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MINIMUM FLUIDIZATION VELOCITY OF A LIGHTWEIGHT CERAMIC AGGREGATE

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Abstract: Fluidized bed technology is widespread in industrial processes and thus understanding of basic behaviour is key issue for effective operation of fluidization devices. This paper focuses on the field of minimum fluidization velocity of a lightweight ceramic aggregate (LWA), which is an external bed material for combustion of biomass. Minimum fluidization velocity represents one of the elementary parameters and is used in calculation of other characteristic parameters of fluidized beds as well. Several equations are available for its calculation, however results of the calculation procedure can be significantly different. In this paper are confronted equations of minimum fluidization velocity available from literature with experimental data using a LWA with three different particle size distributions. The most appropriate equations are used for further calculation of influence of temperature on the point of incipient fluidization.
Keywords: fluidized bed combustion, minimum fluidization velocity, lightweight ceramic aggregate

1. INTRODUCTION

Understanding of fluidized bed material behaviour is essential for a reliable design calculation procedure of bubbling fluidized bed combustors. From this point of view the minimum fluidization velocity and terminal velocity of particles are the most important parameters. Selection of the lightweight ceramic aggregate (LWA) as inert bed material is based on tendency to find appropriate material for biomass combustion application.

Fluidized bed consist of inert particles, which is intended to provide a uniform concentration of reactants as well as improve characteristics of heat and mass transfer. Coal ash and quartz sand are commonly used bed materials in combustion applications, but these materials are characterized by high pressure drop [1] and sometimes by hard predictable behaviour under conditions closed to the minimum fluidization velocity. Due to sufficient properties, such as temperature stability, sphericity and low density, the LWA was tested in CTU laboratories in biomass combustion process with promising results, because it is easier to reach full fluidized bed regime for LWA than for materials with wide particle size distribution. The LWA is distinguished by distinct change from the fixed bed regime to the fluidization regime. In case of coal ash the particulate fluidization regime were observed. It is caused by wide spectrum of particles diameters.

2. EXPERIMENTAL SETUP – Specification of the bed material

Experiments were carried out in experimental plexi-glass fluidized bed reactor at ambient conditions. The reactor is designed as vertical cylindrical chamber with plenum area and perforated plate distributor. Diameter of the reactor is 0.22 m and the height exceeds 1 m. The minimum fluidization velocity was evaluated by means of pressure drop measurement that was measured at two different points. The first one was measured by digital differential transmitter and for second one using a U-tube manometer. The superficial gas velocity was calculated from air flow meter data measured between the plenum area and a blower.

The lightweight ceramic aggregate is also referred as expanded clay aggregate or exclay and is commonly used in civil and construction engineering as insulation backfill or concrete additive. However, this material is well suitable for fluidized bed combustion due to its physical properties, e.g. low overall bed pressure drop at comparable bed heights with other materials and high terminal velocity of particles. For the experiment were selected three samples of LWA with different particle size distribution. Each sample was analysed for particle size distribution, bulk density and particle density. Basic characteristics of the tested materials are summarized in Table 1.

Table 1. Bed materials characteristics

	Sphericity	Bulk density	Particle density	Mean diameter
	[-]	[kg/m^3]	[kg/m^3]	[mm]
LWA 1	0,89	523	881	2,06
LWA 2	0,72	491	871	2,75
LWA 3	0,70	483	815	3,21

Sieve analysis of samples gives necessary data for calculation of average particle diameter and in this case volume-surface mean diameter is used (Sauter diameter), see equation (1). Figure 1 shows plot of cumulative mass fraction passing through a sieve aperture. Details of sphericity determination are shown below. The minimum fluidizing velocities were obtained by evaluating of pressure drop of the beds with same level of bed depth, specifically 15 cm. For case of LWA-2 bed depth at level 20 cm was also tested with almost identical result.
Sauter mean diameter [1]:

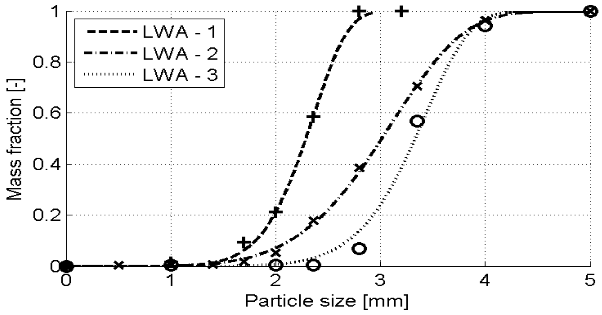

Figure 1. Rosin Rammler approximation of cumulative mass fraction of LWA samples

$$\mathrm{d_m} = \frac{1}{\sum_i \frac{\mathrm{x_i}}{\mathrm{d_{pi}}}} \tag{1}$$

where x_i is mass fraction and d_{pi} is geometric mean of two adjacent sieves.

3. MINIMUM FLUIDIZATION VELOCITY

Minimum fluidization velocity is possible to be determined on the basis of theoretical formula as well as on the basis of a number of empirical formulas. All of these formulas are determined for certain conditions, e.g. range of particle size, range of Reynolds number and or Archimedes number. Also some correlations are intended for narrow particle size distribution and thus the real value of minimum fluidization velocity for bed with wide particle distribution might differ from the calculated value. Correlations used in this paper were chosen from literature [1], [2], [3], [4].

One of the possibilities is Ergun equation (2), which provides pressure drop of fluid flow through a fixed bed of particles. Constants 150 and 1,75 were derived from experiments with different particles and various fluids.

$$\frac{\Delta \mathrm{p_b}}{\mathrm{L}} = 150\frac{(1-\varepsilon)^2}{\varepsilon^3}\frac{\mu_\mathrm{f}\mathrm{U}}{(\varphi \mathrm{d_m})^2} + 1.75\frac{(1-\varepsilon)}{\varepsilon^3}\frac{\rho_\mathrm{f}\mathrm{U}^2}{\varphi \mathrm{d_m}} \tag{2}$$

where Δp_b is pressure drop of the fixed bed, L is height of the bed, ε is fractional voidage, φ is sphericity of particles, μ is dynamic viscosity, U is fluid velocity, d_m is mean diameter and ρ is density. Subscript f in the equation (2) identifies a fluid.

The equation covers laminar flow as well as conditions of turbulent flow. The first term on the right side of the equation (2) is linear and is significant for regime of a laminar flow. The second term becomes more important for higher velocities. Overall pressure drop of a packed bed of particles is given by sum of these two terms. Behaviour of fixed bed pressure drop for particles of LWA - 2 as an example is shown in Figure 2. Here is necessary to mention that the contribution of both terms to overall pressure drop of the fixed bed strongly depends on mean diameter of particles, sphericity and fractional voidage. If we consider particles with similar physical properties with different diameters, for the smaller particles dominates the laminar term. In other words, pressure drop of these particles depends weekly on turbulent term (laminar term dominates in whole range of fixed bed region). With increasing particle diameter the contribution of the turbulent term also increases. Thus the mean particle diameter influences shape of pressure drop curve in fixed bed as well as the sphericity of particles, listed in Table 1. Other necessary characteristics were obtained by analysis, so the sphericity of particles is determined from measured data by fitting the measured pressure drop curve by Ergun equation for flow in the fixed bed.

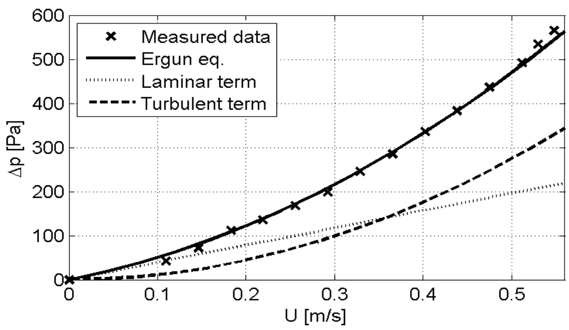

Figure 2. Fixed bed pressure drop behaviour of LWA-2, fluidized by air, t = 15 °C

Minimum fluidization velocity is obtained by solving the Equation (1) for Reynolds number. After rearranging, we obtain:

$$\frac{1.75}{\varphi \varepsilon_{mf}^3} Re_{mf}^2 + 150\frac{(1-\varepsilon_{mf})}{\varphi^2 \varepsilon_{mf}^3} Re_{mf} - Ar = 0 \tag{3}$$

where Re is Reynolds number, Ar is Archimedes number and subscript mf identifies properties at minimum fluidizing velocity. The minimum fluidizing velocity is calculated from definition of Reynolds particle number

$$Re_{mf} = \frac{\rho_f U_{mf} d_m}{\mu_f} \tag{4}$$

Other approach is simplification of the equation (3), where the terms (4)

$$\frac{1}{\varphi \varepsilon_{mf}^3} \ ; \ \frac{(1-\varepsilon_{mf})}{\varphi^2 \varepsilon_{mf}^3}$$

are replaced by constants obtained from experimental data. Constants from different authors are listed in Table 2.
The simplified Ergun equation is then defined as:

$$(Re)_{mf} = \sqrt{C_1 + C_2 Ar} - C_1 \tag{5}$$

Table 2. Coefficients for simplified Ergun equation, [1]

Author	Year	C1	C2
Wen and Yu	1966	33,7	0,0408
Richardson	1971	25,7	0,0365
Saxena&Vogel	1977	25,3	0,0571
Babu	1978	25,25	0,0651
Grace	1982	27,2	0,0408
Chitester	1984	28,7	0,0494

Coefficients listed in Table 2 have certain limitations and are suggested for materials with narrow particle size distribution. Frequently used Wen and Yu correlation is limited for particle diameters in range from 0,04 mm to 20 mm and Reynolds number from 10^{-3} to $4x10^3$. Saxena and Vogel suppose particle diameter from 0,088 mm to 1,41 mm and particle Reynolds number from 6 to 102, which means that these constants cannot be used for the LWA due to insufficient particle size. Other authors did not exactly specify range of suitability of the constants. However, selection of appropriate correlations is simply based on agreement with measured data.

Based on the good results reported in literature [3], three other equations are included, specifically (6) to (8). The article compares the results of an experiment in a temperature range from 30 °C to 600 °C at atmospheric pressure and results for bottom ash and quartz sand fluidized beds are presented. The major difference to the equations above is that these three correlations are determined for a fluidized bed containing a wide spectrum of particle diameters. It means that it includes an influence of particle size distribution on minimum fluidization velocity.

Zhejiang University (ZU) equation (6) was tested on the particles of coal in temperature range from 25 to 800 °C and the Archimedes number range from $2x10^4$ to $700x10^4$.

$$U_{mf} = 0{,}294 \frac{d_m^{0{,}584}}{\nu_f^{0{,}056}} \left(\frac{\rho_p}{\rho_f} - 1\right)^{0{,}528} \tag{6}$$

where ν is the kinematic viscosity and subscript p identifies solid particles.

Northwest University (NU) equation (7) is based on experimental data of coal ash bed

$$(Re)_{mf} = 0{,}129 Ar^{0{,}54} \tag{7}$$

Southeast University (SU) equation (8) is derived from experiments with the fluidized bed of coal ash and quartz sand at temperatures from 30 °C to 600 °C.

$$U_{mf} = 0{,}28 \sum_{i=1}^{n} x_i d_i^{0{,}599} \left(\frac{\rho_p}{\rho_f}\right)^{0{,}533} \frac{1}{\nu_f^{0{,}066}} \tag{8}$$

where x_i is mass fraction of particles with diameter d_i.

Properties of the air used in the following calculations as a fluidizing media are taken from the literature [5].

4. RESULTS AND DISCUSSION

By comparing the calculated results of the minimum fluidizing velocity with measured data is possible to identify unsatisfactory equations. The selection is based on the smallest mean deviation of measured and calculated values, for details see Table 3. The best results were obtained by calculation according to Ergun equation, which has the lowest mean deviation from the measured values (4,8%), Richardson's equation (9,9%), Southeast University equation (8,2%).

In practice, the LWA is fluidized at elevated temperatures that are approximately at level 800 – 900 °C in fluidized bed combustors. It is therefore important to focus on behavior at higher temperatures than in the experiments. Other difference in practice is that the material is particularly fluidized by flue gas that is not considered in the experiments. Fluidization by flue gas results in increase of minimum fluidizing velocity. For selected equations the effect of temperature is calculated in the range from 0°C to 1000°C. The results are plotted in Figure 3, where is possible to observe different shape of temperature effect for Southeast University equation and similar shape has ZU equation and NU equation. All of the simplified forms of Ergun equation have similar function behaviour influenced by different constants. For these equations the temperature, where fluidizing velocity reach its maximum value, is increasing together with particles diameter.

For the three samples of LWA a new coefficients for equation (5) were obtained, C1 = 31,1 and C2 = 0,0314. Promising results are summarized in Table 4.

Table 3. Comparison of minimum fluidization velocity, t = 15 °C

	LWA 1		LWA 2		LWA 3		
	U_{mf}	Deviation	U_{mf}	Deviation	U_{mf}	Deviation	Mean deviation
	[m/s]	[%]	[m/s]	[%]	[m/s]	[%]	[%]
Measured	0,530	--	0,639	--	0,694	--	--
Ergun	0,530	0,0	0,652	2,0	0,607	-12,5	4,8
Groshko	0,446	-15,7	0,563	-11,9	0,525	-24,4	17,3
Wen and Yu	0,569	7,4	0,725	13,4	0,786	13,3	11,4
Richardson	0,570	7,6	0,713	11,5	0,768	10,6	9,9
Saxena & Vogel	0,751	41,8	0,923	44,3	0,988	42,3	42,8
Babu	0,812	53,3	0,994	55,4	1,062	53,0	53,9
Grace	0,603	13,7	0,754	17,8	0,812	16,9	16,13
Chitester	0,670	26,4	0,835	30,5	0,898	29,4	28,8
ZU	0,479	-9,7	0,563	-11,9	0,596	-14,2	11,9
NU	0,815	53,9	0,969	51,5	1,030	48,4	51,3
SU	0,499	-5,8	0,593	-7,3	0,614	-11,6	8,2

Table 4. Minimum fluidization velocity for new coefficients, t = 15 °C

	LWA 1		LWA 2		LWA 3		
	U_{mf}	Deviation	U_{mf}	Deviation	U_{mf}	Deviation	Mean deviation
	[m/s]	[%]	[m/s]	[%]	[m/s]	[%]	[%]
Measured	0,530	--	0,639	--	0,694	--	--
New coeff	0,518	-2,3	0,661	3,4	0,717	3,3	3,0

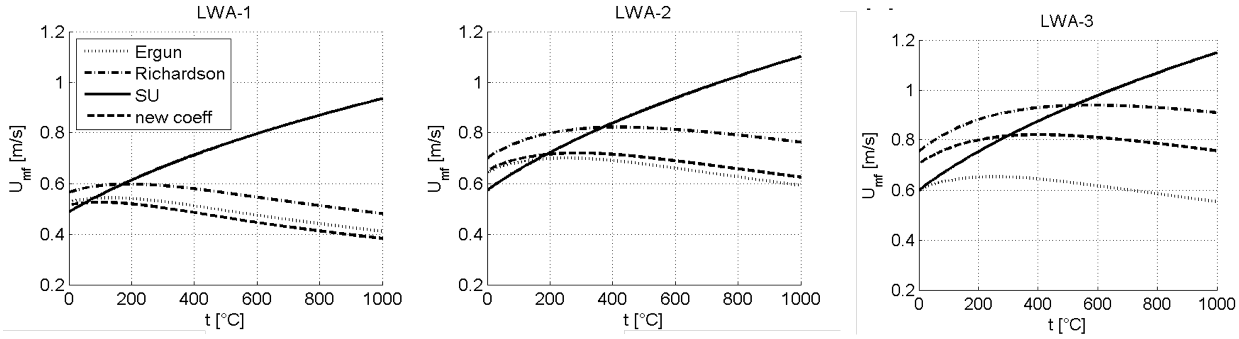

Figure 3. Effect of temperature on minimum fluidizing velocity of LWA

5. CONCLUSIONS

Obtained results show that equations by Ergun, Richardson and Southeast University are very well suitable for LWA under ambient conditions. However, reliable results are sensitive to accurate estimation of bed material characteristics. For example, the Ergun equation is strongly sensitive to fractional voidage at minimum fluidizing velocity. Promising results are given by new coefficients for simplified Ergun equation (5). But three samples are not sufficient number for general coefficient determination. The procedure would require wider set of data. Different function behaviour of equations (6), (7) and (8) under elevated temperatures shows interesting results. The effect of temperature on behaviour of LWA becomes subject of consequent experimental work.

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