A NEW DESIGN METHOD FOR FLUIDIZED BED CONVERSION OF LARGELY HETEROGENEOUS BINARY FUELS

by

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Binary fuels of a fluidized bed combustor or gasifier are solids composed of two groups of particles. Their optimal handling in the same bed becomes rather difficult if their hydrodynamic properties differ by two orders of magnitude or more. Both of these fuel classes are directly fed into the reactor in most cases but the rather homogeneous fuel originally fed switches into a binary character inside the reactor in some others. A typical example of the latter case is the thermal utilization of rubber wastes. A novel design is proposed in the present paper by setting up a non-mixing, non-elutriated binary bed. Design criteria and procedure are formulated as well. One of the known calculation methods is proposed to be applied for assuring a segregated bed by means of choosing the bed components, geometry, and gas velocity conveniently. Cold model experiments are proposed to be applied for assuring no elutriation of the fine fuel particles and no sinking of the coarse fuel particles in the same time. A simple experiment is proposed for determining the common minimum fluidization velocity of the binary bed because known calculation methods can not be applied here.

Key words: *fluidized bed conversion, binary fuel, multi-component bed, segregated bed, minimum fluidization velocity*

Introduction

Flexibility against fuel quality is only one of the widely known advantages of the fluidized bed combustion (FBC) technology, which makes it very successful especially for the thermal utilization of fuels characterized by changing compositions and qualities like biomass and waste-derived fuels [1-3]. Because of it and because of the wide applicability of the fluidization technology also for other conversion processes besides combustion (gasification, for instance), the range of practically significant fuels is very wide as well. Throughout the several decades of the history of this technology, an interesting situation presented itself several times when the co-fluidization of two classes of particles of radically different hydrodynamic properties was required [4]. A typical example is rubber, the primary fragmentation of which results in very fine particles of diameters of several orders of magnitude below those of the raw

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particles [5]. In case of moderate differences between the particle sizes and in case of a reactor to be designed and built as a new one, the problem may not appear or can be handled by an upwards increasing cross-section design. In many other cases this traditional solution can not be applied or if applicable, its outcome is not satisfactory. In the initiating project of the actual researches, an existing combustor chamber had to be kept for two solid fuels the mean diameters of which are several orders of magnitude apart.

Co-fluidization of two solids has attracted much attention from researchers over the past decades. One of the first pieces of work in the subject belongs to Rowe *et al.* [6], who studied the mixing and segregation phenomena of binary beds. According to the nomenclature they proposed, *flotsam* is the component that tends to float to the bed surface upon fluidization, and *jetsam* is the one that tends to sink to the bottom. It is important to mention that this behaviour is determined by several factors, not exclusively by the particle weights or densities [7]. Moreover, a mathematical model was constructed by the same research group to describe the particle segregation in a binary mixture, based on equations formulated to conform with qualitative descriptions of the mechanism [8]. A significant further step in modelling segregated beds was done by another research group describing also the in stationary procedure towards the final steady-state. Formisani *et al*. [9] were able to set-up a unified model of the transition to the fluidized-state. They distinguished two different fluidization processes depending on whether it starts from bed top or bottom. They also made a clear difference between the two limiting velocities of the fluidization process. According to this, the *final fluidization velocity* is where the whole bed mass is suspended, and the final pressure drop level is attained, that is, the *minimum fluidization velocity* commonly used by others for the whole bed. The mathematical model requires the value of the bed voidage, which is proposed to be determined experimentally. Another model was introduced and proofed by Di Renzo *et al.* [7] focusing on the phenomenon of segregation direction reversal. They investigated systems composed of small, dense particles mixed with big, less dense particles. In these cases it is not simple to predict which one of the two components will tend to float or sink. This is why the mathematical tools offered here can be used very beneficially in most cases of applying biomass particles as second components of an inert fluidized bed. Studying the behaviours of binary mixtures of solids is also of high importance if the goal is the separation of these solids. Such a system was described by Palappan and Sai [10]. The two solid products of the separation procedure were called *flotsam* or *top product* and *jetsam* or *bottom product*. The first one was gained as the output of a cyclone separating the particles entrained from the 3.65 m high gas-solid fast fluidized bed riser while the latter product was extracted from the bottom of this apparatus. The aim of this study was to describe separation properties together with product cleanness influenced by the particle densities.

Targeting either perfect separation or perfect mixing of the two solid components, quantifying the actual level of mixing/separation is of very high importance. The first attempt was done by Nienow *et al.* [11] already by defining the mixing index, *M,* as the ratio of the mass fraction of the jetsam in the upper uniform part of the bed to the overall mass fraction of jetsam in the bed: $M = x/\bar{x}$. Besides defining this measure, a calculation method was also given the reliability of which was proven by numerous experimental comparisons. Goldschmidt *et al.* [12] introduced another single parameter measure, the segregation rate, *s*, which considers the averaged elevations of both particle classes. This measure was constructed explicitly for the comparison of segregation experiments at different operation conditions, therefore no calculation method is available for obtaining it. The focus of this paper was on the experimental technique itself, which is a whole-field, non-invasive, digital

image analysis method in order to study segregation of mixtures of coloured particles. Similarly to this, image analyses was used also by Keller *et al.* [13], but they applied X-ray computer tomography for picturing, and they used 2-D CFD simulations as well. For comparing the images corresponding to different conditions, and for enabling direct comparisons to simulations, a new measure, the particle segregation number (PSN) was defined. As another similarity to the previous work, this measure is also based on some heights characterizing the locations of both particle classes. In paper [14], a comprehensive numerical model was presented, which was able to predict the PSN value. Model calculations and measurements showed convincing agreement for all the investigated Geldart B component pairs. This quantifying method of mixedness together with its calculation can be generally applied, however, this calculation is not simple, it needs the entire model built in into a CFD code. In harmony with the goal of Palappan and Sai [15], the indicators proposed by them express the purities of the products of the fast fluidized bed separator. Their first indicator Y_f is the ratio of the amount of the fine particles over the total amount of the top product, and similarly, the second indicator X_j is the ratio of the amount of the coarse particles over the total amount of the bottom product. Empirical correlations considering several factors were suggested by the authors for the investigated layout, but it was no goal to develop a generally applicable model for calculating these indicators.

The minimum fluidization velocity is a crucial point in describing the behaviours of binary beds. Cheung *et al.* [16] analysed the effects of adding a small amount of fine powder to the bed. The main finding was that the minimum fluidization velocity of the mixture would be between the minimum fluidization velocities of the applied particles. Based on their experimental work, an empirical expression was proposed, which was found to be amazingly sufficient if the diameter ratio of the particles was above 0.3. A semi-theoretical equation was presented by Rowe and Nienow [17] as an alternative method. It was an extension to Hatch and Jacobs [18] pressure-drop relationship for a porous body to the case of a bed of multi-component particles of equal density and same shape. A major drawback of this equation is that the knowledge of voidage change is needed, which is rarely available, and the result is extremely sensitive to voidage. Chiba *et al.* [19] together with one author of the previous work investigated later the change of minimum fluidization velocity with composition for the cases of total segregation of the two components and complete mixing. They found that the agreement between the theory and the experiment is varying and the experimental values are extremely sensitive to voidage.

More recently, Nawaz *et al.* [20] studied the co-fluidization of fluid catalytic cracking (FCC) and coarse particles. Their conclusion is that a unique bubble braking phenomenon is responsible for enhancing fluidization properties of binary mixtures. They installed a second distributor at a certain height to re-divide the bubbles and maintain a uniform flow. During the 2-D experiments, phosphor tracer technique was applied to record and visualize the mixing phenomena.

Intensive investigation activities have been carried out on the co-fluidization of solid particles of differing hydrodynamic properties, as indicated by the high number of research articles previously reviewed. The explicit target of most of them was assuring a rather homogeneous suspension by means of assuring a perfect mixing of the inert bed material and the fuel. A basically different goal of other investigations of binary mixtures is enabling effective segregation without any chemical conversions under the circumstances of fast fluidization.

The current paper considers a third aim, assuring non-mixing conditions for a stationary bed consisting of four solid components. This is namely the proposed solution for keeping two classes of fuel particles of radically different fluidization properties simultaneously fluidized. Thus, the system under investigation is set-up of two solids as the bed materials, plus two others as the fuels. Because of the practical significance and lacking published discussions, design conditions for setting up a well-balanced fluidized bed system of the aforementioned four classes of solids is discussed on both theoretical and experimental basis in this paper.

Materials and methods

Laser diffraction particle size distribution analyser

Particle characteristics were determined using a Horiba Partica LA 950 V2 laser diffraction particle size distribution analyser. This piece of equipment is a compact optical bench with an integrated sampling system for measuring particles in water, ethanol and in dry mode. The measuring range of the equipment is 0.01 to 3,000 microns in wet mode (0.1 to 3,000 microns in dry mode).

Average size, *i. e.*, the $D(4, 3)$ – equivalent sphere diameter, can also be determined by this tool. The *particle size* of a non-spherical particle is usually presented as an equivalent sphere diameter. Equivalent sphere diameters can be assigned on the basis of length, surface area, or volume. Laser diffraction initially calculates a distribution based around volume terms and this is why the $D(4, 3)$ is reported in a prominent manner. The advantage of this calculation method is that the formula does not contain the number of particles, therefore the calculations of the means and distributions do not require the knowledge of the number of particles involved.

The preliminary investigations for analysing the fuel materials were always carried out in water based suspensions but because of poor dipping of the samples, the final measurements were done by using ethanol as the suspension medium. Four types of particle handling procedures were applied throughout all the measurements: directly after feeding the samples, after one minute ultrasonic treatment, and two further measurements after a partial replacement of the ethanol. The reason for the final step was a significant reduction in the light transmission capability of the suspension below its optimal level while reaching better and better levels of dispersion.

Similar analyses were carried out for measuring the particle size distribution of sand as the flotsam part of the bed. Water was applied as the suspension medium throughout these measurements and they were repeated three times. It means that after shaking the samples, sand was fed into the apparatus and its particle size distribution was measured three times by assuring a continuous circulating and all these steps were further repeated twice. Because of the bigger particle sizes of the sand samples, an ultrasonic treatment was not necessary.

Particle size distribution curves characterizing two fuel materials and the flotsam part of the bed are presented in the upcoming subsections. They were measured by this piece of equipment, according to the aforementioned procedures.

Fuel materials

The two classes of the fuel particles to be kept simultaneously in the fluidized bed are hereinafter referred to as *coarse* and *fine* fuel particles (see fig. 7). Generally, they may be originated from very versatile sources and reasons, in the actual investigations they are the

raw waste rubber particles and the char powder evolved throughout its primary fragmentation, respectively.

Two sorts of waste rubber were investigated because of their high availability and practical significances, *hoses* and *sprues*. Both of them arise as wastes throughout the production procedures [21], that is the reason why heavy external pollutions are not expected.

The investigated hoses are scrap injection tubes from the local car industry. Their diameters and general structures were similar but their lengths were altering. The main components are the rubber body, the Kevlar fiber and the internal film layer. A small amount of the samples had an external net as well.

The sprues are manufacturing wastes generated by rubber processing methods, for example injection moulding. Their main monomers are butadiene and isoprene. In contrast to the hoses, the sprues look homogeneous but their shapes and sizes are also of great variety. A more detailed description of the hoses and sprues, together with photos and composition data were reported separately [22].

For generating the fine particles from the raw rubber, a programmable oven was applied, with its 1200 °C maximum internal temperature. It is possible to set the desired temperature and the rate of the heat up alike. The internal surface of the oven is covered with refractory concrete insertion and there are two heaters on the sidewalls. The geometric parameters of the heated area are 170 × 130 × 445 mm^3. The temperature of the sample was measured by a thermocouple. This oven is supplemented with a rod in order to keep the sample stable, as presented in more details elsewhere [22].

Both of the fuel materials, *i. e.*, hoses and sprues showed the characteristics of primary fragmentation. Upon the devolatilization temperature of about 340 °C, the rubber body of the hoses and all the sprues lost their flexibility, started to be fragile, and at the end of the process, they fell apart into fine particles, see also [5, 23, 24].

The size distributions of the resulted *fine* particles were measured by the Horiba LA950 laser diffraction analyser as previously discussed, the resulted curves are shown in fig. 1. The characteristic $D(4, 3)$ sizes of the fine particles resulted from the original coarse particles, hoses and sprues are 67.7 μm and 42.7 μm, respectively.

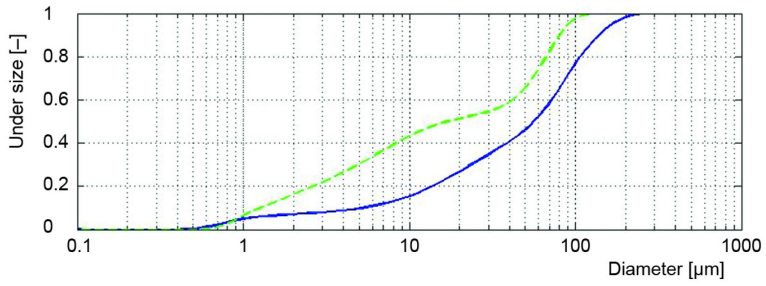

Figure 1. The particle size distribution of the fine fuel particles resulted after the thermal treatments of two sorts of original coarse particles, *i. e.*, hoses (continuous line) and sprues (dashed line)

The densities of the investigated coarse particles hoses and sprues were measured as 857 kg/m^3 and 1120 kg/m^3, respectively [25], while the density of the fine particles can be taken from the literature dealing with soot from rubber waste as 1760 kg/m^3 [26].

Bed materials

Two types of bed materials were used, hereinafter referred to as flotsam and jetsam according to [10, 15, 27-29], with significantly different mean diameters. The main parameters of the flotsam (sand) and jetsam (gravel) particles are collected in tab. 1, while fig. 2 shows the corresponding particle size distributions. The selection of these bed materials was a result of several considerations not discussed here, throughout which economical and practical issues of applicability also played important roles. An interesting characteristics of this choice is that the density of the jetsam (which tends to sink) is somewhat less than that of the flotsam.

It should be emphasised that the large difference between flotsam and jetsam particle diameters was needed to maintain fluidization when the fuel presented in its raw form or as devolatilized char.

Table 1. The properties of the bed materials investigated (claimed by the suppliers)

	Chemical properties		Physical properties	
Flotsam	SiO_2 (min.)	93%	Mean diameter[1]	387 μm
	CaO + MgO (max.)	0.7%	Density	1580 kg/m^3
	Fe_2O_3 (max.)	0.25%	Melting point (min.)	1450 °C
	Loss on ignition (max.)	0.3%		
Jetsam	SiO_2 (min.):	96%	Mean diameter	1.6 mm
			Density	1500 kg/m^3
			Melting point (min.)	1700 °C

[1] Own measurement

If the bed materials are plotted in Geldart's well-known powder classification diagram, [30], fig. 3, it is obvious that the two types behave in a completely different way under fluidization. The flotsam particles belong to the Geldart B class. These particles have very good fluidization properties and if they reach the minimum fluidization velocity, the excess gas appears in the form of bubbles ($u_{mf} = u_{mb}$). The presence of the bubbles and the fact that they can grow to very large sizes means that the mixing is excellent in this case [31]. Most of the industrial sized boilers use bed materials from this class.

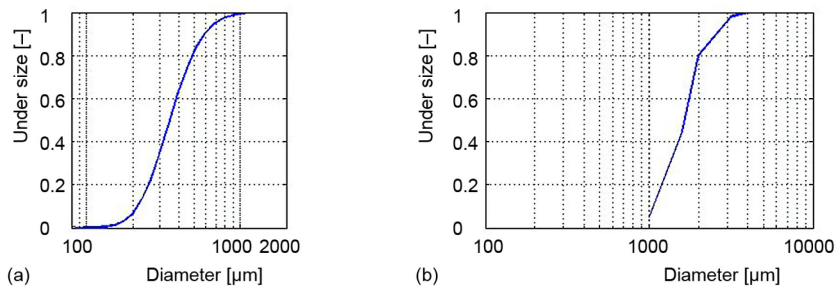

Figure 2. The particle size distributions of the bed materials; flotsam (a), own measurements, and jetsam (b), supplier data

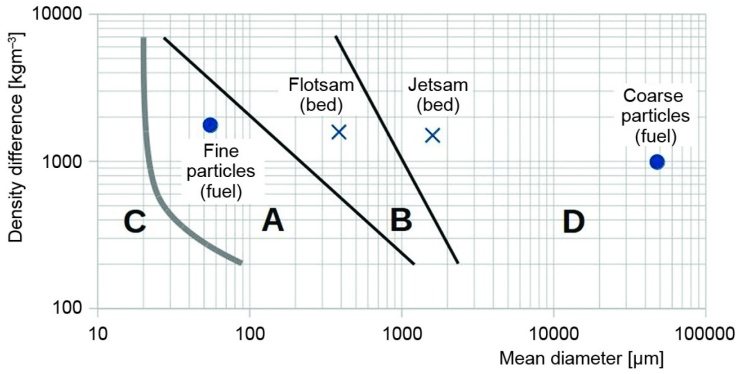

Figure 3. The groups of Geldart's classification and the plot of the actual bed and fuel materials

The jetsam particles fit in the Geldart D class. This class is described in the literature as the set of spoutable particles because as the velocity increases, jets can be formed in the bed and then the particles may be blown out by the air jets with spouting motion. Additionally, bubbles rise more slowly and mixing is poor even at high superficial gas velocities. The phenomena were clearly recognizable during our experiments.

The minimum fluidization velocity of the flotsam and jetsam particles were measured separately and used as benchmark values for the cases with mixed bed materials.

The mixing/segregation behaviour of the bed consisting of the aforediscussed two particle classes (flotsam and jetsam) can be calculated according to the method presented in [11]. The final result of this procedure is the *Mixing index*. This is the ratio of the mass fraction of the jetsam in the upper uniform part of the bed to the overall mass fraction of jetsam in the bed: $M = x/\overline{x}$. The M spanning the range of 0 to 1, the upper region of which corresponds to well-mixed states, while M values below 0.5 mean segregated bed. Its calculation is according to:

$$M = \frac{1}{1 + \mathrm{e}^{-Z}} \tag{1}$$

where Z is calculated as the function of the independent variable u [ms^{-1}] gas velocity, and u_F [ms^{-1}] – the lower one of the minimum fluidization velocities of two bed components:

$$Z = \frac{u - u_\mathrm{TO}}{u - u_\mathrm{F}} \mathrm{e}^{\frac{u}{u_\mathrm{TO}}} \tag{2}$$

where u_TO [ms^{-1}] is the takeover velocity, which can be estimated according to the form of:

$$u_\mathrm{TO} = u_\mathrm{F}\left[\left(\frac{u_P}{u_\mathrm{F}}\right)^{1.2} + 0.9\left(\frac{\rho_\mathrm{H}}{\rho_\mathrm{L}} - 1\right)^{1.1}\left(\frac{\Phi_\mathrm{H} d_\mathrm{H}}{\Phi_\mathrm{L} d_\mathrm{L}}\right)^{0.7} - 2.2\overline{x}^{0.5}\left(1 - \mathrm{e}^{-\frac{H}{D}}\right)^{1.4}\right] \tag{3}$$

where u_P is the higher one of the minimum fluidization velocities of the two bed components and index H always refers to the higher while L to the lower value of density, ρ, sphericity, Φ, and diameter, d, values of the two bed components, $\overline{x}$ is the ratio of mass of the heavier bed

Table 2. The comparison of the mean diameters and densities of the investigated solid materials

		Mean diameter [μm]	Density [kgm^{-3}]
Fuel materials	Fine particles	55.2[a]	1,760[e]
	Coarse (raw) particles	48,000[b]	988.5[f]
Bed materials	Flotsam	387[c]	1,580[d]
	Jetsam	1,600[d]	1,500[d]

[a] $D(4, 3)$, hoses: 67.7 μm, sprues: 42.7 μm; [b] see further details in [22]; [c] $D(4, 3)$; [d] supplier data; [e] from [26]; [f] from hoses: 857 kg/m^3, from sprues: 1,120 kg/m^3 [25]

component over the total bed inventory while H and D are bed height and diameter, respectively.

An overview of the materials discussed in the previous subsections is given in tab. 2. This summary also indicates the measuring methods applied, the variety of which again shows the extreme differences in the sizes of solids applied.

Experimental apparatus

The fluidization experiments were conducted in a 1.2 m long plexiglass column of 192 mm internal diameter with a free outflow section. Instead of nozzles, a bored plate was used as the air distributor. The distribution and diameter of the holes were uniform. Parallel with achieving uniform fluidization during operation, the 1.5 mm diameter bores prevent the particles from escaping under settling conditions. The fluidizing air went through a flexible pipe of ≈0.2 m diameter and a diffusor section before reaching the distributor plate. A short cylindrical section was applied between the diffusor and the distribution plate in order to stabilize the flow before entering the reactor chamber. A radial blower was attached to the experimental layout, which is capable of delivering 540 m^3/h air (at ISO conditions). The necessity of continuous air-flow control was fulfilled by the fitting of an OMRON V-1000 inverter. To measure the actual air-flow, an inlet orifice plate and a differential pressure sensor were used. A robust realization of this standardized air-flow measuring method was applied because of its simplicity and reliability in case of suctioning from the undisturbed atmosphere. The main parameters of the applied configuration are summarized in tab. 3, while fig. 4 shows the arrangement of the main parts.

Table 3. Main data of the experimental apparatus

Inlet orifice equipment		Distributor plate	
Arrangement	vertical	Hole distance	5 mm
External sizes (L × W × H)	400 × 400 × 3500 mm^3	Hole diameter	1.5 mm
Orifice inner diameter	60 mm	Total number of holes	1160
Pipeline inner diameter	108 mm	Sum area of holes	0.0021 m^2
Pipeline length	680 mm	Reactor chamber	
Blower		Height	1.2 m
Nominal airflow	540 m^3/h	Internal diameter	0.192 m
Δp_{static}	47.760 kPa	Cross-section area	0.029 m^2

In order to define the minimum fluidization velocity it is necessary to record the change in the pressure drop of the bed. It was conducted by a differential pressure measurement between the ambient air and the air-flow just below the distributor plate. To minimize the effects of any disturbances in the air-flow, the pressure signals were collected from four points on the perimeter of the cylindrical section. Due to this layout, the pressure drop had to be measured via the distributor plate in function of the air-flow first, thus making a correction was possible during the subsequent measurements.

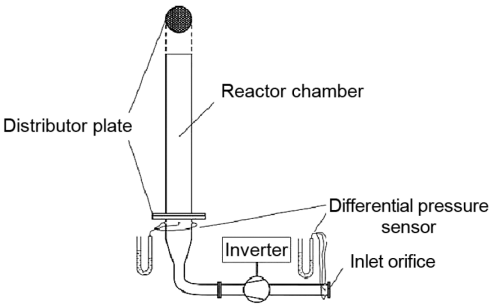

Figure 4. The schematic view of the experimental layout

In each case, the same method was followed in order to quantify the minimum fluidization velocity and observe the fluidization characteristic of the bed. After the desired quality and quantity of solids had been fed into the reactor chamber via the upper open end of the plexiglass, the load rate of the blower was raised carefully. It was shown that a step increment of 2 Hz was satisfactory around the point where the bed came into motion. After reaching the minimum fluidization condition, the raising of the load was persisted until full load. In this layout, it was impossible to cease the air-flow abruptly, which would have been favourable to get additional information about the behaviour of the mixed beds. The used bed material could be removed completely and easily because the reactor chamber was detachable from the distributor plate.

Results and discussions

Observations of the fluidizing characteristic of the different beds and fuel particles were recorded by means of motion pictures which were filmed simultaneously from three different points of view. Multiple tests were carried out with several different conditions and circumstances. The results presented below are based on repeatable observations. The most significant characteristic property of a fluidized bed, the minimum fluidization velocity was measured and used to compare the different cases.

Fines in the flotsam

Firstly, the co-fluidization capability of the Geldart B flotsam particles were analysed with the fine powder evolving from the raw fuels during the early stages of combustion. Due to the cohesive character of the fines (Geldart A, partly also C; see fig. 1, tab. 2), determining its fluid-dynamical properties including characteristic air speeds was not possible. The absence of these data, in turn, did not allow any theoretical calculations or even comparisons on the co-fluidizability of fines and flotsam. Since this seems to be the typical case, another investigation method must be proposed, experiments with the mixture of these solids.

The experiments showed that char (the fine particles) and sand (the flotsam material) particles create a good-mixing bed, as soon as the minimum fluidization velocity of the bed particles is reached.

With special regard to the great size difference between raw and fine fuel particles, the superficial velocity was determined where the carry-out of the fine particles reaches an unacceptable ratio. This was based upon a subjective scale of the fine particle flux on the

reactor chamber outlet surface. Subsequently, as a result of many experiments, the highest allowable gas velocity was determined as 1 m/s. Experiments showed that this type of bed was not suitable for the analysed raw fuel samples, neither the hoses nor the sprues tend to be fluidized below the aforementioned velocity limit.

Coarse fuel particles in the jetsam

In the second part of the experiments the aim was to find a suitable bed material which could be used in order to bring and keep both types of the raw fuel, hose and sprue particles in fluidized-state. Because of the very difficult fluidizability of the raw fuel particles (see main data in tab. 2), experimental investigations were chosen and are proposed here again.

According to the first experiments, the chosen Geldart D class gravel satisfied the requirements but for this achievement a pretty high gas velocity had to be applied. Around 0.9 m/s gas velocity, some parts of the bed started to get into motion, jets were formed, and the spoutable behaviour of the particles was noticed. The applied shallow bed demands 1.4 m/s to get fully fluidized. At this state the fed raw fuel particles stayed constantly in motion, circulating between the bottom and the top of the bed. Thus, the gravel layer was able to fulfil the required task, which was preventing the raw fuel particles to sink at the bottom of the bed and stay de-fluidized during the combustion process.

Flotsam and jetsam

It must be emphasized that the 1.4 m/s gas velocity which is needed to reach the evolved fluidization of the bed composed of the jetsam, is higher than the transportation velocity of the major part of the fine fuel particles. Thus, it is desirable to lower the fluidization velocity of the jetsam layer in order to avoid the elutriation of the fine char particles. Adding finer particles to the bed has a well-known result of better mixing and lowering the minimum fluidization velocity, but there was not any literature reference found proving the phenomena using the particles from the same size ranges as in the present work. However, it was assumed that the addition of Geldart B class particles will tend to lower the minimum fluidization velocity of the mixture as if Geldart A class was added to Geldart B class bed, which is a much more common case.

Table 4. The investigated binary mixtures

Explanation	Ratio
1 kg jetsam and 1 kg flotsam	1:1
1 kg jetsam and 3 kg flotsam	1:3
0.5 kg jetsam and 3 kg flotsam	1:6

During the co-fluidization experiments, three types of binary mixtures were used, each with different jetsam-flotsam mass ratios. The properties of the different binary mixtures are shown in tab. 4.

Applying the calculation procedure (1)-(3) on the previous mixtures of the discussed bed materials results in mixing index values ranging from 0 to 1 if the superficial gas velocity spans the range of 0.5 to 3.5 m/s, as visible in fig. 5. It is interesting that the effect of the mixing ratio is negligible in the actual case, that is, the lines are running very close to each other. It is visible that the non-mixing case ($M < 0.5$) is predicted whenever gas velocity is kept below 1.7 m/s, which is an acceptable criteria in case of bubbling beds.

Determining the minimum fluidization velocity of binary beds, especially with such a high difference in particle features, is more complicated than in the case if only one type of bed material is present. The complexity arises from the substantial mixing and segregating mechanism, which may occur during fluidization. In all the three cases it was observed that

there is a lower gas velocity range within the jetsam particles form a fixed bed but the flotsam above them is thoroughly fluidized, hence it acts as a separate bed. It was also revealed that the sand layer reaches its minimal fluidization-state independently from the actual particle weight ratio at around the same gas velocity where it would if no jetsam layer were there. Raising the superficial velocity further, the whole mixture starts fluidizing.

The results of the experiments did not show any barrier that could fail the co-fluidization of the selected flotsam and jetsam particles. Moreover, if the measured minimum fluidization velocities are plotted correspondingly to the cases, as it was done in fig. 6, it can be seen that the minimum fluidization velocity tends to decrease substantially in accordance with the increasing weight ratio of the added flotsam particles, similarly to the behaviours of mixing beds [16]. Thus, the multi-component bed of the selected particles can fulfil the requirements because with the fine-tuning of the particle ratio the fluidization of the raw fuel particles and the char particles can be done simultaneously as the minimum fluidization velocity of the mixture can be lowered below the transportation velocity of the fine char particles.

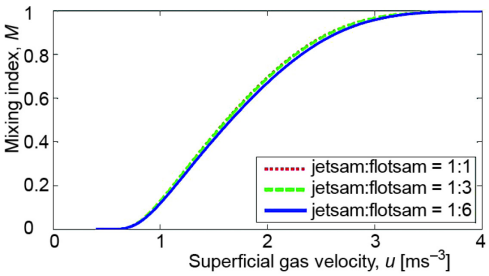

Figure 5. The plots of the mixing indices as functions of the superficial gas velocity for the bed materials in case of three mixing ratios and the differences between the plots belonging to the investigated mixing ratios are negligible in the actual case, as visible

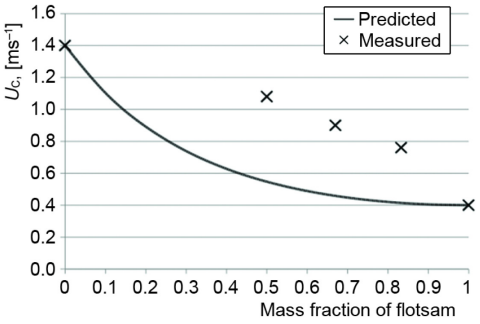

Figure 6. Measured minimum fluidization velocities differ significantly from the predictions of [16] both in values and tendency and the lack of appropriate formula encourages further research, and necessitates measurements in the design procedure

The minimum fluidization velocity of the multi-component bed could be calculated by empirical or semi-empirical equations as well. The simplest equation (obtained clearly in an empirical way) for binary mixtures was introduced by Cheung *et al.* [16]:

$$\frac{u_c}{u_S} = \left(\frac{u_B}{u_S}\right)^{x_B^2} \tag{4}$$

where u_S, u_B, and u_C are the minimum fluidization velocities of the smaller, the bigger particles, and the mixture, respectively. Notation x_B refers to the weight fraction of larger particles. The results obtained by eq. (4) are shown in fig. 6. The significant discrepancy that can be seen between the calculated and measured values is not surprising, as Cheung *et al.* [16] experienced similar errors applying the equation if the diameter ratio d_S/d_B was below 0.3, in the actual case it is 0.18. This shows the need for a new or extended mathematical model which is suitable for particles with a diameter ratio below 0.3 as well.

Rowe and Nienow [29] presented a semi-theoretical equation by extending Hatch and Jacobs [18] pressure-drop relationship for a porous body to the case of a bed of multi--component particles:

$$u_c = u_1 \left[\left(\frac{\varepsilon}{\varepsilon_1} \right)^3 \left(\frac{1-\varepsilon_1}{1-\varepsilon} \right)^{2-n} \right]^{\frac{1}{n}} \left[x_1 + \frac{d_1}{d_2} x_2 + \ldots \right]^{1-\frac{3}{n}} \tag{5}$$

where u_1 and ε_1 are the minimum fluidization velocity and voidage of mono-size particles of diameter d_1. Notation x_1, x_2, … are the weight fractions of particles of diameters d_1, d_2, … in the mixture which has a voidage, ε. The exponent n takes a value a little greater than unity, depending upon the Reynolds regime of the flow. Although eq. (5) is claimed to be general and applies to any number of components, the desired voidage function is rarely available, but the value of the minimum fluidization velocity is obviously extremely sensitive to voidage. Thus, in the actual case calculating u_C from eq. (5) was not possible.

In order to develop the aforementioned mathematical model, further experiments are required to be carried out considering also some further parameters affecting the phenomena. For this, the application of digital imaging process is planned to be applied.

The proposed design procedure

A synthesis of the previous results can be formulated and applied as a system of design criteria for the cases when the simultaneous fluidization of two, radically different fuel particle classes is required in a reactor chamber of constant cross-section area. The proposed design procedure will be summarized in this section as steps built up from criteria and proposed method for fulfilling each. The structure and the key elements of this system of design criteria are summarized in fig. 7. According to it, a binary bed should be applied for this binary fuel composed of two particle classes.

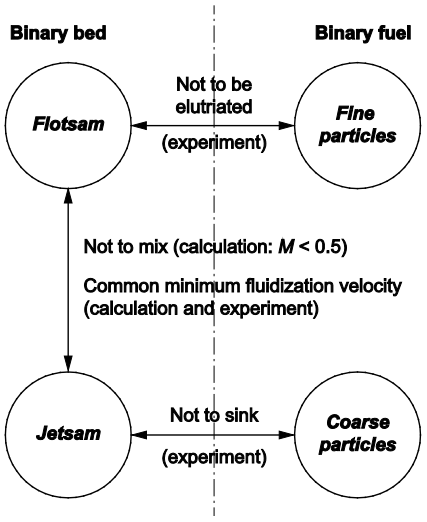

Figure 7. The particle classes and design criteria for binary bed – binary fuel systems

Step 1. Criterion: The particle classes composing the bed (the flotsam and the jetsam) should be applied so that a non-mixing (segregated) stationary fluidization is evolved.

Method: Assure $M < 0.5$ as defined by eqs. (1)-(3).

Step 2. Criterion: The minimum fluidization velocity of the whole binary bed must be less than the transport velocity of the fine fuel particles.

Method: Cold model experiments should be carried out by varying the ratio of the bed components for finding the limit ratio for fulfilling the criteria. (If not possible, choose another pair of bed materials and return to step 1. Equation (5) can be used as a preliminary estimation. An experimental set-up similar to that illustrated in fig. 4, tab. 3 should be applied.)

Step 3. Criterion: The coarse fuel particles must not sink in the jetsam bed.

Method: Cold model experiments should be carried out with jetsam and coarse fuel particles within the air speed range allowed by step 2. (If not possible, choose another pair of bed materials and return to step 1).

This design procedure should be applied in an iterative way in most of the cases considering also some further aspects like financial conditions as well. Other evident criteria of the fluidizability of both beds within the same structure must be fulfilled as well. The transport velocity of the flotsam must be higher than the minimum fluidization velocity of the jetsam, for instance. There is no warranty for the existence of any solutions fulfilling all the above criteria in all particular cases, of course.

Conclusions

A novel design was proposed by setting up a non-mixing, non-elutriated binary bed for keeping two classes of fuel particles of radically different sizes simultaneously fluidized. Thus, the system under investigation is set-up of two solids as the bed materials, plus two others as the fuels. Design criteria and procedure were formulated as well.

One of the known calculation methods is proposed to be applied for assuring a segregated bed by means of choosing the bed components, geometry, and gas velocity conveniently. Cold model experiments are proposed to be applied for assuring no elutriation of the fine fuel particles and no sinking of the coarse fuel particles in the same time. A simple experiment is proposed for determining the common minimum fluidization velocity of the binary bed because known calculation methods can not be applied. The minimum fluidization velocity of the binary bed varies namely not only as function of the properties of the components, but also depending upon their ratios in the bed. This changing character of the resultant minimum fluidization velocity can be advantageously utilized throughout the design but the available forms can not be used for prediction. They do refer to well-mixed beds only and the experiments show that a similar theoretical description of non-mixing beds is still lacking.

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