Characteristic of Atmospheric Fluidized Bed in the Laboratory Conditions

Introduction

History of fluidization

The beginning of the development fluidization process takes a year twenties of the twentieth century. In 1921, Fritz Winkler observed particle motion under influence of flowing the airstream. Five years later, on the basis of this observation was established coal gasification dust technology. Winkler’s method with slight modifications, is used to this day [1,2,3,4]. Studies on the catalytic cracking led by Warren Lewis and Edwin Gilliland in 1938 has resulted in the CFB process – the fluidization in the circulating layer. In the postwar period the company Lurgi using the aforementioned technologies CFB, has developed a process of calcining aluminum. Interestingly, despite some obvious advantages associated with the use of fluidized re-interest in this technology just got back in the sixties. The science world drew attention to the fact that the application of fluidization enables downsizing coal boiler, thus reducing the cost of construction of the plant and increase the combustion efficiency. Furthermore, by fluidization process it was possible to use lower quality fuels and reducing emissions pollution. In 1963, Douglas Elliot, along with British Coal Utilization Accociation Research and the National Coal Board, initiated a research project over fluidized combustion of coal in a bubbling layer. Douglas’s first idea was to use a fluidized bed technology for the recovery of thermal energy from a high-carbon ash, which remained from the combustion of anthracite. Ultimately, however, it was decided to use a single-stage combustion with using the fluidized bed boiler. The promising results of these studies led to the dynamic development of CFB technology [5,6]. The driving force behind the development of fluidized technology was energy use of fossil fuels. In the development of fluidized bed combustion, increased interest among researchers on the combustion a parts of volatiles present in conventional fuels. The first research work was devoted to the combustion of gases, Essenhigha Cole's work was published in 1972.

Increase awareness ecological, dictate a new approach to the issue of waste. The concept of municipal waste incineration as an alternative to depositing their on the landfills, was gaining wider group supporters. Fluidized bed combustion unlike to conventional combustion grate boilers allows for the developed the not only highly energy waste, but also low-calorie and contain moisture sewage sludge and biomass [7, 8, 9, 10]. The biggest development of fluidized bed combustion technology began in the eighties. In 2011 in the 18 European countries, there were 455 municipal incinerators waste with energy recovery, including 19 companies based solely on fluidized bed technology [11, 12].

Characteristic of fluidization process

Fluidization is a two phase process involves on the suspension powdery solid layer in the stream of fluid (gas or liquid) flowing vertically from the bottom of the column. Particles in fluidized phase are in constant motion, moving in the entire volume of the reactor. Fluidized layer reminds in the behavior boiling liquid. The physical properties between the fluidized bed and the liquid exhibit the analogy in features like: lifting of objects with lower density than fluidized layer on the fluidized bed, the possibility of beds pouring, the hydrostatic pressure presence and the presence of viscosity. State of fluidized layer can be described as quasi-stable because is present only in the limited range of fluid flow.

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velocity (dependent on particle size and density’s relative of the two phase). Layer of the fluidized bed can be divided into homogenous and heterogenous. Homogenous layer is characterized by analogous porosity in entire space, this state is typical for liquid and for low velocity gaseous fluidization. Heterogenous layer has very varied porosity.

We can distinguish the following types of heterogeneous layers:

- **Bubbles** – the gaseous bubble presence,

- **Slugging (pulsatile)** – bubbles in diameter equal to the diameter of the reactor and create a transverse layer of gas. In this state there are significant fluctuations in pressure lost. Pulsating flow is characteristic for the columns narrow and high,

- **Channeling** – the presence of vertical channels through which flows bigger part of fluid’s volume. This is a common phenomenon for particles of small size.

- **Spouting** – gas flow takes place mainly through the center of the column, the particles are ejected at high velocity zone and they falling down in the low velocity zone (near the walls of the reactor) This type of fluidization. Accompanied to materials with high specific gravity and big size of particles.

In figure 1 is shown the above-described types of heterogeneous fluidized layers.

![Figure 1. Kinds of layers: a) homogenous b) bobbling c) slugging d) channeling e) spouting.](image)

Nature of the fluidized bed varies depending on the properties of the bed material and the velocity of the gas stream. The initial increase in the gas velocity does not do observable particle motion. This phase is called a stationary state (figure 2 – a). The particles in the stationary state remind in contact with each other, resting on the perforated distributor of the reactor. The increase of velocity of the fluid flow from the bottom causes a relaxation of the stationary layer and the beginning of fluidization. As the minimum velocity of fluidizations muff is considered the speed, that overpressure caused by the flowing gas is equal to the static pressure of stationary bed layer. In a fluidized state can be distinguished dense phase (figure 2 – d, e I) and the relaxed phase (figure 2 – d, e II), when fine particles are lifted above the bed. In the first stage of fluidized bed’s formation the bed’s height rises and gas bubbles have a spherical shape (figure 2 – c, d). Fluid velocity rise causes further bed’s expansion and turbulence phase creation (figure 1 – e). This stage of fluidization is characterized by very intensive particles mixing and big porosity. The end of fluidization is when the gas velocity is equal to the particles free fall velocity (figure 2 – f). Above this velocity the bed is blowing outsider the reactor – the pneumatic transport is began [2, 13, 14].
The pressure lost during the flow of the gas phase through the fixed bed is a linear function of gas velocity. The bed loosening required to overcome the interaction intermolecular forces what causes that the pressure lost for minimum velocity of fluidization ($\Delta p_{\text{max}}$) is bigger than $\Delta p$ accompanying to the process of fluidization. Fluidized layer is characterized by a nearly constant pressure lost. The dashed line represents the pressure lost during the gradual increase of the gas flow velocity $u_0$ (bed expansion), the segment of continuous line parallel to the dashed means state of slow gas velocity’s decrease. This phase is characterized by Lower $\Delta p$ than phase of bed expansion, what is caused the lack of necessity overcoming the adhesion forces. If fluidization velocity exceeds particles free falling velocity, the pneumatic transport began. Decrease of pressure loss for this stage is caused by the blowing of bed material outside the reactor. Letter designations in figure 2 correspond to the visualization of fluid layers in figure 3 [2, 13, 14].

**Fig. 2. Stages of the fluidized bed in the solid-gas system.**

**Advantages and disadvantages of fluidization process**

Fluidization is used in combustion processes, drying and also in catalytic chemical reactions. The fluidized bed is a good alternative to stationary bed due to the following characteristics. Advantages of fluidization are shown in table 1.

<table>
<thead>
<tr>
<th>Combustion</th>
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<tr>
<td>The high interfacial contact area.</td>
<td>Uniform-oxidant access achieved by intensive mixing.</td>
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<tr>
<td>Ability to burning fossil in all states of matter.</td>
<td>The possibility of burning low quality fuels, and with a high moisture content.</td>
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<tr>
<td>The ability to burn fuels with small grains like coal dust that cannot be burned in conventional furnaces with grate</td>
<td>Effective desulfurization process which can be conducted directly in the fluidized bed (bed with sorbents).</td>
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<tr>
<td>Compact design of boilers.</td>
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The fluidized bed has also disadvantages, like the erosion of the reactor’s walls and surfaces immersed within the bed. The destruction of the surface being in contact with the material working in the bed is caused by the high value of the kinetic energy of the bulk material particles. An important issue is also higher energy consumption of the reactor (pump) and the agglomeration of the bed material caused by high temperature sintering. The relatively high thermal inertia of fluidized bed furnaces significantly increases the startup time. In addition the use of a fluidized bed demands controlling the granulation materials which are given into the reactor [2, 5, 15, 16].

The methodology of the study

The study was conducted in a laboratory reactor with bubbling, atmospheric fluidized bed in the form of quartz sand. In order to illustrate the mixing bed material, the sand was divided by 14 mm layer of poppy food. A factor of fluidized, was the air served under the bed through the perforated bottom of the gas distributor. Recorded footage was made using the high-speed camera Basler ACE model acA2000-340kc, which enabled high-definition video recording at a frequency of 500 frames per second. High frequency image registration necessitates adequate exposure of individual film frames. To ensure proper exposure of the working reactor system used two halogen lamps of 400W each. The digital film from the process compared with the mathematical model of the circulation of gases within the bed. The model was made with the help of the „OpenFoam” program.

Results and Discussion

Digital image analysis of the experiments conducted indicates the presence of at least four characteristic phenomena in the fluidization process. In the initial stage, the effect of increasing the gas flow velocity was observed uniform fluidization. In this stage was loosening the bed and increase the level of particles about several millimeters up. By further increasing the gas velocity, in the bed layer occurred of phenomenon piston flow (Figure 4 – 7997 s). Grains were raised by several millimeters in up the columns and has occurred loose material separation. At a time when the fluid pressure equalized with the pressure static exerted by layer of the bed, started to bubble fluidization. Phase of bubble characterized by high porosity. During fluidized could sometimes see the fountain flow. This flow characterized by the centralization of the gas stream which carries the bed material and throws it over the surface.

Fig. 4. The comparison between the real process of fluidization and two-dimensional mathematical model.
Air bubbles were formed at the bottom of the sieve and grew during the flow through the bed as a result of the phenomenon of coalescence. During the studies observed also the ability to not only the growth of bubbles, but also to shared them smaller. Bubble size depends mainly on the speed of the supply air stream and the bed height and weight. Bubbles did not move only vertically upwards, it possible observed also chaotic lateral movement. Velocity of air bubbles was also dependent on their diameter and shape, indicating an analogy with the flow of gas through a bubble's column. The presence of such phenomena as piston flow, chaotic migration of gas bubbles and even the existence of bubbles in the bed moving in the direction of the bottom of the sieve, is a confirmation of the mathematical modeling of the gas flow.

The bubble, which carrying a cargo of gas and bed material, partly push dark material bed, and partly pulled behind him to top layer (figure 4 – 8,477-8,895 s). As a result, the bed material mixed dark and clear was thrown over the surface. In subsequent frames could be observed dark movement of bed material towards the surface of the gas distributor (figure 4 – 9,571-9,921 s). Large great bubbles were formed from smaller bubbles, which combined to form a channel (figure 4 – 8,895 s) or the process of association ran alone (figure 4 – 11,947-12,021 s).

The exact flow of the gas phase was difficult to showing by experimental methods, so was used mathematical model. The visualization of the model could be observed gas phase two-way traffic, which is not practically to observed to experimentally way. In addition to changing the shape and chaotic motion bubbles was observed also changes the local gas phase velocity in them (figure 4).

Conclusions

Intensive mixing and high surface area of contact among phases in a fluidized bed, creating favorable conditions for carrying out processes such as incineration, drying and carrying out reaction chemicals. The bed material was mixed in a little more than 4 seconds when piston flow was observed (figure 4). In the fluidization process, there are different forms of non-uniform mixing of grains, depending on the speed and nature of the gas phase flow. The bed height and speed of the supply airstream affect the shape, size and way of moving air bubbles. Analysis of video footage confirms the mathematical modeling of the process.

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Abstract

Fluidization is a two phase process involves on the suspension powdery solid layer in the stream of fluid (gas or liquid) flowing vertically from the bottom of the column. Intensive mixing occurs in bed and developed interfacial contact area creates the high heat and mass transfer coefficients. Nature of the fluidized bed allows to create a very good environment for the processes such as drying, combustion or conducting catalytic chemical reactions. The purpose of the research was to determine the influence of changing the fluidizing medium velocity to the process of mixing taking place inside the bed of different weights and grain size. The range of the research included the study of heterogeneity of porosity, creation and association of bubbles of different sizes and shapes. The research was conducted in a laboratory reactor with bubbles, atmospheric fluidized bed in the form of quartz sand of varying particle size and weight. The air given through perforated gas distributor was fluidized medium. Image registration was conducted using high-speed and high resolution camera- Basler ace acA2000-340kc, with frequency of 500 frames per second. It was used two 400W halogens lamps for proper exposure of recorded movie. Digital image analysis of the experiments indicate the presence at least four characteristic phenomena in the fluidization process. In the initial stage, as the effect of increasing gas flow velocity the homogeneous fluidization was observed, in this stage the relaxation and a few millimeters rising of the bed occurred. As a result of further increasing the velocity occurred the slugging. At the moment when the fluid pressure equalized with the static pressure exerted by a layer of the bed, the bobbles fluidization began. Bobbles phase was
characterized by high porosity. During the fluidization there can be sometimes observed spouting flow which involving at the flow of the gas through the axis of the reactor and lifting the sand over the bed. Air bubbles were formed at the perforated bottom and grew during the flow through the bed as a result of the coalescence phenomenon. During the researches not only the bubbles coalescence but also those dividing into smaller was observed. The bubbles size was a function of flow velocity, mass and high of the bed. Bubbles did not move only vertically upwards, it could be observed chaotic lateral movement. Velocity of air bubbles was also dependent of their diameter and shape, which is analogous to the barbotage. Intensive mixing and high interfacial surface area in a fluidized bed makes very good conditions for process like drying, combustion or conducting catalytic chemical reactions. In the homogeneous fluidization process, there are different forms grains mixing, depending on the velocity of the gas. The bed height and the velocity of given air have an impact on shape, size, way of moving air bubbles.

**Keywords:** fluidization, fluidized bed, mixing of grains, bubbles bed, two-phase flow.

CHARAKTERYSTYKA PRACY ATMOSFERYCZNEGO ZŁOŻA FLUIDALNEGO W WARUNKACH LABORATORYJNYCH

Streszczenie

Fluidyzacja jest procesem dwufazowym polegającym na utrzymaniu sypkiej warstwy ciała stałego w strumieniu płynu (gaz lub ciecz) przepływającego pionowo od dołu kolumny. Intensywne mieszanie warstwy złoża oraz rozwinięta powierzchnia kontaktu międzyfazowego przekłada się bezpośrednio na wysokie współczynniki wymiany ciepła i masy. Natura złoża fluidalnego umożliwia stworzenie w nim bardzo korzystnych warunków dla takich procesów jak: suszenie, spalanie lub prowadzenia katalitycznych reakcji chemicznych. Celem badań było określenie wpływu zmiany prędkości czynnika fluidyzującego na proces mieszania zachodzący wewnątrz warstwy złoża. Zakres prac obejmował również badanie niejednorodności porowatości, tworzenia i asocjacji pęcherzy o różnych rozmiarach i kształtach. Badania prowadzono w reaktorze laboratoryjnym z pęcherzowym, atmosferycznym złożem fluidalnym w postaci piasku kwarcowego o różnym uzornieniu i masie. Czynnikiem fluidyzacyjnym było powietrze podawane pod złoże poprzez dno sitowe dystrybutora gazu. Registrowanie obrazu prowadzono za pomocą szybkiej kamery firmy Basler model ACE acA2000-340kc, która umożliwiła zapis obrazu z częstotliwością wynoszącą 500 klatek na sekundę w wysokiej rozdzielczości. Dla zapewnienia właściwej ekspozycji pracującego reaktora zastosowano układ dwóch lamp halogenowych o mocy 400W każda. Analiza obrazu cyfrowego z prowadzonych eksperymentów wskazuje na obecność, co najmniej czterech charakterystycznych zjawisk w procesie fluidyzacji. W początkowej fazie, w skutek zwiększania prędkości strumienia gazu zaobserwowano fluidyzację jednorodną, w tym etapie nastąpiło rozluźnienie złoża i podniesienie cząstek o kilka minimetrów. W wyniku dalszego zwiększania prędkości gazu, w warstwie złoża wystąpiło wyraźne tłokowanie. Ziarna zostały podniesione o kilkanaście mm w górę kolumny, nastąpiło rozwarstwienie materiału sypkiego. W chwili, gdy nacisnięcie płynu zrównało się z ciśnieniem statycznym wywieranym przez warstwę złoża, rozpocznala się fluidyzacja pęcherzowa. Faza pęcherzy charakteryzowała się dużą porowatością. W trakcie fluidyzacji można było niekiedy zaobserwować również przepływ fontannowy, charakteryzujący się centralizacją strumienia gazu, który porywa materiał złoża i wyrzuca go ponad powierzchnię. Pęcherze powietrza powstawały przy dnie sitowym i rosły podczas przepływu przez złożę na skutek zjawiska koalescencji. W trakcie badań zaobserwowano również możliwość nie tylko wzrostu pęcherzy, ale także dzielenia się ich na mniejsze. Wielkość pęcherzy zależała głównie od prędkości strumienia podawanego powietrza oraz wysokości złoża i jego masy. Pęcherze nie poruszały się wyłącznie pionowo w górę, zauważać można było chaotyczny ruch poprzeczny. Prędkość pęcherzy powietrza zależała była również od ich średnicy i kształtu, co wskazuje na analogię z przepływem gazu przez kolumnę barbotową. Intensywne mieszanie oraz wysoka powierzchnia kontaktu między fazowego w złożu fluidalnym, tworzy korzystne warunki dla prowadzenia takich procesów jak spalanie czy suszenie. W procesie fluidyzacji niejednorodnej występują różne formy mieszania ziaren, zależne od prędkości i charakteru przepływu fazy gazowej. Wysokość złoża oraz prędkość podawanego powietrza mają wpływ na kształt, rozmiar, sposób poruszania się pęcherzy powietrznych.
**Słowa kluczowe:** fluidyzacja, złoże fluidalne, mieszanie ziaren, złoże pęcherzowe, przepływ dwufazowy.

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