ISSN 1453 – 7303 “HIDRAULICA” (No. 3/2014)
Magazine *of Hydraulics, Pneumatics, Tribology, Ecology, Sensorics, Mechatronics*

STUDY OF THE FLUIDIZED BED HYDRODYNAMICS FROM THE ENERGETIC BOILERS USING DIFFERENT TYPE OF SOLID PARTICLES

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Abstract: *This paper presents the determination manner of the pressure drop, the minimum fluidization velocity and the floatation velocity of the solid particles in the fluidized beds, depending on the type of material used and on the size of the solid particles, making a comparison between the theoretical and experimentally determinations.*

Keywords*: fluidizing, fluidization minimum velocity, pressure drop in the bed, floatation velocity of the particles*

1. The fluidized bed - introductory notions

Definition

The fluidized bed is a system in which a gas, distributed by a distribution device (grid or jet nozzles), is expelled, from bottom to top, through a bed of solid particles, so that the particles float in the gas stream into a constant agitation.

Overview of fluidized bed combustion technology

The basic concept of the fluidized bed combustion technology consists in that in the combustion chamber is realized a hot bed of solid particles (e.g., coal, coal ash, gypsum, dolomite, calcium carbonate, silica sand, etc .) and is fluidized by an air flow which is introduced into the outbreak over to the bottom, keeping the bed in a sustentation state. Due to the layer homogeneity, the fuel particles are rapidly distributed in bed and are burned rapidly producing heat at elevated temperatures to generate steam, to heat water or for other technological purposes. Solid particles are continuously fed in layer and the ash which remains after burning is always removed to maintain a constant volume of solids in bed. Due to the rapid mixing of the particles layer respectively due to the higher combustion efficiency, the amount of unburned material layer is low. For a proper functioning of the layer, it is maintained in the temperature range 750°C÷950°C, the temperature at which the ash is soft and fine.

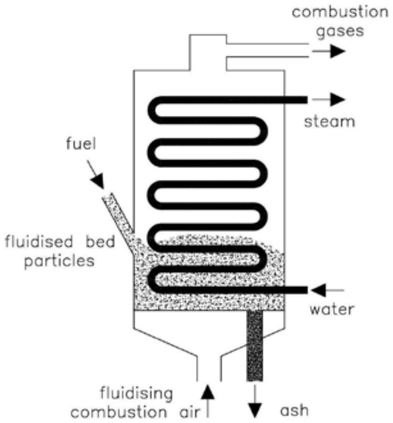

Fig. 1 The principle of fluidized bed combustion of the solid fuels

2. Aspects of fluidized bed combustion process

It is assumed that the combustion in the fluidized bed takes place in the same way as the combustion of a single particle because the carbon concentration in the fluidized bed combustion is about 1÷2%.

The fluidized bed combustion process for a single particle is performed in four stages:

- heating and drying;
- release and combustion of the volatiles;
- primary fragmentation;
- fuel combustion, secondary fragmentation and abrasion.

The Figure 2 shows in a schematized form this burning process.

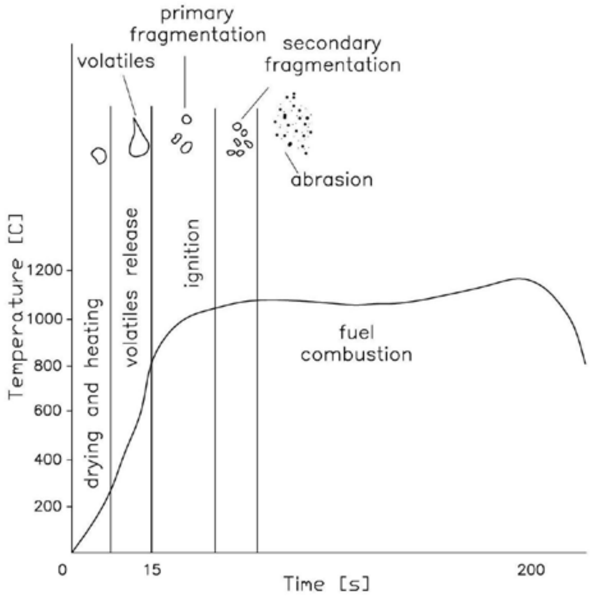

Fig. 2 The stages succession for combustion of solid fuel particles [4]

So, it is necessary to analyze the combustion of a single particle before getting an overview of fluidized bed combustion process, after which may be quantified the results.

In literature there are many models for specific processes (hydrodynamics, heat and mass transfer, combustion) occurring in steam generators with fluidized bed combustion technology, but their use must be made with more caution.

3. The fluidized bed hydrodynamics

3.1 Determination of the pressure loss and of the minimum fluidization velocity

The fluidization state represents a biphasic dispersed system, one phase being constituted of solid particles and gas flowing amongst the particles (dispersion) and a bubble phase, made up from the gas phase and a small proportion of the solid particles found in sustentation, inside the bubbles. [5]

The fluidized bed, because of its structure and laws, is an intermediate state between two limit regimes: fixed bed and pneumatic transport. For this reason, its study is approached for particularizations on the two cases. There is a critical value of the velocity at which it starts to produce the expansion of a solid phase fraction, while the majority of the particles are still fixed. In this case, the pressure loss of the gas in the layer is equal to the weight of the solid phase reported to the surface of the fluidization grid:

$$\Delta p_{mf} = (1-\varepsilon_{mf}) \cdot (\rho_s - \rho_g) \cdot g \cdot H_{mf} \text{ [Pa]} \tag{1}$$

where: H_{mf} [m] is the height of the layer at incipient fluidization conditions;

ε_{mf} [-] is the bubbles fraction in the layer at incipient fluidization conditions;

ρ_s, ρ_g [kg/m³] represents the density of solid and gas;

g [m/s²] is the gravity acceleration.

In order to determine the pressure loss in a fixed bed with solid particles of diameter d_p and sphericity ϕ_s, it is used the Ergun's equation: [4]

$$\frac{\Delta p}{H} = 150 \cdot \frac{(1-\varepsilon)^2}{\varepsilon^3} \cdot \eta \cdot \frac{w}{(\phi_s \cdot d_p)^2} + 1{,}75 \cdot \frac{1-\varepsilon}{\varepsilon^3} \cdot \rho_g \cdot \frac{w^2}{\phi_s \cdot d_p} \tag{2}$$

where: η [N·s /m²] is the dynamic viscosity of the gas;

w [m/s] is the gas velocity.

Replacing $\Delta p/H_{mf}$ from (1) in (2) it obtained a criterial relationship from which it can determine the minimum fluidization velocity:

$$Ar = 150 \cdot \frac{1-\varepsilon_{mf}}{\phi_s^2 \cdot \varepsilon_{mf}^3} \cdot Re_p + 1{,}75 \cdot \frac{1}{\phi_s \cdot \varepsilon_{mf}^3} \cdot Re_p^2 \tag{3}$$

where: $Ar = \frac{g \cdot d_p^3}{\nu_g^2} \cdot \frac{\rho_s - \rho_g}{\rho_g}$ is the criterion of Archimedes;

$Re_p = \frac{w \cdot d_p}{\nu_g}$ is the criterion of Reynolds;

ν_g [m²/s] is the kinematic viscosity of the gas.

For small particles ($Re_p < 20$) predominate the viscous forces, the equation (3) can be simplified, resulting the minimum fluidization velocity:

$$w_{mf} = \frac{(\phi_s \cdot d_p)^2}{150} \cdot \frac{\rho_s - \rho_g}{\eta} \cdot g \cdot \frac{\varepsilon_{mf}^3}{1-\varepsilon_{mf}} \text{ [m/s]} \tag{3'}$$

For larger particles ($Re_p > 1000$) predominate the kinetic energy losses, the minimum fluidization velocity being approximated with:

$$w_{mf} = \sqrt{\frac{\phi_s \cdot d_p}{1{,}75} \cdot \frac{\rho_s - \rho_g}{\rho_g} \cdot \varepsilon_{mf}^3 \cdot g} \text{ [m/s]} \tag{3''}$$

If ε_{mf} or ϕ_s are unknown, can be made following approximations, valid for a variety of systems: [6]

$$\frac{1}{\phi_s \cdot \varepsilon_{mf}^3} \cong 14 \text{ and } \frac{1-\varepsilon_{mf}}{\phi_s^2 \cdot \varepsilon_{mf}^3} \cong 11 \tag{4}$$

After replacing in (3), (3’) and (3”) results:

$$w_{mf} = \frac{d_p^2 \cdot (\rho_s - \rho_g) \cdot g}{1650 \cdot \eta} \text{ [m/s], if } Re_p < 20 \tag{5'}$$

$$w_{mf} = \sqrt{\frac{d_p \cdot (\rho_s - \rho_g) \cdot g}{24{,}5 \cdot \rho_g}} \text{ [m/s], if } Re_p > 1000 \tag{5''}$$

In order to calculate the minimum fluidization velocity are given many relationship in the literature (See Table 1). [7]

Tab. 1 Calculation relationships of the minimum fluidization velocity obtained on the experimentally way

No.	Authors	Minimum fluidization velocity, w_{mf} [m/s]	Validity domain	d_p [μm]
1	Baerg	$0{,}361 \cdot \frac{[d_p \cdot \rho_s \cdot (1-\varepsilon_{mf})]^{1{,}23}}{\rho_g}$	$Re_{mf} < 20$	6 – 880
2	Miller, Logwinuk	$0{,}00125 \cdot \frac{d_p^2 \cdot (\rho_s - \rho_g)^{0{,}9} \cdot \rho_g^{0{,}1} \cdot g}{\eta}$	--	97 – 249
3	Leva	$0{,}0079 \cdot \frac{d_p^{1{,}68} \cdot (\rho_s - \rho_g)^{0{,}94}}{\eta^{0{,}88}}$	$Re_{mf} < 10$	51 – 970
4	Frantz	$0{,}001065 \cdot \frac{d_p^2 \cdot (\rho_s - \rho_g) \cdot g}{\eta}$	$Re_{mf} < 32$	46 – 305
5	Davis, Richardson	$0{,}00078 \cdot \frac{d_p^2 \cdot (\rho_s - \rho_g) \cdot g}{\eta}$	--	--
6	Pillai, Raya Rao	$0{,}000701 \cdot \frac{d_p^2 \cdot (\rho_s - \rho_g) \cdot g}{\eta}$	$Re_{mf} < 20$	58 – 1100
7	Baeyens	$0{,}0009 \cdot \frac{d_p^{1{,}88} \cdot (\rho_s - \rho_g)^{0{,}934} \cdot g^{0{,}934}}{\eta^{0{,}87} \cdot \rho_g^{0{,}066}}$	$Re_{mf} < 10$	--

3.2 The floatation velocity

The gas flow through the fluidized bed is limited on the one hand by the minimum fluidization velocity, w_{mf}, and on the other hand by the entrainment of solid particles. When the solid particles are entrained in the layer, they must be recirculated or replaced with a fresh material to keep the operation equilibrium. The upper limit of the gas velocity is approximated by the floatation velocity or by the freefall velocity of the solid particles, which can be estimated from the equilibrium equation between the gravity force and the particle resistance force at the displacement of the gas stream:

$$w_{pl} = \sqrt{\frac{4 \cdot g \cdot d_p \cdot (\rho_s - \rho_g)}{3 \cdot C_x \cdot \rho_g}} \text{ [m/s]} \tag{6}$$

In (6) the coefficient C_x is experimentally determined. An alternative variant for determining the floatation velocity is to calculate the C_x coefficient for spherical particles, replacing in (6) and applying some correction factors.

For calculation of the C_x coefficient exist a lot of variants, the most commonly used being the method proposed by M. Leva: [3][8]

$$C_x = \frac{24}{Re} \text{ for Re < 2; } C_x = \frac{18{,}5}{Re^{0{,}6}} \text{ for 2 < Re < 500;}$$

$$C_x = 0{,}44 \text{ for Re < 200.000} \tag{7}$$

Kuni and Levenspiel propose the same method of calculation with small differences in formulas and in validity domains: [7]

$$C_x = \frac{24}{Re} \text{ for Re < 0,4; } C_x = \frac{10}{Re^{0{,}5}} \text{ for 0,4 < Re < 500;}$$

$$C_x = 0{,}43 \text{ for Re < 200.000} \tag{8}$$

4. Results

According to the theoretical method of determining the minimum fluidization velocity respectively the pressure loss in layer, there were determined its values depending by the variation of the solid particle diameter (Figures 3 and 4). There were taken into account several types of solid particles with following densities:

Coal	ρ_s = 1545 kg/m³
Gypsum	ρ_s = 2320 kg/m³
Dolomite	ρ_s = 2872 kg/m³
$CaCO_3$	ρ_s = 3320 kg/m³

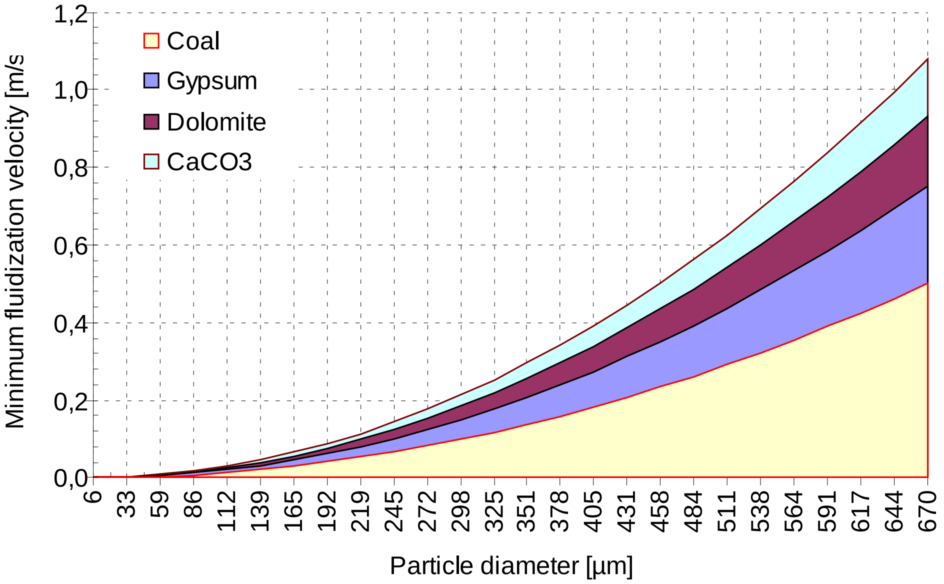

Fig. 3 Variation of the minimum fluidization velocity (theoretically determined) depending by the particle diameter

Conditions: $\rho_g = 0,4\ kg/m^3$, $\varepsilon_{mf} = 0,45$, $\eta_g = 1,5\times10^{-5}\ Ns/m^2$

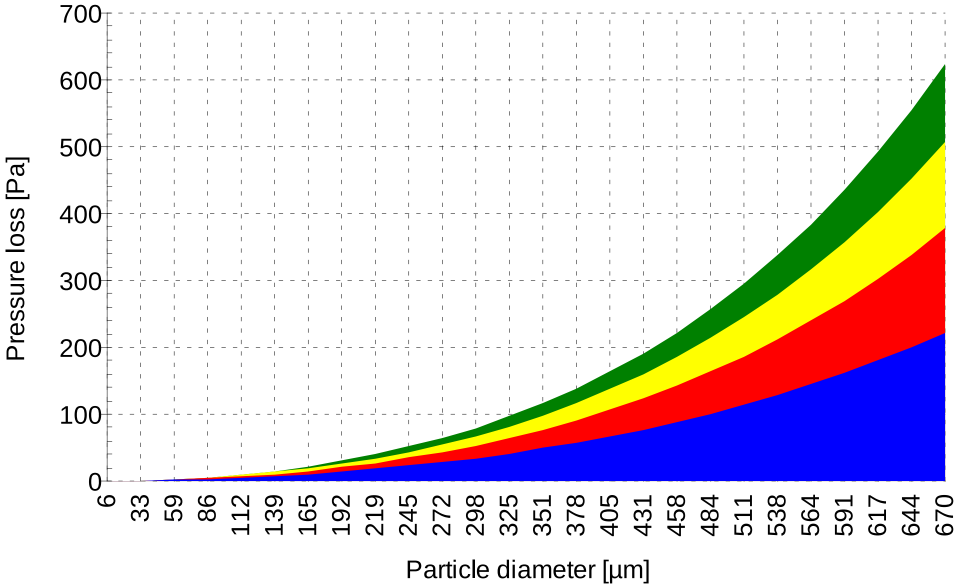

Fig. 4 Variation of the pressure loss in layer depending by the particle diameter

Conditions: $\rho_g = 0,4\ kg/m^3$, $\varepsilon_{mf} = 0,45$, $\eta_g = 1,5\times10^{-5}\ Ns/m^2$

Considering the calculation manner of the minimum fluidization velocity in the specific conditions of fluidized bed combustion (shown in the Table 1), below, there were graphically presented its values depending by the particle diameter modification, for each solid material taken into account.

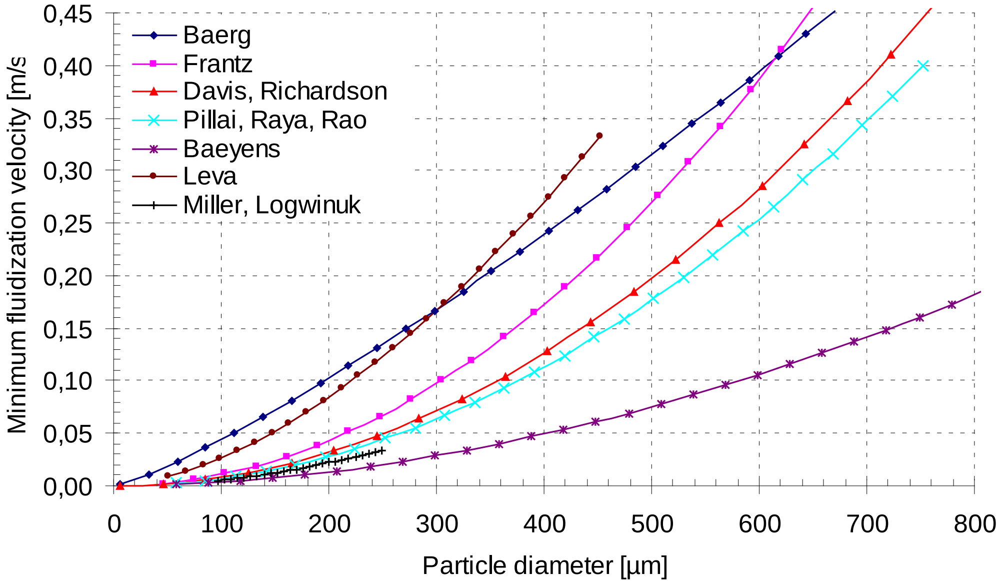

Fig. 5 Variation of the minimum fluidization velocity depending by the particle diameter, determined with calculation relationships proposed by various authors

Conditions: ρ_s = 1545 kg/m^3, ρ_g = 0,4 kg/m^3, ε_{mf} = 0,45, η_g = 1,5×10^{-5} Ns/m^2

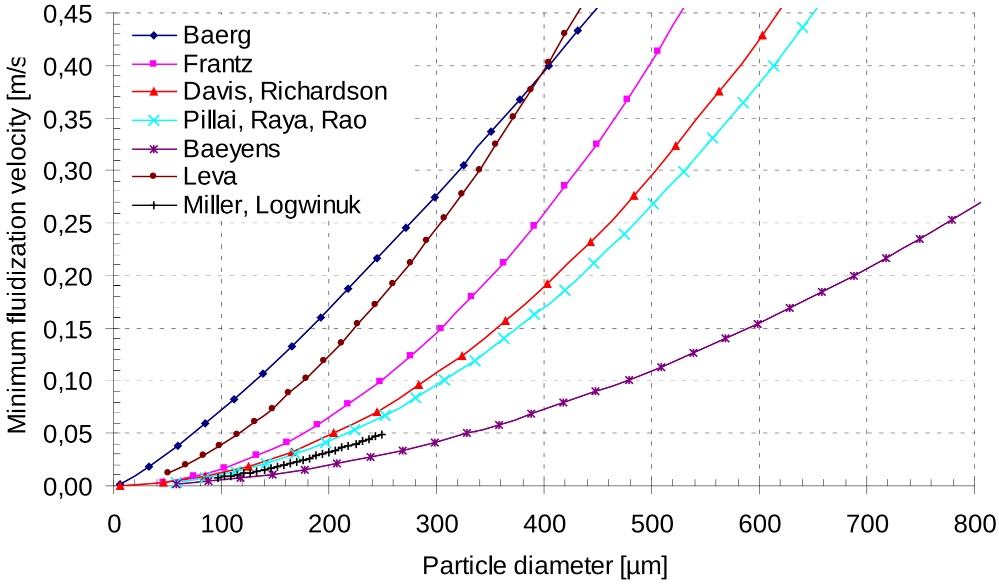

Fig. 6 Variation of the minimum fluidization velocity depending by the particle diameter, determined with calculation relationships proposed by various authors

Conditions: ρ_s = 2320 kg/m^3, ρ_g = 0,4 kg/m^3, ε_{mf} = 0,45, η_g = 1,5×10^{-5} Ns/m^2

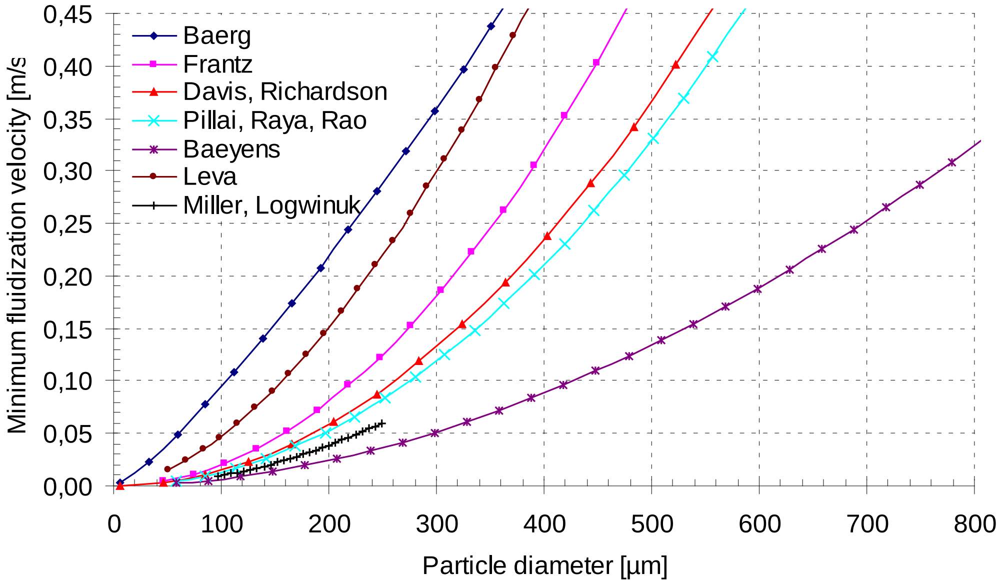

Fig. 7 Variation of the minimum fluidization velocity depending by the particle diameter, determined with calculation relationships proposed by various authors

Conditions: ρ_s = 2872 kg/m^3, ρ_g = 0,4 kg/m^3, ε_{mf} = 0,45, η_g = 1,5×10^{-5} Ns/m^2

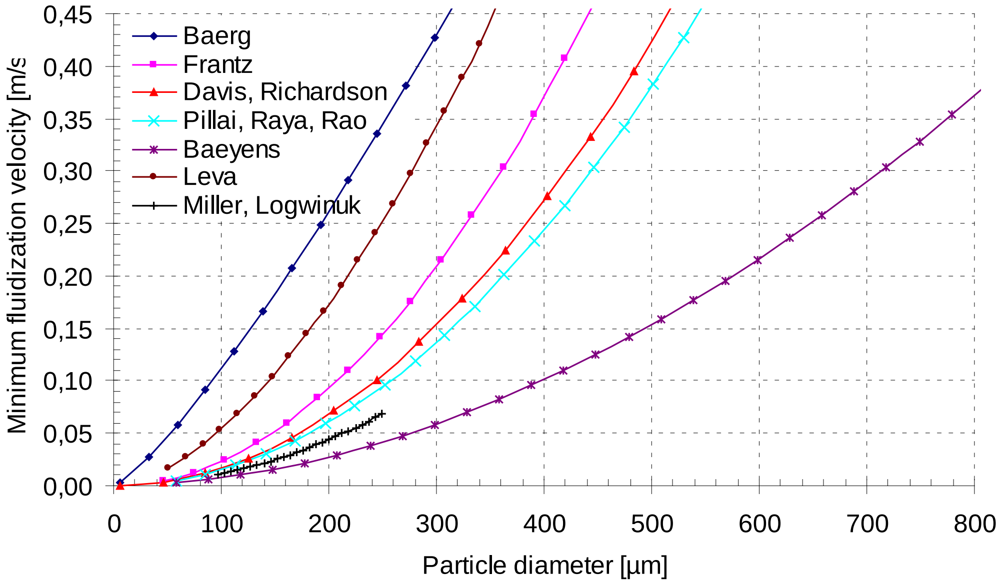

Fig. 8 Variation of the minimum fluidization velocity depending by the particle diameter, determined with calculation relationships proposed by various authors

Conditions: ρ_s = 3320 kg/m^3, ρ_g = 0,4 kg/m^3, ε_{mf} = 0,45, η_g = 1,5×10^{-5} Ns/m^2

In the Figure 9 it shows the variation of the floatation velocity depending by the particle diameter, in the specific conditions of the fluidized bed combustion, for the mentioned solids particles.

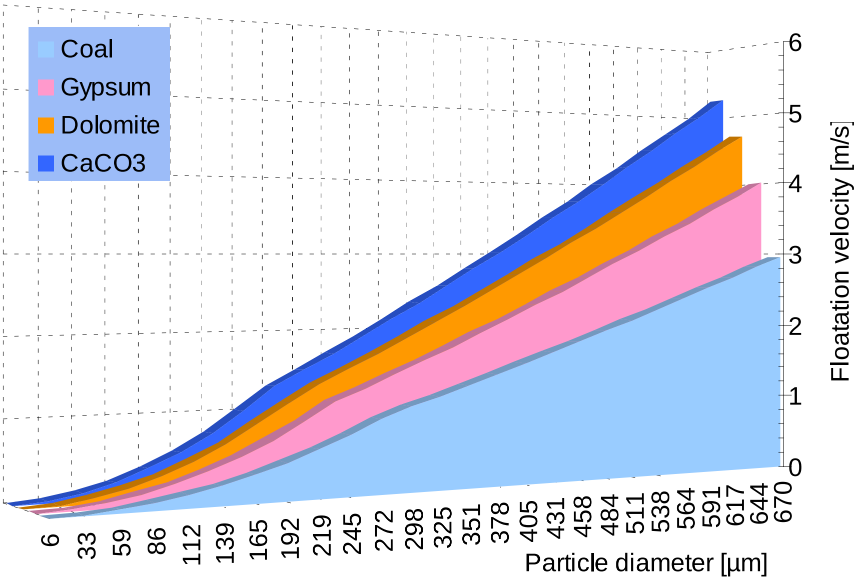

Fig. 9 Variation of the floatation velocity depending by the particle diameter

Conditions: $\rho_g = 0{,}4\ kg/m^3$, $\varepsilon_{mf} = 0{,}45$, $\eta_g = 1{,}5\times10^{-5}\ Ns/m^2$

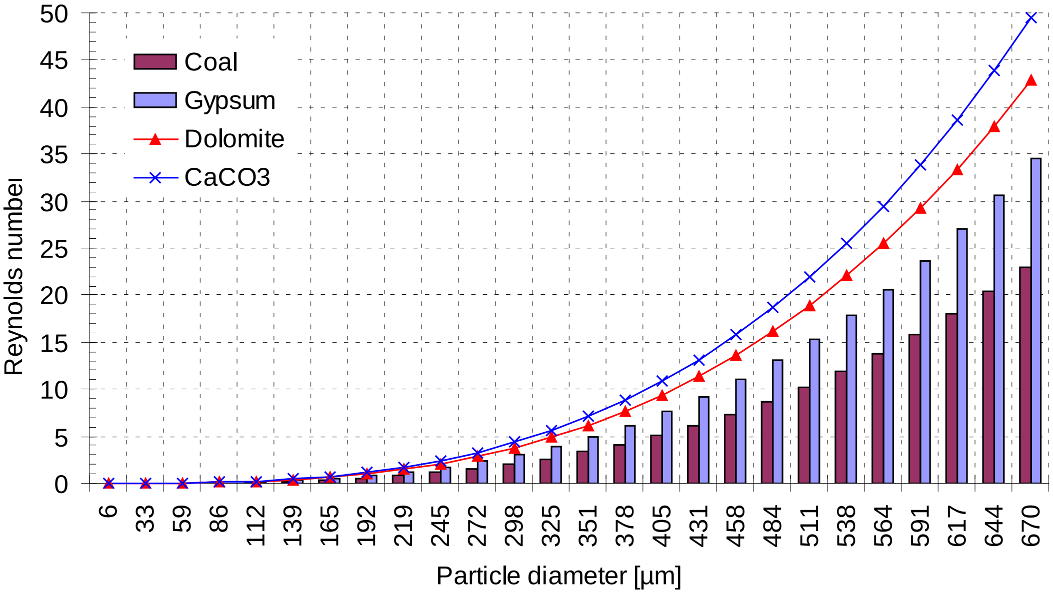

Fig. 10 Variation of the Reynolds criterion depending by the particle diameter to determine the floatation velocity

Conditions: $\rho_g = 0{,}4\ kg/m^3$, $\varepsilon_{mf} = 0{,}45$, $\eta_g = 1{,}5\times10^{-5}\ Ns/m^2$

4. Conclusions

When determining the theoretical values of the minimum fluidization velocity respectively the pressure loss in layer depending on the particle diameter, using several types of solid materials, it resulted that: the minimum fluidization velocity values have an increasing trend with rising of the particle diameter, and also when the material used has an increasingly larger density. In terms of pressure loss determined under the same conditions, its values increase in the same way as minimum fluidization velocity values.

Given the results of the calculations of minimum fluidization velocity, shown in the Figures 5, 6, 7 and 8, it is noted that the minimum fluidization velocity has an upward trend with increasing of the particle diameter. For the whole values range of the particle diameter, it recorded close values between the curves of Frantz, Davids, Richardson and Pilai, Raza, which also have a pronounced upward tendency. The curves of Baerg and Leva have maximum values and Baeyens have minimum values for whole range of values. Since the material is different, it changes its density, and thus, the minimum fluidization velocity is even higher with increasing of the used material density. Considering the minimum fluidization velocities found on the experimentally and theoretically way, for the considered solid materials, it appears that, for the experimentally determination, the minimum fluidization velocity values are lower than the ones resulted by the theoretical determination.

From the Figure 9 it is observed that the floatation velocities, calculated for different solid materials depending on the particle diameter variation, have higher values with increasing of the particle diameter and of solid material density, taking into account the values of the Reynolds criterion determined by the particle dimension size (shown in Figure 10).

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List of notations:

Notation	Description	UM
NO_x	Nitrogen oxides	-
SF	Fluidized bed	-
Δp_{mf}	Pressure drop of the gas layer	Pa
ε_{mf}	Bubble fraction in the layer under the incipient fluidization conditions	-
ρ_s	Density of solids	kg/m^3
ρ_g	Density of gas	kg/m^3
g	Gravitational acceleration	m/s^2
H_{mf}	Layer height under the incipient fluidization conditions	m
d_p	Particle diameter	m
ϕ_s	Particle sphericity	-
η	The dynamic viscosity of the gas	Ns/m^2
w	The gas velocity	m/s
Ar	Archimedes criterion	-
Re	Reynolds criterion	-
ν_g	Gas viscosity	m^2/s