Refereed Proceedings

The 13th International Conference on Fluidization - New Paradigm in Fluidization Engineering

Engineering Conferences International *Year* 2010

EVALUATION OF FLUID DYNAMICS IN A HOT AND A COLD SYSTEM OF INTERCONNECTING FLUIDISED BEDS

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ABSTRACT

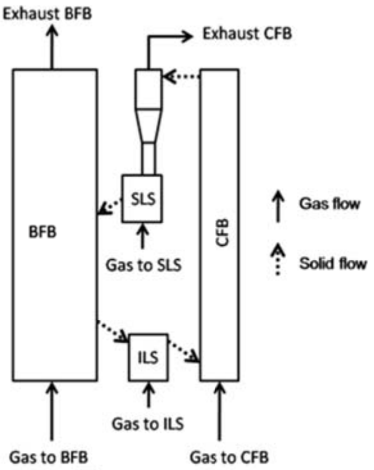
Operation controllability and fluid dynamics were evaluated in a system of interconnecting fluidised beds. Results indicate that the solid circulation is controllable and possible to determine from pressure measurements. Sufficient gas tightness of the loop-seals and flexibility in controlling of solid fluxes was indicated.

INTRODUCTION

Gasification is a promising method for converting crude biomass to renewable transport fuels, Devi et al (1). Nevertheless, the complications in handle the unwanted components in the raw gas, such as condensing hydrocarbons (often referred to as tars), are still a drawback and a major issue to solve, Li and Suzuki (2).

In this work, a novel technique for catalytic gas cleaning of biomass derived raw gas based on the concept for chemical lopping combustion (CLC), Lyngfelt et al (3) is investigated from an operational point of view. The concept of the gas cleaning system is to circulate catalytically active particles between two reactors, while the gases in the two reactors are kept separated. By means of the particles oxygen is transferred and reactions are catalysed. In contrast to CLC the required amount of oxygen transferred by the bed material is small, as only a share of the gas, the tars, should be combusted. Therefore, this work is focused on the control of the circulation rate as it is crucial for the development of this gas cleaning process. A survey of fluid dynamics is conducted in a cold system of interconnecting fluidised beds (IFBS), identical in size as an existing hot gas cleaning system.
The cold flow model used to determine the parameters relevant for circulation consists principally of a Circulating Fluidised Bed (CFB) and a Bubbling Fluidised Bed (BFB), Fig 1. The two beds are coupled by two fluidised loop-seals (LS); Superior Loop-Seal (SLS) and inferior Loop-Seal (ILS), which allows solid circulation, but prevents gas mixing between the two reactors. Inert gases are selected for the fluidization of the LS.

The identical design of the two systems is to avoid size related effects in fluid dynamics and to facilitate the transfer of fluidisation characteristics between the hot and the cold system. The advantage of the perspex cold system compared to the hot system is the possibility to visually revise the fluid dynamics and to measure the solid circulation rate. This knowledge received from the cold system is then transferable to the hot system by the simplified scaling laws presented by Glicksman et al (4).



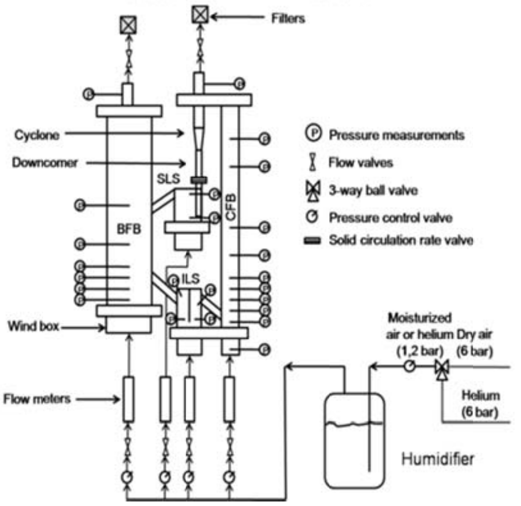


Figure 1 System of interconnecting fluidised beds

Figure 2 Cold system setup

Operations were conducted with both air and helium as fluidising media. Helium was selected because of the good agreement in fluidisation properties with the hot system.

The potential to control the operation of the gas cleaning IFBS is investigated from a set of experiments. The important criteria investigated in these measurements are:

i. **Solid circulation rate/solid flux:** Possibilities to control the solid flux between the CFB and BFB from varying the fluidisation velocity in the riser are investigated. The prospect of transferring the gained data between the cold and the hot model is evaluated from the simplified scaling laws by Glicksman (4). The solid flux determines the amount of oxygen that is transport via the solids to the BFB. In the gas cleaning unit this is important, as only enough oxygen supply for partial oxidations and breaking down of the unwanted components in the raw gas is desired.

- **ii. Leakage via LS:** The influence in gas leakage from pressure difference between the CFB and BFB is evaluated. That this has a strong influence on the leakage has previously been shown by Eva Johansson et al (5).
- **iii. System behaviour and supervision:** Relations between solid fluxes and pressure drop in the riser are investigated. The reason is to establish a relation to determine the solid fluxes in the hot unit from its pressure signals. Previously, Johnson et al (6) showed a correlation between the two parameters for a CFB boiler.
  The behaviour of the fluidization in the system is characterised by the fluidisation regimes, which is determined from the sampled pressure signals. The different regimes in the riser reflect solid inventory and can be coupled to particle residence time, which is important for the oxidation of the catalyst.
- **iv. Flexibility:** The possibility to control the solid fluxes by changing the velocity in the ILS is investigated. Pröll et al (7) indicated that regulating the fluidization in the LLS is influencing the solid flux in the system.

EXPERIMENTAL

The cold IFBS setup is shown in Fig 2. The system is supplied with air or helium at a pressure of 1.2 bars. To minimize effects from static electricity between the particles and the perspex surfaces the gas is humidified in an air tight water bottle. The moisturized gas is distributed to the four fluidising stems where the pressure is adjusted to a pressure slightly higher than atmospheric conditions, followed by manually tuning of the volumetric flow rates by the use of rotameters. The gas enters the reactor system via wind boxes, which are placed beneath the porous plates, in order to reduce potential pressure fluctuations in the gas feed. Flow control valves are mounted on the outlets of the CFB and BFB for regulation of pressure in each reactor. A filter is mounted after each flow control valve for collection of elutriated particles.

The system is equipped with 24 pressure taps and 24 pressure transducers. The pressure can be measured as differential pressure between two taps in the system or as differential pressure between one tap and atmospheric pressure. The pressure taps are inclined with an angel of 45° to prevent bed material from blocking the tubes. A manually controlled valve is mounted in the downcomer for solid circulation rate measurements.

Scaling Parameters

To transfer data between the cold and the hot reactor it is necessary to keep the following dimensionless numbers constant, Glicksman et al (4)

$$\frac{u_0^2}{gL}, \frac{\rho_s}{\rho_f}, \frac{u_0}{u_{mf}}, \frac{L_1}{L_2}, \frac{G_s}{\rho_s u_0}, \Phi, \textit{Particle size distribution}$$

Table 1 summarizes the operating parameters and the dimensionless numbers for the CFB and BFB in the hot and cold system.

Table 1 Operation parameters and dimensionless numbers for the hot and cold unit

Parameter	Units	Hot CFB	Hot BFB	Cold CFB	Cold BFB
Media	gas	Air	Raw gas	Helium/Air	Helium/Air
Temperature	T (K)	1173	1173	293	293

Pressure	P (Pa)	1×10^5	1×10^5	1×10^5	1×10^5
Gas viscosity	μ (Pa s)	4.59×10^{-5}	3.43×10^{-5}	1.96×10^{-5} $/1.82 \times 10^{-5}$	1.96×10^{-5} $/1.82 \times 10^{-5}$
Gas density	ρ_f (kg/m^3)	0.297	0.276	0.146 / 1.188	0.146 / 1.188
Bed geometry	(m)	L	L	L	L
Particle diameter	d_p (μm)	150	150	150	150
Solids density	ρ_s (kg/m^3)	5240	5240	2600	2600
Superficial velocity	u_o (m/s)	1.00	0.039	1.00	0.039
Sphericity	Φ	0.9	0.9	0.84	0.84
Particle size distribution	p	P	p	p	p
Solid flux	G_s (kg/m^{2}s)	G_s	G_s	$0.5 \times G_s$	$0.5 \times G_s$
Dimensionless number	ρ_s / ρ_f (x10^4)	1.76	1.89	1.58 / 0.218	1.58 / 0.218
Dimensionless number	u_0/u_{mf}	40.82	1.12	40.32/37.45	1.57 / 1.46

Solid Circulation

Before each experiment, the system was refilled with new bed material and operated for 30 min in standard conditions with air, Table 2 to stabilize the conditions. Five sets of experiments for solid circulation were performed by varying the fluidisation velocity in the riser, from the highest velocity to the velocity were the bed started to have a slugging behaviour, Table 2 (Experimental run 1 – 5). The fluidisation velocity in the BFB, ILS and SLS was kept constant during each experiment.

The velocity in the riser was decreased with approximately 6 cm/s between each measurement for air and approximately 17cm/s for helium. The number of performed measurements at each fluidisation velocity of the riser is presented in Table 2. The solid circulation was measured by closing the valve in the downcomer with simultaneous start of timekeeping. Intermediate times were registered when the sand column reached 1, 2 and 3 cm of height in the downcomer. The registered heights (h_i') were recalculated to mass fluxes in downcomer ($G_{s,Downcomer}$) from the density of the bed material (ρ_{solid}) according to

$$G_{s,Downcomer} = \sum_{i=1}^{n} \frac{h_i^{'}}{n} \cdot \rho_{solid} \quad \left[kg/m^2 s\right] \qquad (1)$$

Leakage

One leakage test was performed to investigate the potential slip of gases between the CFB and BFB. A gas chromatograph was coupled to the exhaust of the BFB and five measurements were performed at each fluidisation condition to determine the oxygen content. With the use of nitrogen in BFB, SLS, ILS and air in the CFB, the measured oxygen concentration in the BFB was coupled to the leakage of air from the CFB.

Before the experiment, the entire system was operated with nitrogen for 30 min with fluidisation velocities according to Table 2. The fluidisation velocity in the riser was varied from the highest velocity to the velocity were the bed started to have a slugging behaviour, Table 2.

Table 2 Experimental operation velocities for gases

Fluidisation media	Experimental run	CFB U_0 (cm/s)	BFB U_0 (cm/s)	SLS U_0 (cm/s)	ILS U_0 (cm/s)	Number of measurements[1]
Standard, Air	-----	100.22	3.92	3.60	3.09	-----
Air	1	120 → 61	3.92	3.60	2.57	2

Air	2	120 → 61	3.92	3.60	3.09	3
Air	3	120 → 61	3.92	3.60	3.26	3
Helium	4	201 → 116	5.65	5.73	5.55	3
Helium	5	201 → 132	5.65	5.73	6.48	5
Standard Nitrogen	-----	100.27	4.00	3.68	3.32	-----
Nitrogen (N) + Air (A)	6	107 → 74 (A)	4.00 (N)	3.68 (N)	3.32 (N)	5

[1] Number of measurements at each fluidisation velocity in the riser

RESULTS AND DISCUSSION

Scaling parameters

The dimensionless numbers for solid/gas density ratio between operation conditions for the hot and the cold unit operated with helium is well adjusted, with deviation of 11 % in the CFB and 20 % in the BFB. Whereas the dimensionless number for solid/gas density ratio in the comparison between the hot unit and the cold unit fluidised with air differs with a factor of 8 in the CFB and a factor 9 in the BFB. The ratio for superficial velocity and minimum fluidisation velocity deviates with 1 % for the CFB and 40 % for the BFB between the hot unit and the cold unit fluidised with helium. Whereas the ratio for superficial velocity and minimum fluidisation velocity deviates with 9 % for the CFB and 30 % for the BFB between the hot unit and the cold unit fluidised with air. The deviation in the ratio between superficial velocity and minimum fluidisation velocity for the BFB is of less importance in the gas cleaning IFBS compared to the same ratio for the CFB. The reason to this is that the solid flux, controlled by the fluidisation properties in the riser, is more vital for the operation.

Sufficient agreement in the dimensionless numbers for the scaling relationship between the hot unit and cold unit fluidised with helium indicates that fluid dynamic properties are transferable between the two systems. In the case air is used for the fluidization, the deviation in solid/gas density ratio between the hot unit and the cold unit implicates that results from transferring fluid dynamics between the systems are more approximate.

Solid Circulation

Figure 3 shows that, independent of gas, efficient control of solid circulation between the two reactors can be achieved by varying the fluidisation velocity in the riser. The scattering effect at high velocities in the riser is coupled to the visual reading of the sand column height in the downcomer during measurements of the solid flux; the height of the column is increasing too fast to get a precise measure with the applied method.

In the air experiments two distinct plateaus are formed in the experiments with low fluidisation velocity in the ILS. This indicates that the friction in the ILS exceeds the hydrostatic pressure of the sand column surplus in the BFB reactor and hinders a smooth particle transport. The lower solid circulation can be explained by wall friction induced by the small volume in the ILS and is in accordance with previous observation by Pröll et al (7). This effect gives one additional possibility to control the solid inventory in the BFB by using the ILS as solid flow valve.

From Fig 3, it is evident that the solid circulation controllability is valid for both air and helium operation, even if, the solid/gas density ratio is seven times higher for air than for helium.

Pressure Drop in Riser

In Fig 4, solid circulation is plotted as a function of pressure drop in the riser for the experimental runs 3 and 5. The results show that the pressure drop in the riser is an adequate parameter to determine the transport of solids between the CFB and BFB, which agrees well with work performed by Johnson et al (6). Close agreement is shown in the trends for air and helium. The agreement point to that the difference in gas properties between air and helium are of low importance for stipulating the solid flux, which indicates that the method for determine solid flux should be valid also in the hot system.

The amplitude of the sampled pressure drop signal in the riser reflects the fluidisation regime in the riser, Fig 5. During pneumatic transport a smooth and non oscillating signal is received whereas for the transition to a fast fluidised bed the signal starts to oscillate. During the transition from fast fluidised bed to slugging bed an even more oscillating signal with increased amplitude is received. The slugging bed regime in the riser is not a preferred operation condition, as the pressure fluctuations can have impact on the whole system. The possibility to observe different transitions in regimes indicates that pressure fluctuations, coupled to the bed movement in the riser, can be reduced.

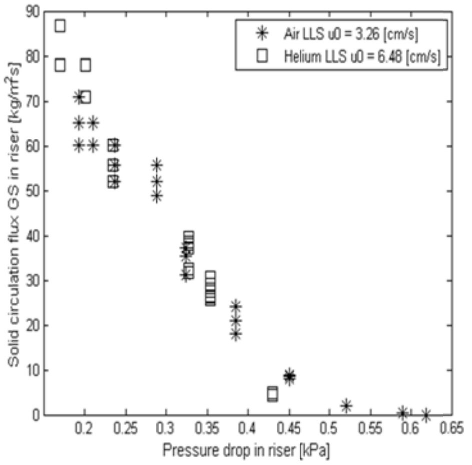


Figure 3 Solid circulation rates versus pressure drop in riser

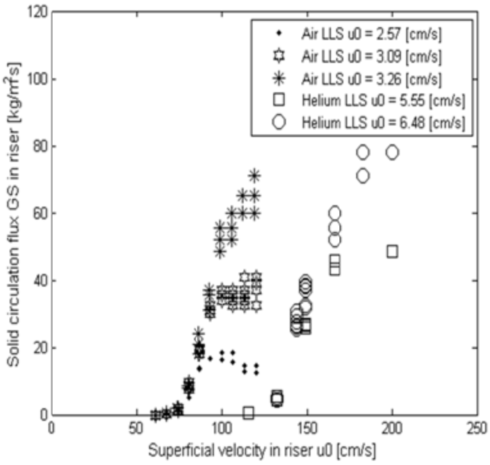
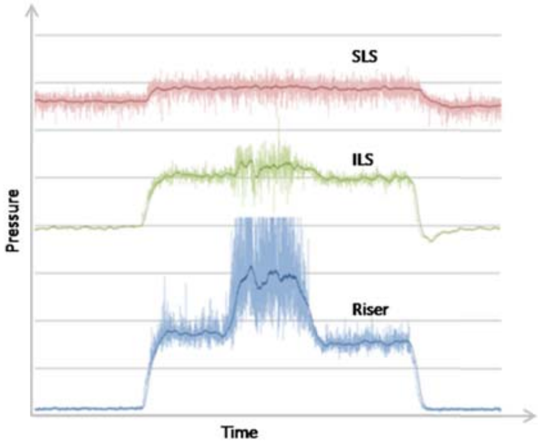


Figure 4 Solid circulation fluxes versus superficial gas velocity in riser



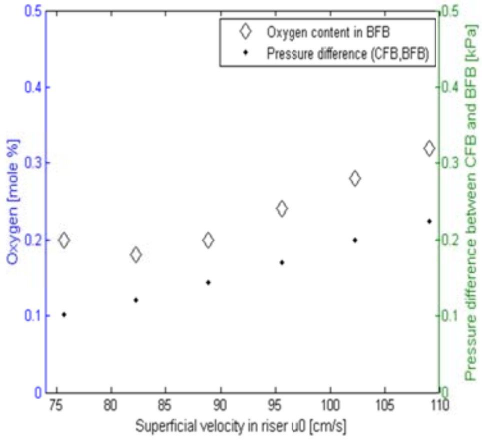


Figure 5 Pressure signals in riser
pressure
BFB
in riser

Figure 6 Oxygen leakage and
difference between CFB and
versus superficial velocity

Leakage

In Fig 6, oxygen concentration in the CFB and pressure difference between the CFB and BFB are plotted against superficial velocity in the riser. The figure also shows that the oxygen concentration in the BFB is less than 0.4 mole % at the highest fluidisation velocity in the riser, which indicates that the performance of the loop-seals is sufficient. Nevertheless, a trend in oxygen concentration can be notable; the oxygen concentration in the BFB is increasing with increased superficial velocity in the CFB. The reason for the higher oxygen concentration is coupled to the increased pressure difference between the CFB and BFB, caused by the raised gas flow in the riser. The leakage related to this pressure difference agrees well with work performed by Johansson et al (5). The oxygen concentration profile during increased superficial velocity in the riser can most likely be levelled out by a slightly increase of the BFB operation pressure. In the hot and the cold unit the pressure in the BFB can be changed by throttling the exhaust gases.

CONCLUSION

The possibilities to control solid circulation rate in a system of interconnecting fluidised beds for cleaning of biomass derived raw gas have been investigated. Experiments were performed in a perspex cold system identical in size as an existing hot gas cleaning system. The difference in solid/gas density ratio between hot and cold system was compensated by the use of helium as fluidising media. The performed experiments points out that, independent of air or helium, solid circulation rate can be efficiently controlled by the fluidisation velocity in the riser. Good agreement of the dimensionless numbers from the scaling principles by Glicksman et al (4), between the helium experiments in the cold system and the gases in the hot system was achieved. The agreement implies that the measured solid fluxes in the cold system are transferrable to the hot system with the only correction for the