COAL GASIFICATION – SCALING INTO PRESSURISED CFB SYSTEM

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Abstract - Coal gasification experiments were performed under oxidative atmosphere enriched with CO_2 in pilot scale circulating fluid bed (CFB) reactors operating under transport regime and preferably under fast fluidization. Two different CFB reactors were used, the first one - atmospheric and the second one - pressurized. The atmospheric gasification reactor consists of two sections: the lower, composed of two inverted cones connected with a cylindrical section of 0.38 m I.D., and the upper part – a riser of 0.14 m I.D. The total length of the riser is 4.39 m. The reactor operation depends on a gas phase velocity and on a solid phase concentration. The bottom section operates as a turbulent or a bubbling fluidized bed. The same arrangement was applied for a pressurized system, in which riser diameter was 0.076 m I.D. and bottom section was 0.16 I.D. The height of the riser is 3.67 m, at total height of 3.30 m. For comparative tests, the lignite coal was used from Belchatow mine. The test results, in terms of aerodynamic conditions, were analyzed in both systems. Additionally the choking gas velocity and saturation carrying capacity factors were considered for atmospheric and pressurized systems and the flow conditions were mapped to find the scaling factors from atmospheric to pressurized systems.

INTRODUCTION

Gasification is a primary conversion process used to produce hydrogen and carbon monoxide from carbonaceous materials. The obtained syngas can be used to generate electricity or to synthesize chemicals. A great attention has been paid recently to enhancing both the efficiency and environmental acceptability of coal gasification technologies. It can be completed by the additional conversion of externally provided CO_2. To the date, CO_2 has not often been considered as a co-gasifying agent to be fed into a gasification reactor at industrial scale. The CO_2-enhanced gasification process allows the chemical sequestration of CO_2, which can be considered competitive in relation to geological storage. The CO_2 used in gasification would be delivered through capture from flue gas and/or other industrial gases.

The effective use of CO_2 as a carbon and oxygen carrier in a gasification process requires several primary conditions to be met. A process temperature above 650°C shifts the equilibrium of the Boudouard (carbon-CO_2) reaction towards the formation of CO. To ensure that the Boudouard reaction will proceed, the following conditions are essential: carbon availability, a suitable reaction duration under the applicable kinetic constraints, and intensive contact between the gaseous and solid phases (i.e. CO_2 and char). The application of a circulating fluidized bed reactor ensures favorable conditions for heat and mass exchange, and it is an efficient route for the process, and an important element in the concept of coal gasification technology involving CO_2 use . In a circulating fluidized bed gasifier, the recirculation of partly converted reactive char removed from the gas creates conditions involving high concentrations of the solid phase (char) that is well mixed with the gas. A reactive char with high carbon content is present in the reactor. On the surface of this char, the CO_2 introduced to the reactor is converted to the basic component of syngas – carbon monoxide. It was also experimentally confirmed that the higher pressure in a system is favorable to promote the CO_2 conversion on circulated char (Chmielniak, et al., 2014).

The experimental results on gasification in fluidized bed reactors were reported previously among others by Adschiri et al. (1986), Luo et al. (2001) and Fang et al. (2001). However, all of the described experiments were performed only at the bench scale and under atmospheric pressure for chars and CO_2 gasification. All of these authors found a significant effect of parent coal rank on the obtained results.

The aim of this study was to evaluate and compare the effect of pressure on CO_2 enhanced gasification process particularly focusing on scaling factors. For this purpose, the experiments were conducted using the same wide size distribution coal in two different pilot plant gasification rigs. The flow conditions for stable operation were determined experimentally and validated theoretically considering limiting fluidization factors defined by mean and maximal particle size, choking velocity and saturation carrying capacity. The mean residence time needed for char to stay in a riser was a leading factor for scaling the process. It was evaluated for two investigated cases. The stable operation was recognized by uniform temperature distribution in the riser.

TEST RIG DESCRIPTION

The experiments were performed in a 1.5 MW circulating fluidized bed gasification reactor operating at ambient pressure and in a 0.5 MW pressurized circulating fluidized bed gasification reactor. The testing facilities used for the study aimed to determine optimal process parameters for a stable operation i.e. first of all determined by flow conditions and temperature distribution. Char and combustible gas are the main products of the process. The main components of the experimental rigs were as follows: system for feedstock preparation, circulating fluidized bed reactor, cyclone unit for the separation of char from the hot processed gas, and a flare for processed gas utilization.

The ambient pressure gasification reactor consists of two sections: a lower section composed of two inverted cones connected by a cylindrical section of 0.38 m I.D. and an upper part – a riser of 0.14 m I.D. The total length of the riser is 4.39 m. The reactor operation depends on the gas velocity and on solid phase concentration.

The pressurized gasification reactor consists similarly of two sections: a lower section composed of two inverted cones connected by a cylindrical section of 0.16 m I.D. and an upper part – a riser of 0.076 m I.D. The total length of the riser is 3.67 m. The bottom section of reactors operates as a turbulent or bubbling fluidized bed. The basic operational stability was executed experimentally by the observation of the stability of temperature distribution along the height of the reactor. It resulted in confirmation of properly adjusted flow conditions to the largest size fraction of a circulated char. Additionally, char conversion ratio and processed gas composition were considered. Basically hey depend on achieved hydrodynamic conditions.

After drying and air forced elutration of fines, coal was delivered to the test facility, into the containers. The plant configuration and instrumentation enabled studies of the gasification processes over a wide range of temperatures, using air, O_2, CO_2, and steam as gasifying agents. The coal feed capacity for rig testing ranged from 50 to 250 kg/h. The schemes of both reactors are shown in Figure 1.

The temperature and pressure distributions were measured throughout the system, and gasifying agents together with the process gas flow rates were recorded for mass balance calculations. Coal and char mass flow rates were determined by averaging the measured mass of the solids fed or received over the testing time. Char particle size distribution was used for solids flow analysis.

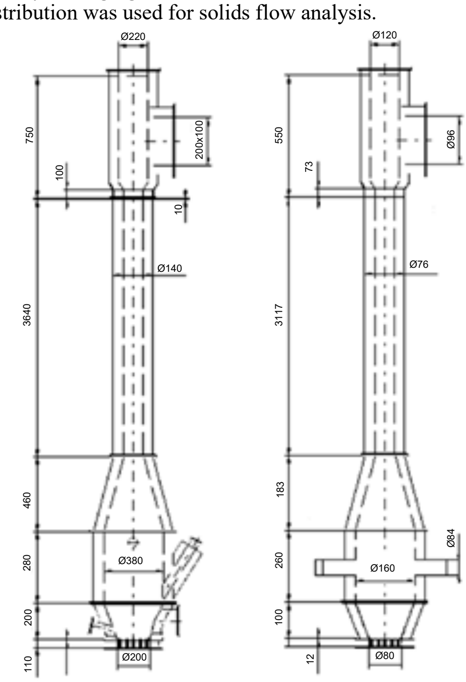

Fig. 1. Schematic diagram of CFB gasification reactors. From left – ambient pressure reactor, from right – pressurized reactor.

PROPERTIES OF COAL AND CHAR

Lignite (Belchatow) prior to the experiments was dried, grounded and sieved to particle sizes below 3 mm. The results of the proximate and ultimate analyses of samples are listed in Table 1.

Table 1. Properties of coal and size distribution of char

Property	Belchatow - lignite	Belchatow – char P=0.1MPa	Belchatow – char P=0.5 MPa
Proximate analysis, w/w % (fed to reactor)			
Moisture	5.8	1.6	4.3
Ash content	10.0	20.7	21.2
Volatile matter	47.60	7.87	8.42
Ultimate analysis, w/w % (air-dried basis)			
Total sulphur content	0.69	1.18	0.78
Total carbon content	57.2	64.7	56.9
Hydrogen content	4.53	0.88	2.73
Nitrogen content	0.60	1.01	0.69
Particles size, mm			
3.0-2.0	2.5	2.1	1.1
2.0- 1.4	12.6	6.2	7.0
1.4-1.0	24.2	18.6	17.6
1.0-0.71	24.8	31.2	27.2
0.71-0.63	21.1	21.8	21.8
0.63-0.5	8.9	9.7	11.7
0.5-0.315	4.3	6.9	7.9
0.315-0.2	1.2	2.3	3.7
0.2-0.1	0.2	1.2	1.8
<0.1	0.2	0.2	0.2
Arithmetic mean particle size, mm	0.992	0.885	0.847
Harmonic mean particle size, mm	0.798	0.694	0.649

PROCESS DATA

Temperature distribution in both testing units was relatively uniform, fitting into the range 881-915°C at P=0.1MPa and 860-870°C at P=0.5MPa. To maintain a smooth operation of the process and stable flow of solids and the gas, it was concluded that producer gas flow rate amounted to 161.7m^3/h and 82.9m^3/h (at normal conditions of pressure and temperature), respectively. As a result, the superficial gas velocity in a riser was 11.24 and 4.01m/s for process conditions. At atmospheric pressure, the value of superficial gas velocity in a riser is almost the same as respective terminal velocity for largest char fraction transported (mean size d_p=2.5mm), at higher pressure the experimental gas velocity refers to the terminal gas velocity for a fraction with a mean size of 1.6mm. For largest char fraction terminal gas velocity is 5.73m/s. It seems that in that case it is sufficient for stable operating to use lower gas velocity than it is required for transportation of largest size fraction, that is due to the effect of larger concentration of particles fluidized at higher pressure.

Table 2. Process parameters of gasification tests

Test data	P=0.1MPa	P=0.5MPa
Temperatures		
Gasification zone, °C	888	866
Riser, °C	881	870
Expander, °C	915	860
Flow rates		
Air to the reactor, m^3/h	42.0	14.7

O_2 to the reactor, m^3/h	16.0	13.9
CO_2 to the reactor, m^3/h	65.0	43.1
Process gas at the cyclones battery, m^3/h	161.7	82.9
Reactor pressure, MPa	0.105	0.498
Coal flow rate, kg/h	97.0	54.3
Superficial gas velocity in riser , m/s	11.24	4.01

SCALING UP METHODOLOGY

Taking into account that the reactor should be operated in a circulating fluid bed mode considering the riser. The key issue is to define the critical values for choking gas velocity and a saturation carrying capacity of the gas for both cases. The term “choking” refers to the conditions, at which there is an abrupt change in the behaviour of gas-solid system resulting in the suspension collapse and the formation of bottom dense bed. This phenomenon can take place due to the low gas velocity, which is close to the terminal gas velocity. Very similar observation can be noticed at higher gas velocity due to high solids loading and insufficient kinetic energy of the gas to transfer the energy to high flux of solid particles. This is called the saturation carrying capacity, which is on the other side of the expected operation region. This is the phenomenon, which does not show directly rapid changes in a flow structure. However it defines the conditions at which the suspension moves from a dilute phase conveying to a fast fluidisation regime. This is accompanied by the appearance of reverse flow of solid particles at the wall of the riser and densification of flow. Further increasing of solid flux will produce internal solids circulation at bottom of the dense bed with decayed solid concentration above it. In a riser, sufficiently long, the outlet gas will contain solids at concentration reflecting saturation carrying capacity. Adopting this interpretation the following phase diagram (Fig. 2) can be developed. It shows the curves of pressure drop vs. gas velocity at different solid fluxes. Additional two lines reflect choking phenomenon and saturation carrying capacity. Both determine the left and right boundaries of the fast fluidisation region. It is clear that in order to operate the bed at higher gas velocity it is necessary to increase the solid flux. It can be also deduced that for some solids and their flux, the line of saturation carrying capacity can cross $\Delta P=f(U_g)$ at minimum pressure drop what is also referred in literature as boundary for fast bed operation (Reddy Karri & Knowlton et al.,1991). The point of intersection of choking line with saturation carrying capacity line can be considered as a critical loading and gas velocity for which the discussed phenomena reveal the same mechanism.

Choking conditions can be expressed by the equation (Sciazko, 2001):

$$Re_{ch} = 2.439Ar^{0.474} \tag{1}$$

or as an approximation simply equation $U_{ch}=1.2U_t$.

In case of saturation carrying capacity, the equation (2) should be used (Sciazko, 2002):

$$L_{sat} = \frac{F_{sat}}{U_g \rho_g} = 0.096 Fr_t^{0.633} Ar^{0.121} \left(\frac{\rho_s}{\rho_g} \right)^{0.013} \left(\frac{D}{D_0} \right)^{-0.05} \tag{2}$$

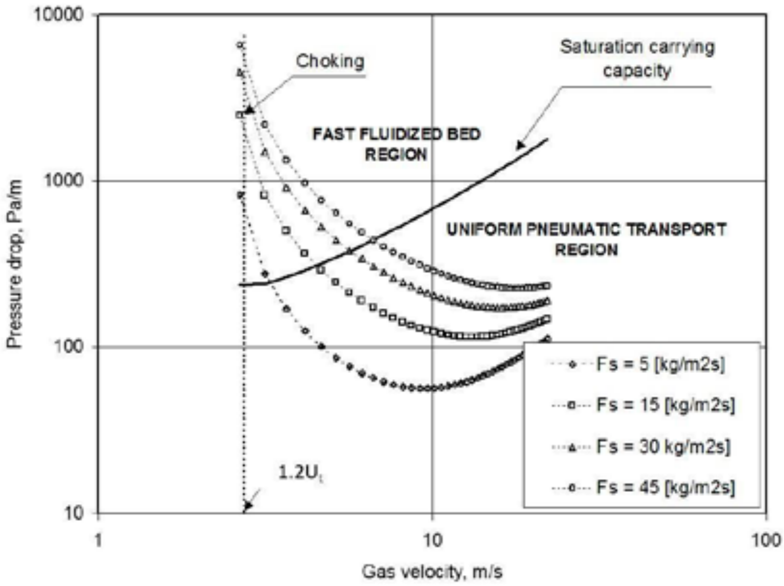

Fig. 2. Phase diagram of solid – gas flow (calculated for tube diameter – *0.059mm*, particle diameter – 0.5mm, solid density- *1250 kg/m³*, air at ambient conditions).

Applying classical approach for pressure drop (Capes, Nakamura, 1978) the pressure drop diagrams can be developed for considered pressures, i.e. P=0.1MPa and P=0.5MPa. The particle size distribution of char was applied as in the experimental testing. The operating point is shown on both diagrams based on pressure drop measurement in a riser.

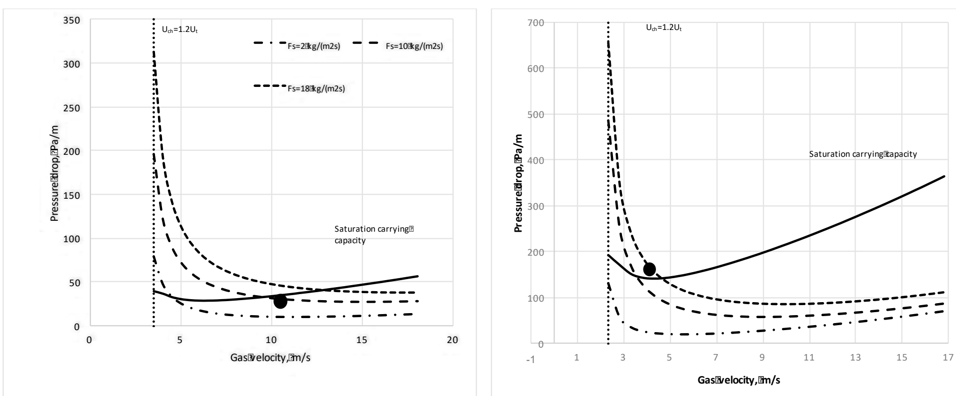

Fig. 3 Comparison of pressure drop for P=0.1MPa and P=0.5MPa. (Black dot – operating point)

It can be seen, that at higher pressure the entire fast fluidization region is shifted to the left towards the lower gas velocities. The diagrams are developed for the solids particle size distribution presented in the Table 1. The harmonic mean particle size was used for calculation.

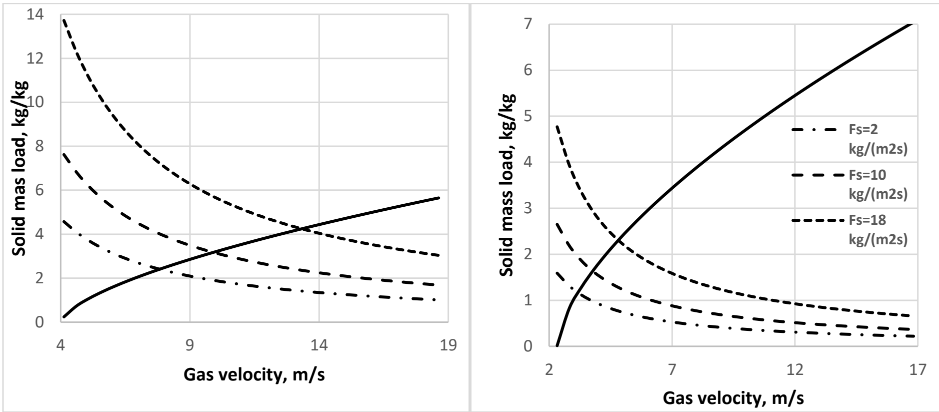

Fig. 4 Critical loading of solids for P=0.1MPa and P=0.5MPa.

Considering saturation carrying capacity and related to this conditions loading of solids it can be concluded that at gas velocity applied for both cases U_0=11.24 m/s and 4.01 m/s the critical loading respectively for P=0.1 and 0.5 MPa is equal to 3.71 kg/kg and 1.72 kg/kg. It means that it is required to feed less solids to the system in case of pressurized conditions to achieve internal circulation. Comparing solid flux at these conditions in both systems one can conclude that the values are not too much different resulting in 13.61 and 11.59 kg/m^{2}s. It is necessary to mention that the saturation carrying capacity was evaluated using weight mean value for char size distribution which is in circulation. Taking into account that coal/processed gas ratio at P=0.1MPa, which is 0.48kg/kg and 0.51 at P=0.5MPa it can be seen that at higher pressure required circulation ratio of char to maintain critical conditions for internal circulation is lower by a factor of 2.

Finally having basic information about the required mean residence time (20s) one can calculate height of the riser for both cases applying exponential formula for solids hold up. It was assumed that at the bottom of the riser the porosity of a fluid bed is 0.85. The simulation results are presented below. It seems that at the conditions applied in the experiment and for circulation ratio calculated according to assumed model the riser of the pressurized system may be shorter. This is the case used in reactors.

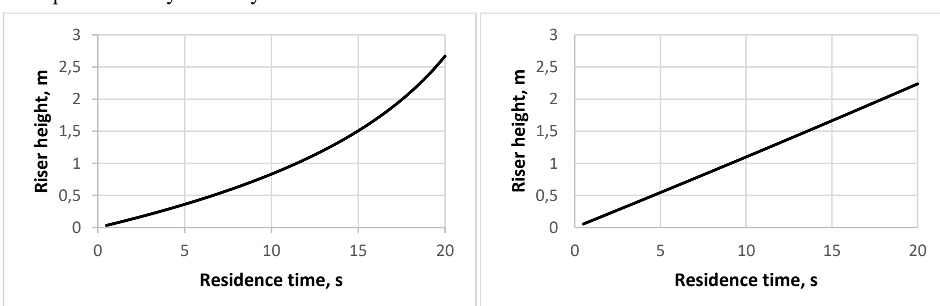

Fig. 5 Solids concentration distribution in a riser at P=0.1MPa and P=0.5MPa

CONCLUSIONS

It can be concluded that:

- The fast bed fluidization, characterized by internal circulation needs to be operated in the reactor between choking gas velocity and saturation carrying capacity of the gas in a riser. This was calculated for both the atmospheric pressure and the higher pressure systems, assuming the value of gas velocity at the choking conditions for the biggest particle fraction.
- Applied gas velocity was used successfully for fluidization, in both systems considering differences in particle size distribution and applied pressure, respectively.

- In both cases the circulation ratio was evaluated and taking into account the coal/gasification gas ratio. Reaction kinetics allows to use coal/feeding gas ratio of 0.60-0.65 kg/kg, which is 5 times less in case of P=0.1MPa and 3 times less for P=0.5MPa required for the development of internal circulation.
- Application of char circulation allowed to keep solids required 20 s in a riser. The riser height is a little shorter under pressurized conditions. This was also experimentally confirmed.
- Scaling of circulating fluid bed riser can be done by considering pressure drop map including border lines for choking and saturation carrying capacity. Gas velocity in a riser should be at terminal gas velocity of larger fraction of particle size and proper solids concentration needs to be adjusted by external circulation of char.

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