NUMERICAL STUDY FOR EVALUATING EFFECT OF MASS FLOW RATE TOWARD PARTICLE CIRCULATION RATE ON SEAL POT IN CIRCULATING FLUIDIZED BED BOILER

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Abstract.

Circulating Fluidized Bed (CFB) boiler is the second largest number of boilers for power generation in Indonesia, after Pulverized Coal boiler. CFB boiler has advantage in higher energy efficiency for combusting fossil fuel. There are three main components in CFB boiler, namely: riser or furnace for performing circulating fluidized bed, cyclone for separating flue gas with solid particle and seal pot for returning solid particle from cyclone into furnace. During operation, CFB boiler frequently experience failure caused by overheating and abrasion. Common failure in seal pot is overheating caused by change in particle size distribution and flue gas flow rate.

Overheating in seal pot occurs when flowrate of secondary air is not able to deliver whole solid particle into furnace. As consequence, some fraction of solid particles remain stay in seal pot and accumulated for long period of time. Since solid particles contain incombustible material (bed material) and combustible material (coal particle), accumulation of coal particle creates overheating in seal pot. This simulation work is intended to evaluate the effect on secondary air flowrate change in preventing solid particle accumulation in seal pot. The case study is taken operational condition of CFB boiler at PLTU Tenayan 1, Pekan baru- Riau. Variations used are mass flow rate secondary air from supply chamber and recycle chamber by 100%, 150%, 200% and percentage 57%:43% and 43%:57% for each parameter. Two Particle Size distribution with Sauter Mean Diameter (SMD) values 154 microns and 308 microns are obtained from the cyclone's performance. The presence of coal particle and its combustion effect is neglected. Simulation is performed using a Computational Particle-Fluid Dynamics (CPFD) software with Wen Yu drag modeling, and Large Eddy Simulation turbulence model.

Simulation results showed that increasing of secondary air mass flow rate will increase fluidization process, mass flow rate fluctuation at outlet and particle circulation rate. An optimum operation, smallest accumulation of solid particle remain in seal pot, is obtained at maximum flowrate with percentage of supply chamber 57% and recycle chamber 43% and solid particle size is 154 microns.

The worst circulation rate occurs at maximum flowrate with percentage of supply chamber 43% and recycle chamber 57% and solid particle size is 154 microns.

Keywords: Circulating Fluidized bed, Computational Particle-Fluid Dynamics, Energy efficiency, Fossil-fuel, clean energy, boiler, seal pot, overheating, supply chamber, recycle chamber.

1 Introduction

In 2016, consumption of coal for fueling steam power plan reach 69 million ton in each year. The consumption will keep increasing until 2035 [1]. The most important equipment in power plan is boiler. As the second largest number, Circulating Fluidized Bed (CFB) boiler promising more efficient combustion and more environmentally friendly. Circulation mechanism keeps unburn coal being sent back by cyclone and seal pot into furnace for re-combustion process [2]. Boiler also uses limestone as bed material for capturing NOx and SOx that is formed during coal combustion. It means that CFB boiler is suitable for producing clean energy. The disadvantages of CFB boiler are abrasion on furnace and cyclone and overheating on seal pot. It occurs when there is change in flow characteristic of fluidized bed.

Present simulation work focuses on investigating effect of flow characteristic change of loop seal due to flue gas flow rate and bed material change. Case study is taken on CFB boiler of PLTU Tenayan Riau. The boiler experience overheating in seal pot due to bed material accumulation [3]. Circulation of bed material in seal pot is managed by secondary air flowrate from supply chamber and recycle chamber. By finding best composition of secondary air flow rate from both chambers, the occurrence of overheating in seal pot can be eliminated. Simulation is performed using a Computational Particle-Fluid Dynamics (CPFD) software.

2 Literature Review

Seal pot is a non-mechanical valve that control circulation of bed material from cyclone into furnace by controlling flow characteristic of bed material [4]. Function of supply chamber in seal pot is for creating bed fluidization, and recycle chamber is for sending/recycling bed material back into furnace (see Fig. 1). Improper flow composition in supply chamber and recycle chamber can reduce performance of seal pot in circulating bed material.

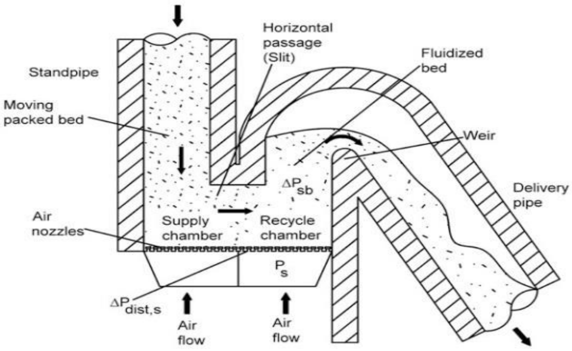


Fig. 1. Circulating mechanism of bed material in seal pot]

Simulation will use software named Virtual Reactor. A method of Computational Fluid Dynamics developed by CPFD Inc. [5] for fluidized bed reactors (FBR's) industry. Virtual Reactor uses modeling of 3D Multiphase Particle-in-cell that considering thermal and chemical reaction on all solid particles. Virtual reactor provides 3 (three) turbulence model, namely: laminar flow, Algebraic and Large Eddy Simulation (LES). Differ from CFD software [6], Virtual reactor computes Eddy pattern on each grid using Courant-Friedrichs-Lewy (CFL) number that depends on local velocity (u) time step of iteration and grid size. The equation is:

$$\mathrm{CFL} = \frac{\mathrm{u}\,\Delta \mathrm{t}}{\Delta \mathrm{x}_{\mathrm{cell}}} \quad (1)$$

LES modeling uses sub-grid scale (SGS) by counting Eddy viscosity and Reynolds stress tensor [S].

$$\vartheta_{\mathrm{t}} = \mathrm{C}_{\mathrm{s}}\ \rho_{\mathrm{f}}\, \theta_{\mathrm{s}}\, \Delta^2\, [\bar{\mathrm{S}}] \quad (2)$$

$$[\bar{\mathrm{S}}] = \sqrt{2\mathrm{S}_{\mathrm{ij}}^2} \quad (3)$$

Some investigation on flow characteristic in seal pot has been performed. Some simulation includes Bandara et. al. [7], Wang Q., et. al. [8] and, Yukselenturk and Yilmaz [9]. Bandara et. al. [7] investigate the effect of aeration flow rate increase toward fluidization and circulation rate of bed material in seal pot. Simulation domain consists of cyclone, standpipe, and seal pot. Simulation was performed by closed-loop system for solid material where bed material outlet from seal pot equals to inlet bed material for cyclone. This condition can be performed by setting boundary connector in CFD (see Fig. 2). Air flow rate for aeration process ranging from 0,6 Nm^3/h until 1,7 Nm^3/h with an interval of 0,1 Nm^3/h.

Simulation result shows that increase of aeration flow rate can increase solid fluidization (see Fig. 3) where maximum particle volume fraction reduce from 0.6 into 0.5. Aeration flow rate of 0.9 Nm^3/h gives optimum condition since it has narrower area of high particle volume fraction and smallest value of volume fraction. Increase of aeration flow rate from 0.9 Nm^3/h until 1.7 Nm^3/h cause fluctuation in area and value of high particle volume fraction. Rate of particle circulation in seal pot increase significantly from 0.4 to 0.9 Nm^3/h. Aeration flow rate above 0.9 Nm^3/h causes rate of particle circulation unchanged due to dynamic interaction of particle and fluid flow as indicated by fluctuating pressure difference between inlet and outlet boundary condition (see Fig. 4). An optimum solid circulation on seal pot is obtained at aeration flowrate of 0.9 Nm^3/h.

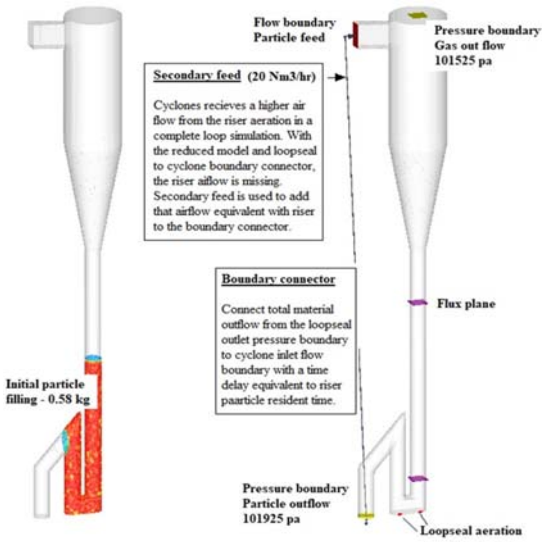


Fig. 2. Initial and boundary condition on loop seal [7]

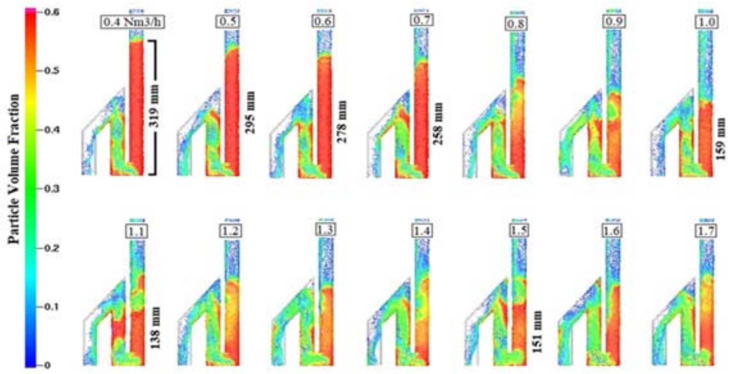


Fig. 3. Change of Particle volume fraction caused by increase of aeration flowrate [7].

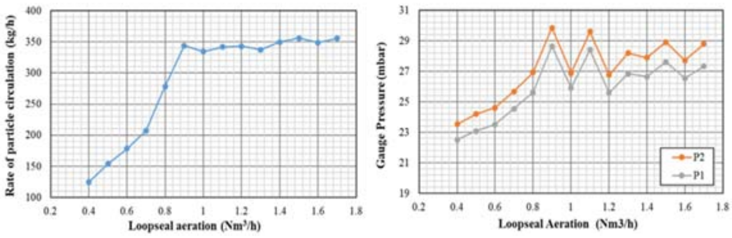


Fig. 4. Circulation rate and Pressure difference in seal pot due aeration flow rate increase [7]

Another simulation work performed by Wang et.al. that performed simulation in a full domain of circulating fluidized bed [8]. Simulation has been validated with experiment to find most accurate result in estimating static pressure in whole flow domain. The most accurate result in estimating pressure is obtained with fine mesh. Large value of pressure difference occurs between cyclone exit (P_T) and standpipe outlet (P_5).

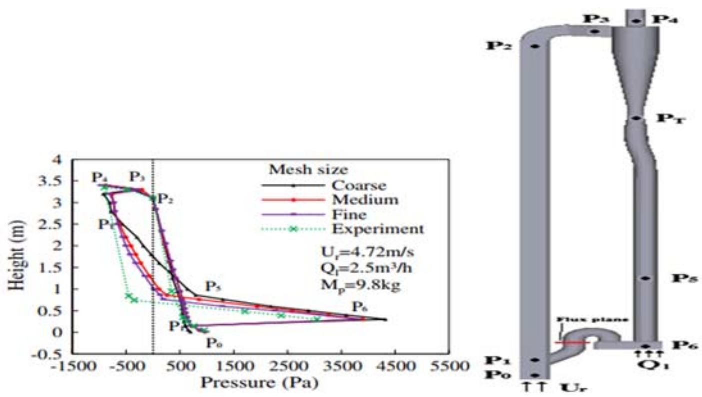


Fig. 5. Validation of static pressure distribution along domain [7].

Simulation result shows that increase of aeration flow rate can increase solid fluidization and solid circulation flow rate (see Fig. 6). The increase of aeration flow rate also increases particle circulation flow rate (G_s), pressure gradient along riser (ΔPr) and pressure gradient along standpipe (ΔPs/Hs) (see Fig. 7a and 7b). A better solid fluidization also reduces the height of packed bed and gas/fluid flowrate in standpipe (see Fig. 7b and 7c).

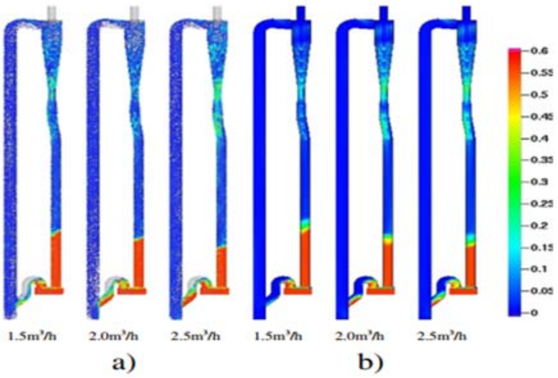


Fig. 6. Particle volume fraction distribution under different aeration flowrate [8]

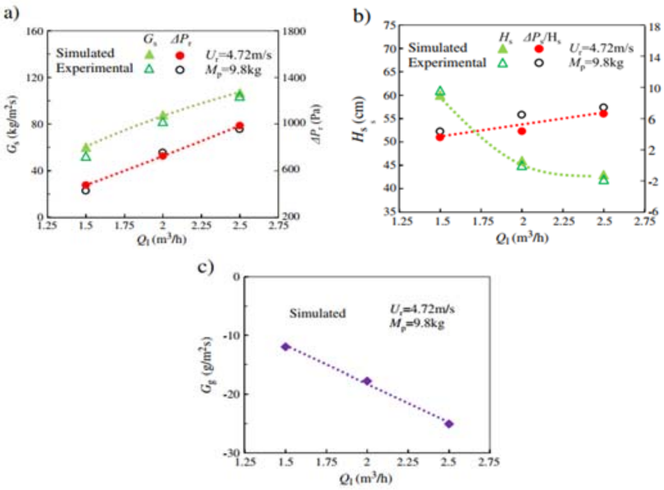
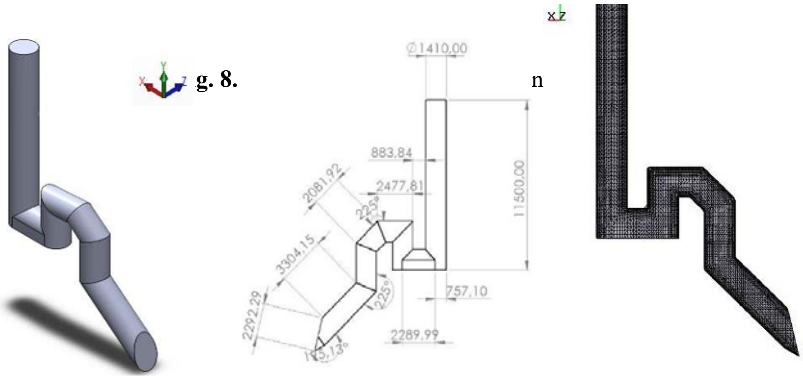


Fig. 7. Comparison of simulation and experiment results on the effect of aeration flow rate increase toward: (a) particle circulation and pressure gradient in riser (ΔP_{riser}), (b) height of packed-bed and pressure gradien, (c) fluid flow rate on stand pipe [8].

3 Simulation Set up

Present simulation is focused on loop seal with detailed domain and meshing as shown on Fig. 8. Simulation assumes there are no combustion from remaining coal (isothermal), heat transfer between fluid and wall (isothermal) and no presence of limestone and coal. Inlet boundary condition for fluid and solid bed material is based on operational data of boiler operation for cyclone and seal pot. Air inlet for supply and recycle chamber is obtained from secondary air fan (see Fig. 9 left). Increase of air supply for both chambers will not change air mass flow balance since the increase of air supply from both chambers obtained by decreasing supply of secondary air for riser. Initial particle in bottom side of seal pot (see Fig. 9 right) is the remaining bed material from previous boiler operation.



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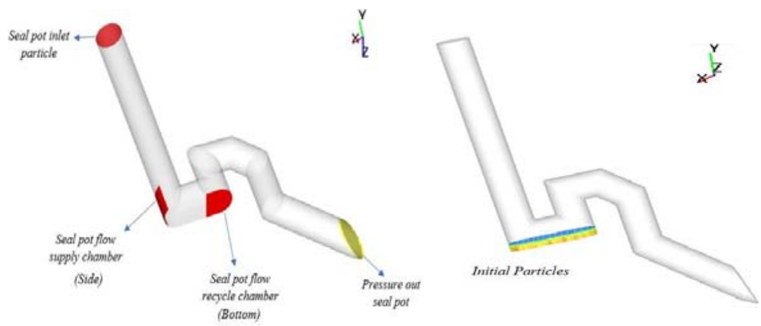


Fig. 9. Boundary and initial condition for present simulation

Simulation is performed to investigate effect of secondary air supply increase toward circulation rate of seal pot. The variation is 100%, 150%, dan 200% from the existing operating condition (see Table 1). In addition to flow rate increase, simulation variation is also performed by changing different percentage of flow for supply chamber and recycle chamber, and particle size distribution. Particle size distribution is measured by Sauter Mean Diameter (SMD) where the size of existing condition is 154 μm and additional size is 308 μm (see Fig. 10).

Table 1. Boundary condition variation for the simulation

Variation of mass flow rate (%)	Value of mass flow rate (kg/s)	Percentage of mass flow rate composition	Value of mass flow rate composition
100% (Existing condition/m_1)	2.3	Supply chamber : Recycle chamber = 57%:43%	1.3 kg/s : 1 kg/s
		Supply chamber : Recycle chamber = 43%:57%	1 kg/s : 1.3 kg/s
150% (m_2)	3.45	Supply chamber : Recycle chamber = 57%:43%	1.95 kg/s : 1.5 kg/s
		Supply chamber : Recycle chamber = 43%:57%	1.5 kg/s : 1.95 kg/s
200% (m_3)	4.6	Supply chamber : Recycle chamber = 57%:43%	2.6 kg/s : 2 kg/s
		Supply chamber : Recycle chamber = 43%:57%	2 kg/s : 2.6 kg/s

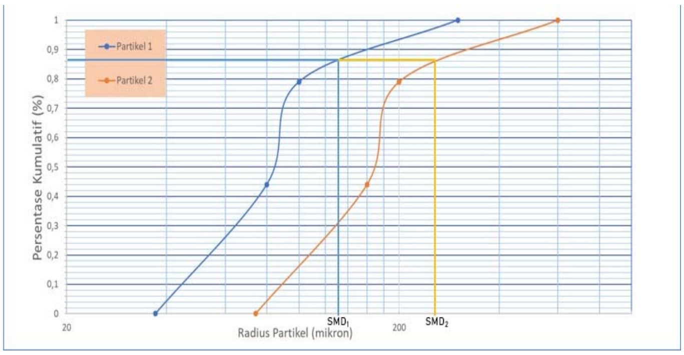


Fig. 10. Particle size distribution for existing condition (SMD_1) and bigger size (SMD_2)

Simulation result for inlet and outlet are calculating over surface area for averaged result and over points starting from center area (point 0) until near wall area (point 0.75) for transient result (see Fig. 11).

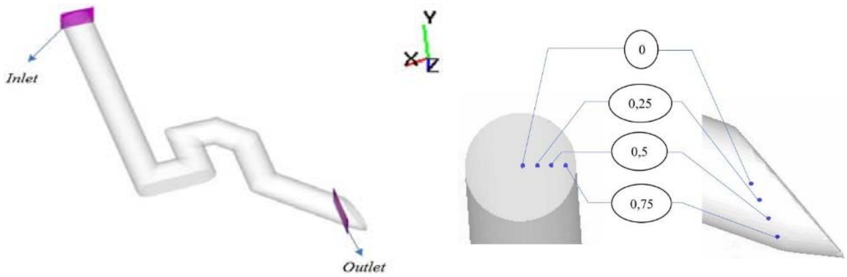
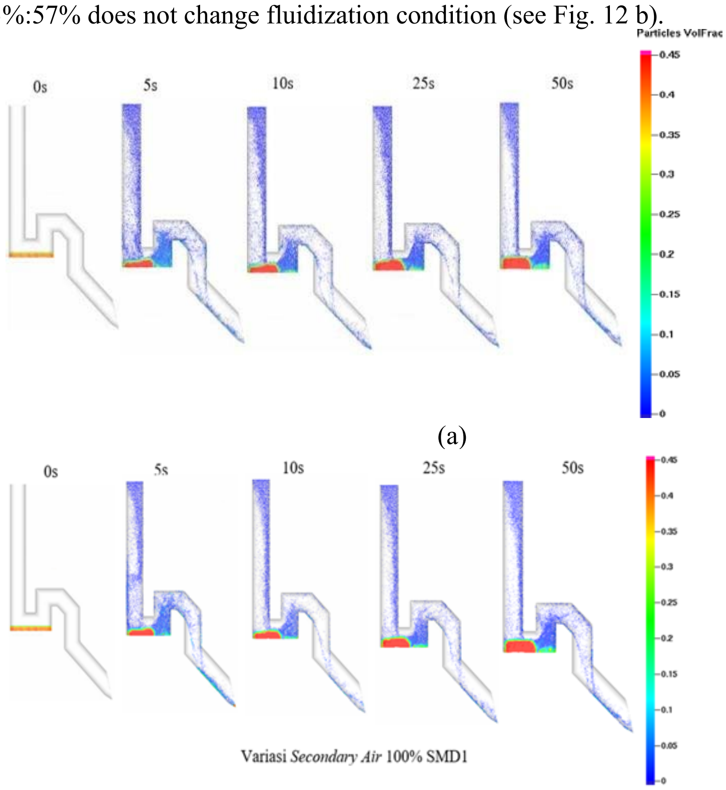


Fig. 11. Data extraction for averaged result (left) and transient result (right)

4 Result and Discussion

Fluidization process for the existing condition, namely: 100% air supply from secondary fan, Supply: Recycle chamber flow equals to 57%:43% and Sauter mean Diameter equals to 130 µm; is shown in Fig. 12a. At a time of 50 seconds, there is a formation of packed bed in area between supply chamber and recycle chamber with particle volume fraction as high as 0.45. Changing percentage of Supply: Recycle chamber into 43%:57% does not change fluidization condition (see Fig. 12 b).



(a)

(b)

Fig. 12. Fluidization process for existing flowrate (m_1), SMD_1 and Supply: Recycle chamber ratio = a) 57%:43%, b) 43%:57%

Fluidization for all variations is shown on Fig. 13. Variation of Supply chamber: Recycle chamber ratio and particle size on existing secondary air flow rate (m1), does not change fluidization process as indicated by same area of packed bed (volume fraction equals to 0.45). On the contrary, increase of secondary air flow rate (m_2 and m_3) significantly reduce area of packed bed.

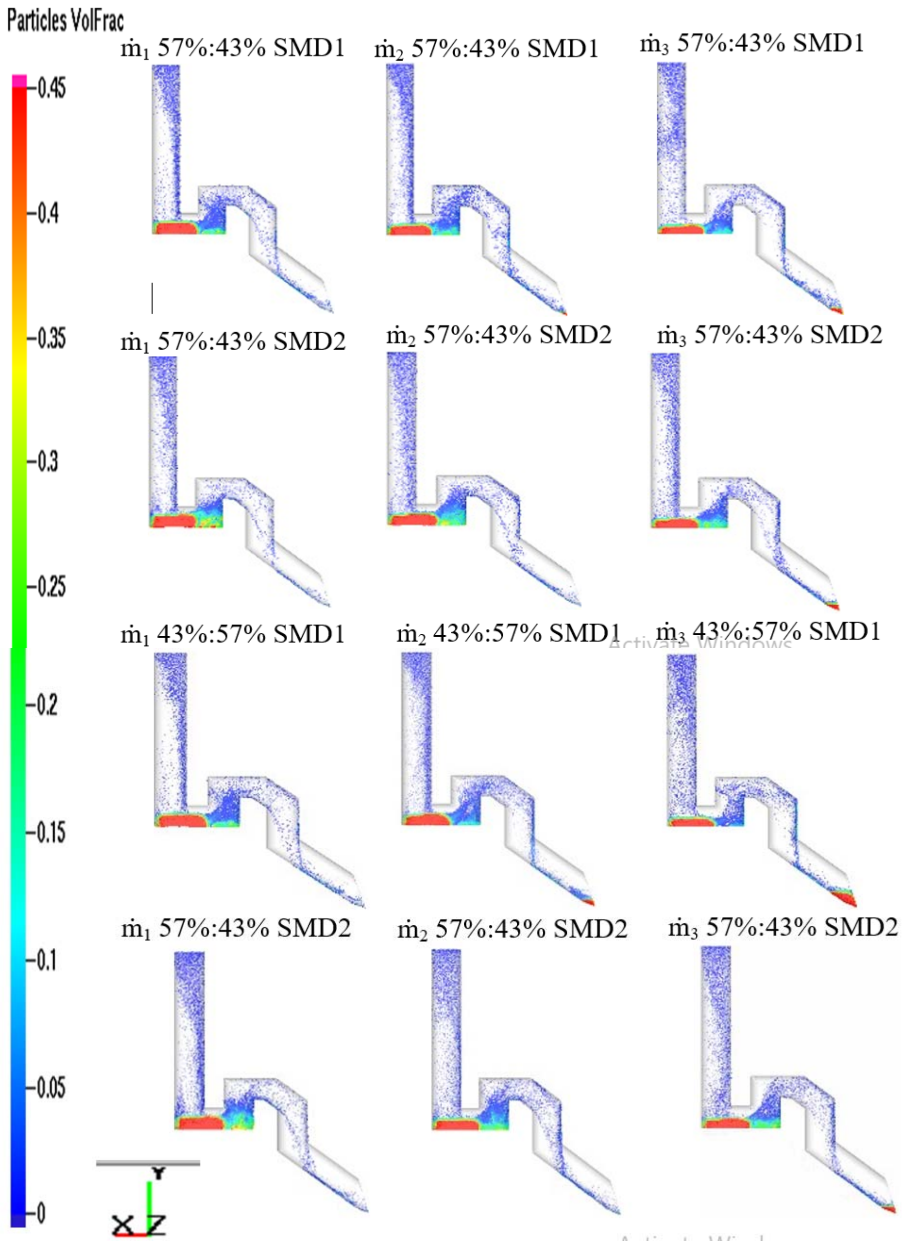
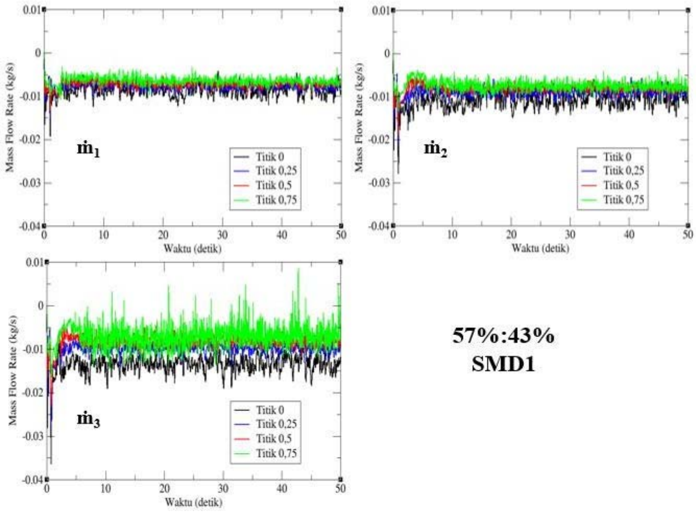
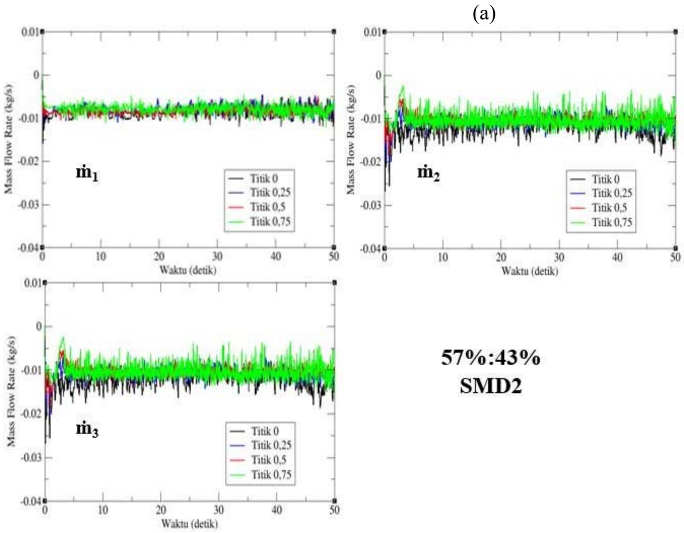


Fig. 13. Particle volume fraction for all variations

The measurement of outlet mass flow rate all points show a permanent fluctuation (Fig. 14). Most of simulation show that the increase of secondary air flow rate causes increase mass flow rate fluctuation. It indicates that higher secondary air flow rate will cause higher fluidization and higher dynamic interaction between solid particle and fluid. An exceptional condition occurs on variation of Supply: Recycle chamber equals to 43%:57% and SMD1 (see Fig. 14c), where at the highest secondary air flowrate (200%), mass flow rate fluctuation is disappeared. The close location to the wall, the sooner mass flow rate fluctuation will be disappeared. It seems that higher portion of flow for recycle chamber causes a flow blockage and eliminates dynamic interaction between solid and fluid.



(a)



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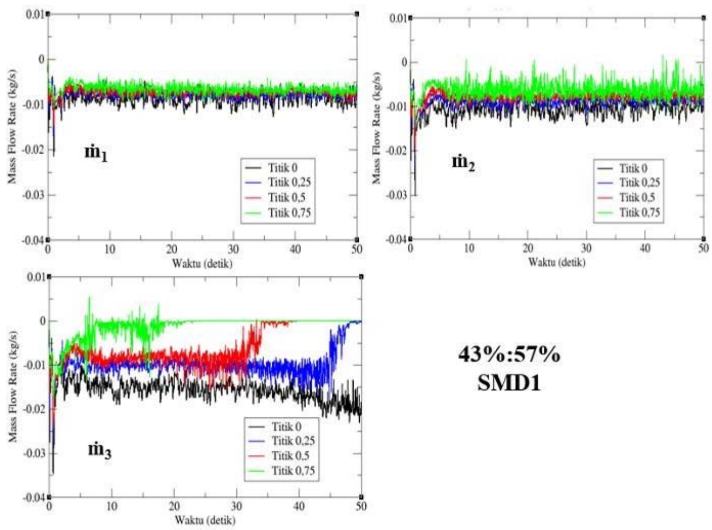
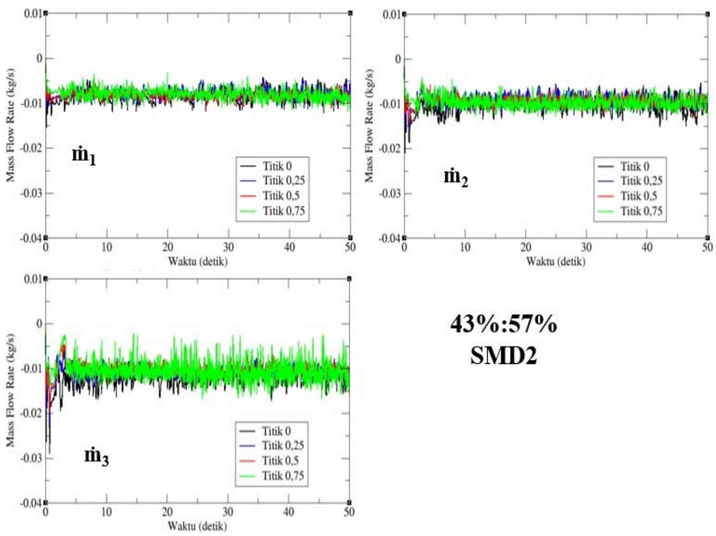


(c)



(d)

Fig. 14. Mass flow rate fluctuation at outlet for existing secondary air flow rate (100%) and Supply:Recycle chamber ratio: (a) 57%:43% SMD1, (b) 57%:43% SMD2, (c) 43%:57%, dan (d) 43%:57% SMD2

Similar result is also shown for circulation rate of solid particle in seal pot. Cumulative mass of particle remains in seal pot, as shown on Fig. 15, indicates circulation rate of particle. Smaller cumulative mass on seal pot indicates that more particles will be sent back to furnace. It means a better circulation rate of solid particle. On variation of Supply: Recycle chamber equals to 57%:43%, increase of secondary air flowrate will properly reduce cumulative mass particle. For existing particle size (SMD1) and Supply: Recycle chamber equals to 43%:57%, increase of secondary air flowrate will reduce cumulative mass particle. However, the reduction tends to weaker as secondary air flowrate increase. The worst condition occurs in variation of larger particle size (SMD2) and Supply: Recycle chamber equals to 43%:57%. At maximum secondary air flowrate (200%), cumulative mass particle will increase compared to 150% flow rate. Increase of secondary air flowrate will have proporsional correlation with particle circulation rate if the percentage of flow rate for Supply chamber is higher than Recycle chamber.

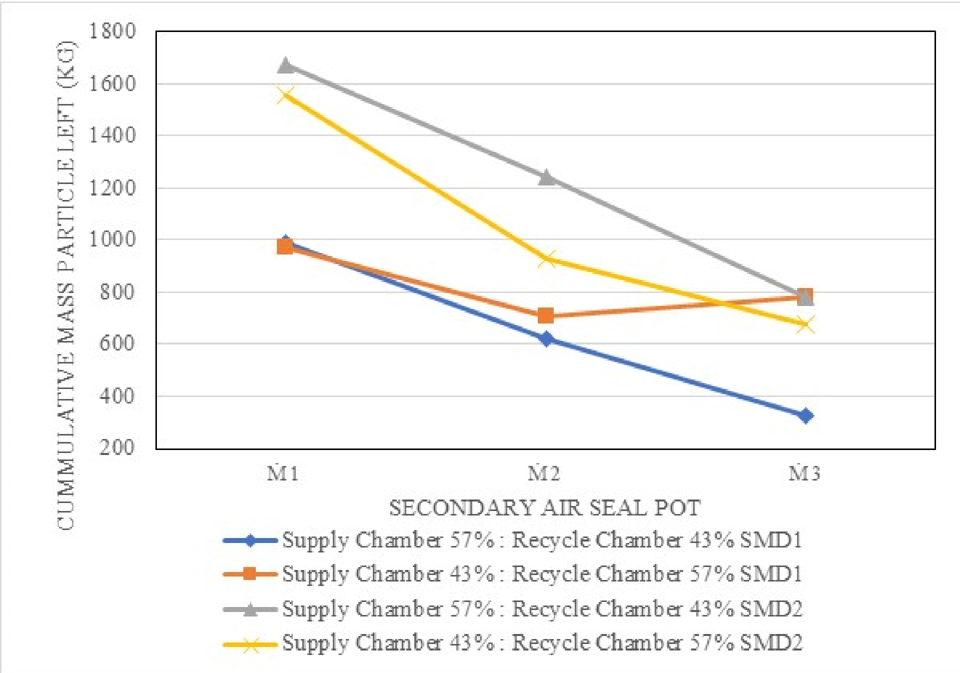


Fig. 15. Cumulative mass of particle remains in seal pot.

5 Conclusion

Based on the simulation result and discussion, it can be concluded:

- Increase of secondary air flowrate will reduce packed bed area in the bottom of seal pot. It is indicated by narrow area of particle volume fraction equals to 0.45.
- Increase of secondary air flowrate will creates higher fluidization and creates higher fluctuation in mass flow rate outlet.
- Percentage of Supply chamber : Recycle chamber equals to 43%:57% tends to block fluidization and reduce circulation rete of solid particle.
- Increase of secondary air flowrate have proportional correlation with particle circulation rate if the percentage of flow rate for Supply chamber is higher than Recycle chamber.
- The maximum circulation rate is obtained at variation of Supply chamber : Recycle chamber equals to 57%:43%, secondary air flowrate 200% and larger particle size (SMD2).
- The worst circulation rate is obtained at variation of Supply chamber : Recycle chamber equals to 43%:57%, secondary air flowrate 200% and smaller particle size (SMD1).

6 Acknowledgement

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