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VERTICAL SOLIDS DISTRIBUTION UNDER AIR/CARBON DIOXIDE FLUIDIZATION CONDITIONS IN A CIRCULATING FLUIDIZED BED

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Abstract

The oxy-fuel combustion is one of the options for CO_2 capture from power plants. Knowledge in the fluidization process in the CO_2 atmosphere is very important for the oxy-fuel combustion where carbon-rich fuels are combusted in mixture of almost pure oxygen with recycled flue gases.

The distribution of the solids concentration within the riser is one of the most important parameter influencing the heat transfer in the circulating fluidized bed (CFB) boiler. This paper contains the impact of fluidization gas on solids concentration changes during fluidization with air and carbon dioxide as a fluidization gas in a cold model CFB installation. The analysis includes also the effect of gas mixture on gas velocity changes.

The investigations were carried out in the 3D cold model stand which consists of chamber in the plan of square, with the similarity to the 460 MWe supercritical Lagisza boiler height in the scale of 1:20, connected via a crossover duct to recirculation system which consists of the cyclone, return leg and a non-mechanical syphon. Air or carbon dioxide is fed to the wind box. Cold model is equipped with ports for glass beads samples collecting. Pressures in the contour of the riser are measured in 22 measuring ports.

The particle size distribution of used glass beads were prepared on the base of two scaling methods of the scaled down material taken from furnace of Lagisza 460 MWe CFB boiler. Both air as carbon dioxide was fed to the furnace only as primary air/carbon dioxide.

Introduction

Fluidization technologies are well a well established technology for a generation of power from not only carbon rich fuels like coal but also biomass and waste-fuels as a CO_2 neutral fuels. The aim of the paper is determining of the knowledge of fluidization hydrodynamics and solids concentration in the contour of riser in the atmosphere of carbon dioxide in a circulating fluidized bed and comparative analysis between fluidization's hydrodynamics and solids concentrations in the contour of the riser in the atmosphere of carbon dioxide and air atmosphere. Knowledge of fluidization process in the carbon dioxide atmosphere is very important from the oxy-fuel combustion point of view where rich in carbon dioxide recirculated flue gas is mixed with oxygen and put into the combustion chamber as fluidization gas. Commercial development is much more rapid than scientific investigations carried out in the case of fluidization in atmosphere of other gases than atmospheric air, because the demo oxy-fuel power plant are built or are during of the construction process but there is total lack of any information about changes in hydrodynamic condition after change of fluidization gas.

The solids concentration in the contour of the combustion chamber and the particle size distribution (PSD) of the circulating material determining e.g. the solids circulation rate and the heat transfer has the significant influence on the operating

performance of the power plant. The PSD of the circulating material is affected by the PSD of the ash formed during the combustion process and is influenced mainly by the separation inside the boiler and the cyclone efficiency [1].
The PSD together with solids flows fed into to the boiler: limestone, bed material, fuel, re-circulated fly ash/bottom ash and internal material recirculation depending on the separator efficiency, as well reactions are the key features influencing population balance [2, 3].
Types of powders employed strongly influence the fluidization phenomena of the gas-solids system. On the base of the behavior of solids fluidized by gases, powders were divided by Geldart into four recognizable groups i.e. Groups A, B, C and D [4, 5]. These groups are classified by the characterization of the density difference between the particle and fluidization medium ($\rho_p - \rho_g$) and mean particle size d_p. It is worth of saying that these data are received for ambient pressures and temperatures and air as a fluidization gas, so it is not applicable for elevated pressures and temperatures and other than air fluidization gases. That's provided to conclusion that demarcating line for each Group will be shifted in elevated pressures and temperatures and other gases.
Taking into consideration the vertical distribution of solids particles, the combustion chamber is divided into following zones: bottom bed zone, splash (diluted) zone and transport area. On the base of [6, 8, 9] investigations, the bottom bed zone can be consider as a bubbling bed with constant solids concentration and exploding bubbles, the constant pressure drop with negligible influence of the gravity acceleration, average bulk density about 800 to 1200 kg/m^3 and these values correspond to bed porosity of 0.54 to 0.70. Despite if it is a bubbling fluidized bed or a CFB this area is the entrance zone for fuel, air and recirculated bed material and for the CFB boiler in normal operating conditions is present in the lower part of the combustion chamber [7]. The upper zone is characterized by the exponential decay of the solids particles concentration in the vertical direction and with strong solids backmixing throughout the cross-section. The core-wall layer of the transport zone in the large-scale capacity units has it equivalent in the core-annulus structure for the circular cross-sectional combustion chamber with small capacity (significant axial segregation of particles) [10]. On the base of investigations [10] it is seen that the significant backmixing is presented in the wall region and flow is low in the core area downward. In this area are visible two kinds of vertical transports: external (particles which attained the furnace exit) and internal (particles from the wall-layer). The core and upper dilute regions are almost about 70% to 80% of the combustion chamber volume [11].
The purpose of this study is to define the influence of the type of fluidization gas – air and carbon dioxide, on the suspension density to investigate the hydrodynamic differences for two types of gases.

Experiment

The investigations were carried out in the cold model stand. A schematic of the cold model circulating fluidized bed riser in which experiments were carried out is shown in Figure 1a. The 3D cold model installation is made of transparent plexiglass what give possibilities to observe processes during the test. The only one element is made from the steel – expansion tank where after expansion of fluidizing gases the smallest particles which were not separated by the cyclone falling to the bottom of the tank and falling into plexiglass vessel (Figure 1b). The 3D cold model stand consists of chamber in the plan of square with the side diameter of 0.1 m, with the similarity to the Lagisza boiler height in the scale of 1:20, connected via a crossover duct to the cyclone. Glass beads separated in the cyclone are returned to the riser via a 0.05 m I.D. return leg and a non-mechanical siphon (Picture 1c). Air or carbon dioxide is fed to the wind box as in the real combustor. A syphon located in the recirculation part has additional wind box where additional air or carbon dioxide is fed to transport recirculated glass beads back to the riser. The cold model is equipped with ports for bottom, circulating, in riser samples and equivalent of fly ash samples collecting ports. Pressures in the contour of the riser are measured by the Aplisens sensors in 22 measuring ports. The measuring system has an electronic pressure convertor Aplisens of ±2.5kPa and ±50kPa working in current loop.

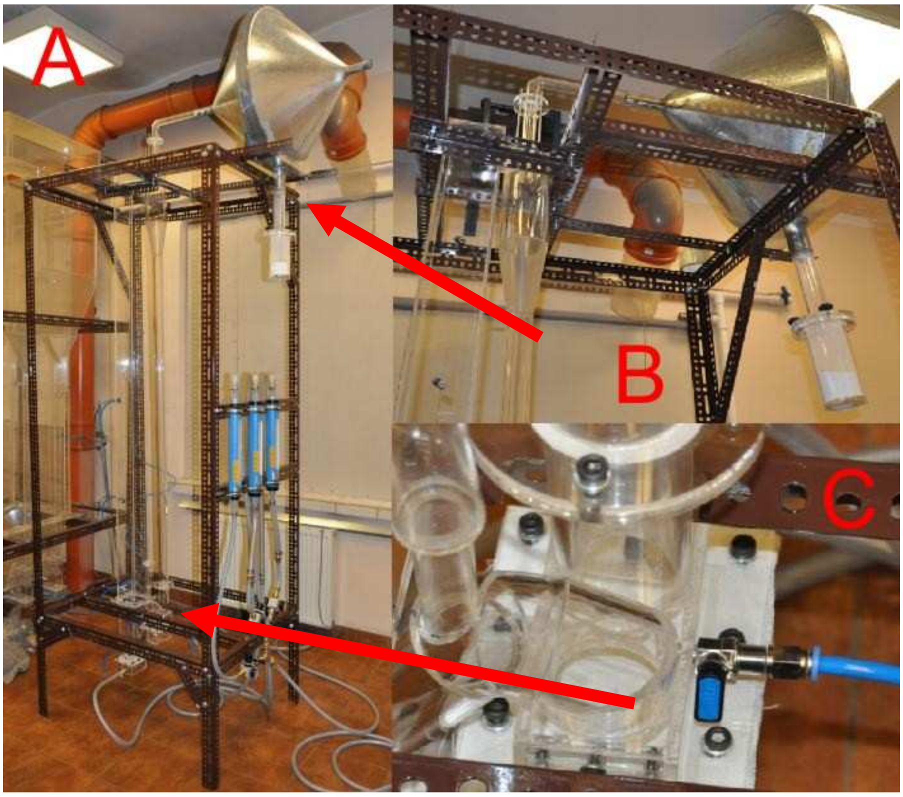

Figure 1. a) 3D cold model plexiglass circulating fluidized bed installation; b) cyclone and expansion tank; c) non-mechanical syphone and port for circulating glass beads collecting.

Glass beads are used as the bed material. They are prepared on the base of two scaling down methods. According to this method the particle size distribution of inert material from Lagisza Power Plant is scaled down for the laboratory conditions. These methods are presented wider in [12].
As long as the bed is fluidized, the pressure drop increases and follows the Ergun equation (Eq.1).

$$\frac{\Delta P}{H} = 150\frac{(1-\epsilon)^2}{\epsilon^3} \times \frac{\mu U}{(\emptyset d_p)^2} + 1.75\frac{(1-\epsilon)}{\epsilon^3} \times \frac{\rho_g U}{\emptyset d_p} \qquad (1)$$

The minimum fluidization velocity U_{mf} can be determined from the equation below

$$Re_{mf} = \frac{d_p U_{mf} \rho_g}{\mu} = [C_1^2 + C_2 Ar]^{0.5} - C_1 \quad (2)$$

where

$$Ar = \frac{\rho_g(\rho_p - \rho_g) g d_p^3}{\mu^2} \quad (3)$$

C_1 and C_2 are equal 27.2 and 0.0408, respectively [13]. The U_{mb} was considered as equal to U_{mf} what means that the bed will form bubbles immediately.
The minimum slugging velocity U_{sl} is calculated on the base of Stewart and Davidson equation [14]

$$U_{sl}=U_{mf} + 0.07(gD)^{0.5} \quad (4)$$

The terminal velocity is essentially the slip velocity between the gas and particle in a pneumatic transport and for the spherical particles was obtained from the equation

$$\frac{d_p U_t \rho_g}{\mu} = \left[\frac{Ar}{7.5}\right]^{0.666} \text{Intermediate Law } 0.4<Re<500 \quad (5)$$

These relations gave the base for the tests assumptions. In Table 1 parameters of Lagisza SC-CFB boiler and two small scale equivalents received on the base of scaling methods are shown.

Table 1. Parameters of Lagisza SC-CFB boiler and small scale equivalents received on the base of scaling methods.

Parameter	Unit	Lagisza SC-CFB	Scale-down model A
U_0	m/s	5.10	1.48
d_{32}	µm	122.99	44.05
d_{50}	µm	234.57	84.01
P_S	kg/m^3	2700	2500
P_f	kg/m^3	0.3095	1.204
µ	Pa s	4.456*10^{-5}	1.813*10^{-5}
t	℃	850	20
U_T	m/s	0.479	0.139
Re_D	-	4.357	4.357
Ar	-	7.68	7.68
U_{mf}	m/s	0.00639	0.00186

Results and discussion

All tests were carried out for the one scaling down method and the same amount of glass beads. According to the preliminary investigations, the amount of glass beads which results in proper pressure distribution in the contour of the riser is 1.5 kg of glass beads. Glass beads were prepared on the base of scaled down in-furnace material's particle size distribution (PSD) from Lagisza Power Plant with a mean diameter of d_{32}=44µm.
There were carried out ten test for ten different velocities varied from 0.01 m/s to 1.25 m/s. Investigations were carried out than smaller velocity U_0 than calculated from Lagisza Power plant, which should be equal 1.48 m/s for 100% of load.

The suspension density was obtained on the base of pressure differences between each pressure measuring port, from the following equation

$$\rho_{susp} = \Delta p \cdot 9.81^{-1} \cdot \Delta h^{-1} \qquad (6)$$

Investigations for a bubbling fluidized bed were carried out for velocities: 0.01 m/s, 0.02 m/s, 0.04 m/s, 0.05 m/s, 0.07 m/s, 0.09 m/s, 0.11 m/s, 0.14 m/s, 0.16 m/s both air and carbon dioxide. The distribution of solids concentration along the height of combustion chamber for each bubbling fluidized bed velocity is presented in Figure 2. As it is seen below, the largest difference between air and carbon dioxide condition is presented for the smallest velocity of U=0.01 m/s and suspension density is equal even 600 kg/m^3 and this difference is present at the height of 0.07 m from the grid and it is higher ca. 38% for air conditions than for carbon dioxide. At this velocity only at the lowest level – at the height of 0.03 m from the grid, the suspension density is 14% higher for carbon dioxide conditions. This means than coarser material is more concentrated in the lowest part in a bubbling fluidized bed. With the rise of velocity only till 0.04 m/s (Figure 2c) the situation changes and the suspension density is higher for air blown conditions about 13% at the level of 0.03 m from the grid and 9% lower for the air blown conditions at the level of 0.05 m from the grid. This can be caused that coarser material is transported into higher level at higher velocity in the case of carbon dioxide conditions and influence of higher carbon dioxide density and viscosity when compare to air. Material at the lowest level at the lowest velocity is “glued” by carbon dioxide. With an increase of velocity above 1m/s, differences are really small and mainly not higher than 13% between each other – average is 4-5% (values lower for the carbon dioxide conditions). The largest differences favored air blown condition are noticeable in the lowest level of the chamber – 0.03 m from the grid and equal about 10% - the highest difference is seen for the velocity 0.09 m/s and is equal 13%. As it is seen in the Figure 2 g, h the differences between suspension densities increase and values are higher for the air conditions in the range of bed height from the grid to 0.15 m below the grid – differences are in the range from 7 to 16% in the lowest level of combustion chamber, and above the level of 0.15 m from the grid are almost the same.

The solids concentration distribution for air and carbon dioxide velocity equal 1.25m/s – circulating fluidized bed condition is shown in Figure 3. In this graph are strongly visible zones characteristic for the circulating fluidized bed, what provide to conclusion that the installation is well designed and operate in right way. As it is seen the largest difference is in the bed-bottom zone which is equal almost 300 kg/m^3 and is higher for air condition (26% higher) – the same situation was presented for the bubbling fluidized bed condition (Figure 2). Visible difference is present also in transition zone and is equal only about 7 kg/m^3 but in both cases in percentage mean it is more than range from 20% to 30%. In the dilute upper region the difference is equal ca. 30% for air blown conditions. According to investigations the suspension densities are higher for the air conditions in the case of the same velocity along the whole combustion chamber.

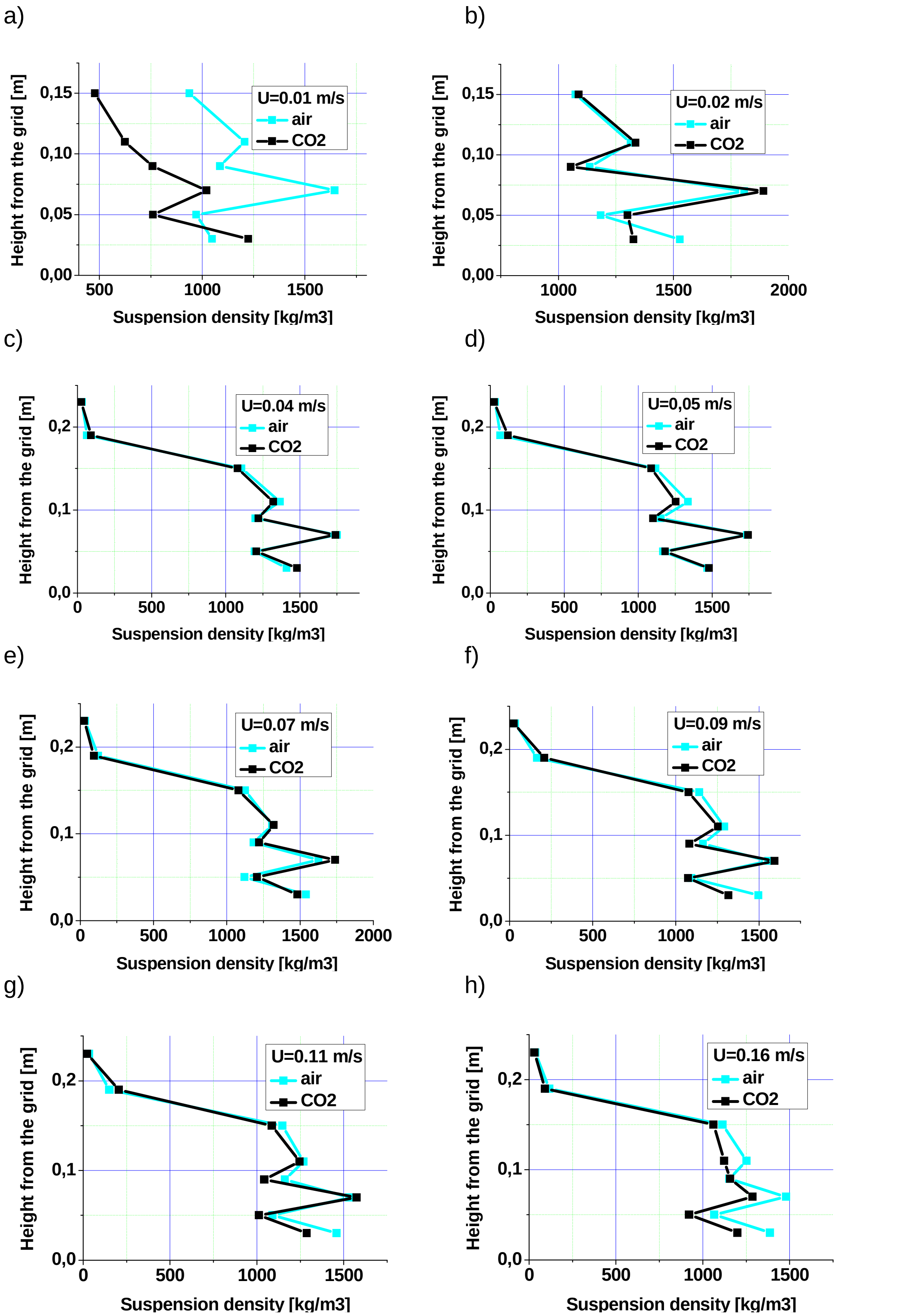

Figure 2. Distribution of solids concentrations for air and carbon dioxide velocities equal 0.01 m/s, 0.02 m/s, 0.04 m/s, 0.05 m/s, 0.07 m/s, 0.09 m/s, 0.11 m/s, 0.16 m/s, respectively.

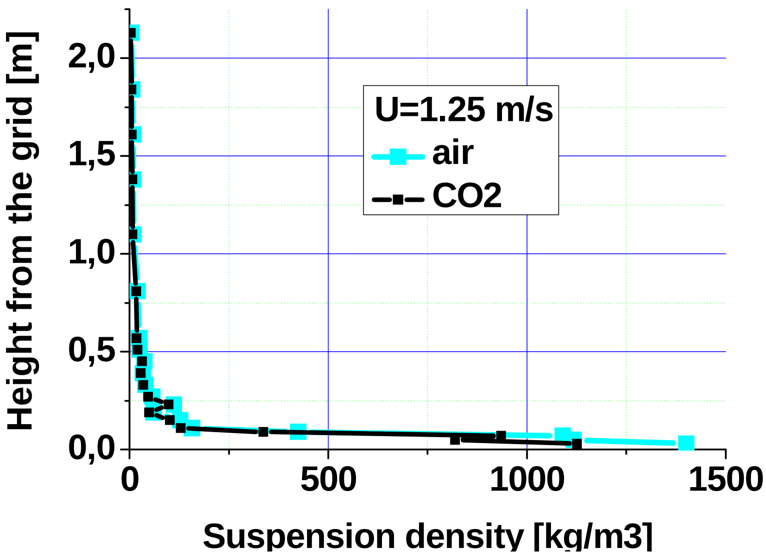

Figure 3. Distribution of solids concentration for air and carbon dioxide velocity equal 1.25 m/s.

Conclusions

According to investigations, the fact that there is present even large difference between suspension densities for each gas, not only in the bottom dense zone, but along contour of combustion chamber for the highest velocity, is caused by the differences in the gas density and viscosity. The largest differences in the suspension densities between air and carbon dioxide both in term of quantity and in percentage terms are registered for the smallest velocity – 0.01 m/s – the nearest to the U_{mf}. For the smallest velocity, in the lowest level of the chamber, the value of the suspension density is higher for the carbon dioxide and at this level is strongly visible the influence of higher carbon dioxide density and viscosity. The Increase of the velocity gives higher values of the suspension density and if it increase is more visible, values of the suspension density are higher for air conditions, almost along the whole riser – not only in the lowest part of it. For circulating fluidized bed conditions, suspension density values along the whole combustion chamber for air as fluidization gas are higher than for carbon dioxide. These investigations give realistic results because of the fact all test were conducted for the scaled-down material from the large-scale boiler, not for mono-fraction.

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Symbols:
U - the superficial gas velocity (defined as the gas flow rate per unit cross section of the bed), m/s
$\in$ - the void fraction in the bed, -
d_p - the diameter of bed solids, µm
Ø - sphericity of bed solids,
µ - the viscosity of the gas, Pa*s
D – diameter of the bed, m
ρ_g, ρ_p - the density of the gas and solids, respectively, kg/m^3
ρ_{susp} – suspension density, kg/m^3
Δp – pressure difference, Pa
Δh – difference between pressure measuring ports, m

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