. Later, He [7] agreed that any increase in the aerations leads to an increase in the gas leakage from the main bed to the V-valve orifice, resulting in the increase in the SCR. Yan and Rudolph [8] developed a new CFBG reactor design which demonstrated that the SCR depends on the gas flow rates to the V-valve and riser. Bhattacharya et al. [9] showed that the SCR is a function of fluidization conditions in upstream bed, V-valve and riser, solid size and upstream bed height. In the latest work done by Chok [10] and Wee [11] in a pilot-scale cold-flow CFBG, their findings are consistent with results as mentioned by previous authors. To date, the first and only numerical modeling of SCR in CFBG was done by Wee [11] using a commercial CFD package. The numerical results also agreed with the experiment findings.

The objective of this paper is to study the extended operating range for main beds aeration (Q_b), v-valves aeration (Q_v), risers aeration (Q_r) and static bed height (H) for higher SCR range by employing a CFD package at cold-flow model with only river sand as fluidizing medium. The results are then compared with Wee (2012) of smaller operating range.

2. Computational Setup and Methods

The schematic of the model is shown in Figure 1. The CFBG of diameter of 0.66m and a height of 1.8m is partitioned into two compartments, the combustor and the gasifier. The combustor or gasifier compartment is neither full cylindrical nor semi-cylindrical but rather a segment of a cylindrical. More details on working principles can be obtained in Wee [11].

The simulation of CFBG is performed by using a commercial CFD package. A multi-fluid Eulerian-Eulerian model, which considers the conservation of mass and momentum for the gas and fluid phases, is applied. The kinetic theory of granular flow is used to describe the solids phase stress. Further details on the modeling strategy can be found in Wee [11]. Table 1 summarizes the flow parameters to be used in the simulation of 3D CFBG. Mesh independence study is carried out to ensure that the numerical results are not significantly affected by number of mesh elements. As a result, fine mesh of 175498 elements is recommended for the SCR simulation:

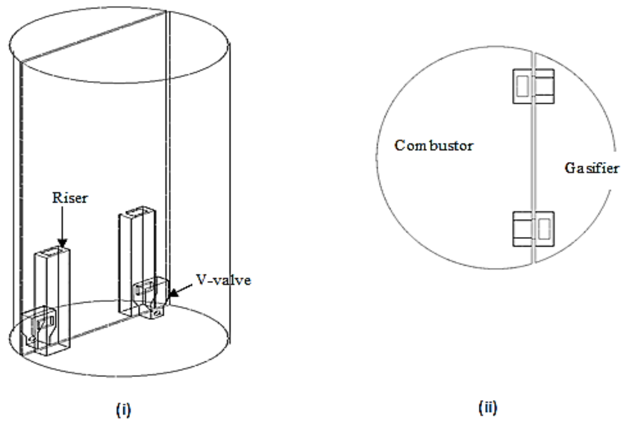


Figure 1. (i) Isometric view (ii) top view of CFBG.

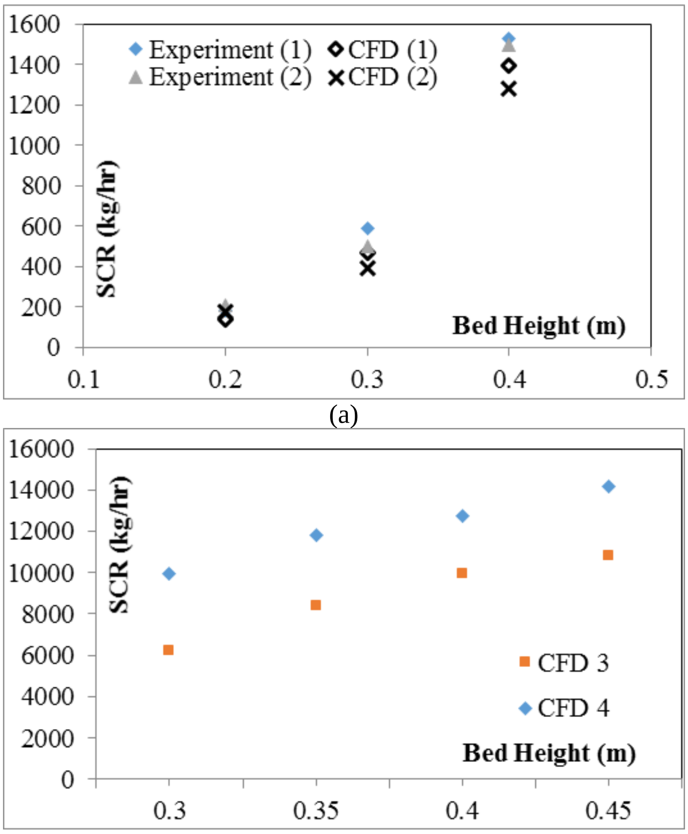
Table 1. Simulation model parameters/ conditions.

Properties of Sand Particles	**Description**
Mean particle diameter D_p	$272\ \mu m$
Density, ρ_p	$2620\ \ kg/m^3$
Minimum fluidization velocity,U_{mf}	0.06 m/s (determined experimentally)
Boundary Condition	**Description**
Combustor/ gasifier inlet condition	$1.3 - 1.7\, U/U_{mf}$ (low)$1.5 - 2.25\ U/U_{mf}$ (high)
Combustor/ gasifier riser inlet condition	$8.0 - 12.0\, U/U_{mf}$ (low)$13.0 - 19.0\ U/U_{mf}$(high)
Combustor/ gasifier v-valve inlet condition	$5.0 - 9.0\, U/U_{mf}$ (low)$10.0 - 16.0\ U/U_{mf}$(high)
Initial bed height	0.2-0.45m

3. Results and Discussions

3.1. Effect of Static Bed Height on SCR

Figure 2(a) & (b) shows the effect of static bed height on the SCR. The SCR increases with the increase in bed height. The SCR is dependent on the hydraulic head of the bed.



(a)

(b)

Figure 2(a) & (b). Effect of the static bed height on the SCR.
(1) $Q_b = 1.3U_{mf}$, $Q_r = 12U_{mf}$, $Q_v = 5U_{mf}$; (2) $Q_b = 1.3U_{mf}$, $Q_r = 8U_{mf}$, $Q_v = 9U_{mf}$
(3) $Q_b = 1.5U_{mf}$, $Q_r = 13U_{mf}$, $Q_v = 10U_{mf}$; (4) $Q_b = 2.25U_{mf}$, $Q_r = 19U_{mf}$, $Q_v = 16U_{mf}$

The higher the static bed height, the larger the hydraulic force exerted, thus induces higher SCR. These trends are similar to those observed by other researchers in this type of reactor [7-9]. Numerical simulation under-predicts the SCR values, however the tendency of the profile is still following the

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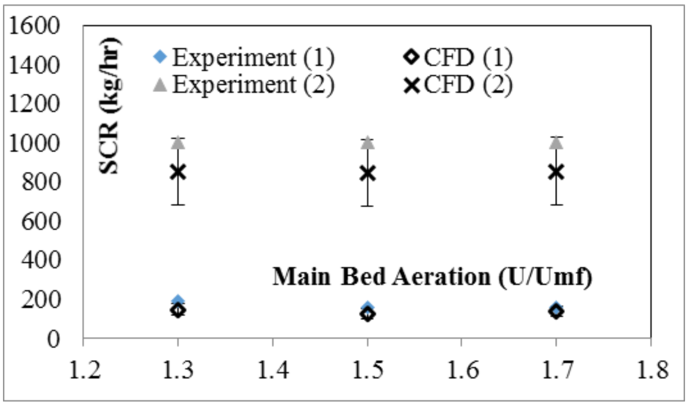
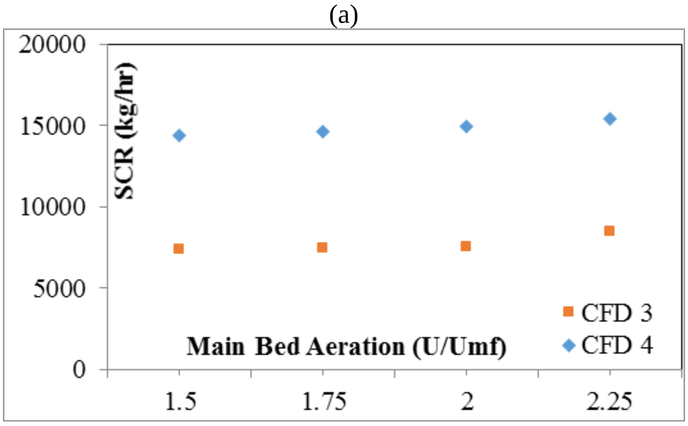
experimental ones as shown in Figure 2(a). This could be due to higher U_{mf} as predicted by the numerical standard drag law for the specified sand size. Figure 2(b) is produced by using the same assumption with operating condition dissimilar from experimental setting. Figure 2(b) shows a consistent increment in SCR for higher operating range. The operating static bed height of CFBG is limited by the height of riser. At higher bed height, the expanded bed hinders the outlet flow from the riser hence disrupts the solid circulation between compartments.

3.2. Effect of Main Bed Aeration on SCR

The effect of the main bed aeration on the SCR is illustrated in Figure 3(a). The different main bed aeration does not have any noticeable impacts on the experimental SCR. When the bed is fluidized, the bed pressure drop remains unchanged with further in-crease in the main bed aeration. As a result, one can expect the experimental SCR to remain constant when the compartmented bed is fluidized within this range of velocity. The numerical simulation predicts the similar behavior like those observed in experimental results. The SCR remains nearly constant with the variation in the main bed aeration from 1.3Umf to 1.7Umf. The trend is well captured by the numerical solution. However, the SCR values are under-predicted by around 20%. In order to obtain improved results, numerical simulation needs to be fine-tuned so that wide spectrum of particles size can be set to cater for the actual experimental vicinity.



(a)



(b)

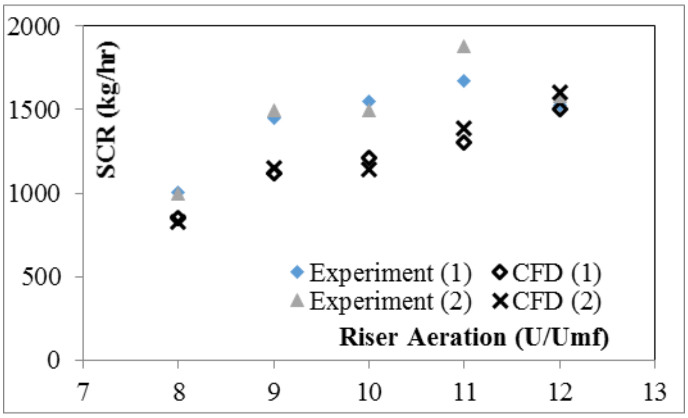
Figure 3(a) & (b). Effect of the main bed aeration on the SCR.
(1)H_b = 0.2m, Q_r = 12U_{mf}, Q_v = 5U_{mf}; (2) H_b = 0.4m, Q_r = 8U_{mf}, Q_v = 5U_{mf}
(3)H_b = 0.3m, Q_r = 13U_{mf}, Q_v = 10U_{mf}; (4) H_b = 0.3m, Q_r = 19U_{mf}, Q_v = 16U_{mf}

Figure 3(b) is plotted simulation result that have not been confirmed experimentally. Figure 3(b) shows the effect of main bed aeration on the SCR at the higher operating range. SCR increases gradually with the increase in main bed aeration. This observation is opposite to the trends in Figure

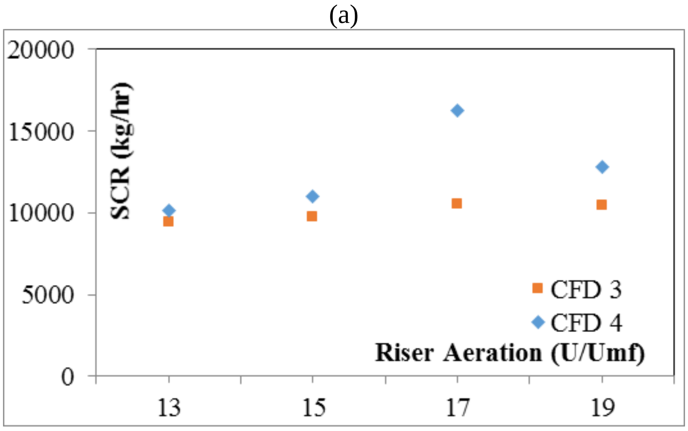
3(a). However, these results are consistent with the experimental findings by Bhattarcharya et al. [9] and He [7]. According to Bhattarcharya et al. [9], there are two opposing forces affecting SCR when the bed aeration increases. On one hand, increasing bed aeration leads to the reduction of the driving force due to an increase in bed porosity. This results in a reduction of SCR. On the other hand, gas cross-flow from v-valve aperture to riser increases with the increase of bed aeration. The latter reduces the pressure drop across the v-valve and riser thus increasing SCR. This is also supported by He [7].

3.3. Effect of Riser Aeration on SCR

Figure 4(a) & (b) demonstrates the effect of the riser aeration on the SCR. It is observed that the SCR initially increases then decreases with the increasing riser aeration. It is expected that the increase in riser aeration would increase the SCR due to the higher entrainment rate. However, further increase of the riser aeration may increase the frictional and acceleration pressure drop in the riser. This may eventually result in a reduction in the SCR. This trend is consistent with the results reported by Bhattacharya et al. [9]. He [7] explained this phenomenon as the presence of frictional and acceleration pressure drops. The pressure drop components increases with riser aeration, which results in reduction of solid circulation rate. This is however predicted differently by the numerical simulation at lower operating range. The SCR is linearly increased with the increment in riser aeration for the range of studies. The behaviour at higher riser aeration as discussed before is not apprehended by the numerical solution. This could be attributed to the higher Umf from numerical simulation than actual Umf as discussed earlier. On the other hand, at higher operating range, the numerical simulation is able to capture the reducing trend as observed from the experimental results.



(a)

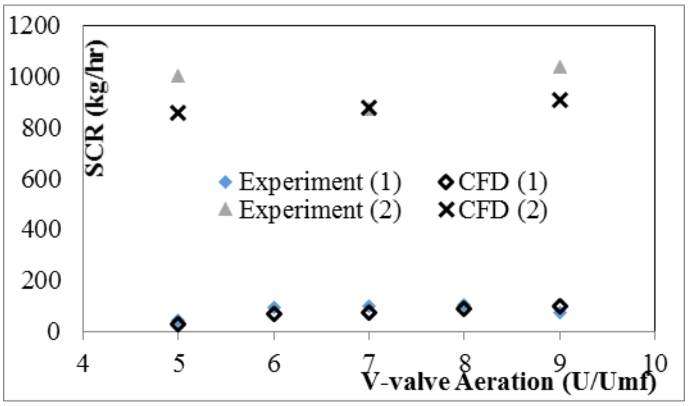


(b)

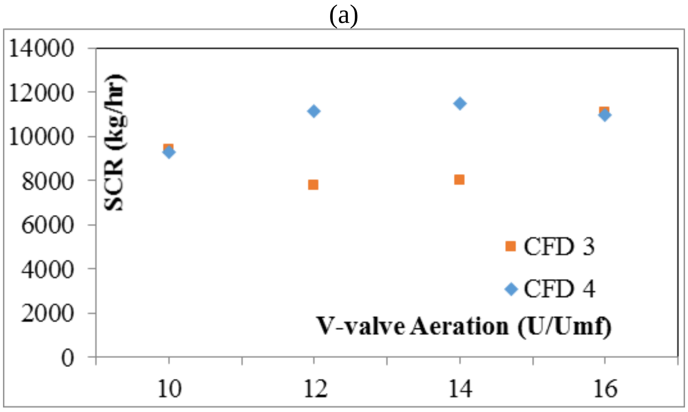
Figure 4(a) & (b). Effect of the riser aeration on the SCR.
(1)H_b = 0.4m, Q_b = 1.3U_{mf}, Q_v = 5U_{mf}; (2) H_b = 0.4m, Q_b = 1.7U_{mf}, Q_v = 9U_{mf}
(3)H_b = 0.3m, Q_b = 1.5U_{mf}, Q_v = 10U_{mf}; (4) H_b = 0.3m, Q_b = 2.25U_{mf}, Q_v = 16U_{mf}

3.4. Effect of V-valve Aeration on SCR

Figure 5(a) & (b) depicts the effect of the v-valve aeration on the SCR. For experiment (1), the SCR in-creases then decreases with increase in the v-valve aeration. Conversely, for experiment (2), the v-valve aeration has no obvious effect on the SCR. Ideally, aeration through the v-valve creates a low pressure region that induces a pumping effect. Greater aeration through the v-valve will therefore lead to a greater pumping effect, where more solids are being drawn which results in higher SCR. Nevertheless, it also in-creases the resistance across the v-valve-to-riser orifice. Thus, the two opposing effects explain the different SCR observed at experimental data.



(a)



(b)

Figure 5(a) & (b). Effect of the v-valve aeration on the SCR.
(1)H_b = 0.2m, Q_b = 1.3U_{mf}, Q_r = 8U_{mf}; (2) H_b = 0.4m, Q_b = 1.7U_{mf}, Q_r = 8U_{mf}
(3)H_b = 0.3m, Q_b = 1.5U_{mf}, Q_r = 10U_{mf}; (4) H_b = 0.3m, Q_b = 2.25U_{mf}, Q_r = 16U_{mf}

The numerical simulation predicts dissimilar tendency of SCR at the lower operating range. The SCR increases linearly with the increase in the v-valve aeration. However, at the higher operating range, the numerical results are somehow agreed with the experimental trends at lower operating range. The pumping effect is well predicted by the numerical simulation but the resistance across the v-valve-to-riser as discussed before is not captured.

4. Conclusion

The solid circulation rate in CFBG with only river sand in cold-flow condition has been studied experimentally and numerically. The SCR is predominantly affected by static bed height, main bed aeration, riser aeration and v-valve aeration. At a lower operating range of the four parameters mentioned, the numerical simulations under-predict the SCR as compared to that of the experimental results. Also, it predicts slightly different trends over the range. On the other hand, at a higher operating range, the numerical simulations are able to capture those trends as observed in the experimental results at the lower operating range. Further experimental work is needed to validate the numerical results at the extended range.

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