A virtual laboratory setup for studying the drying process of a wide range of bulk solid fractions in fluidized bed apparatuses

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Abstract. The paper presents a software package for the simulation of the processes of gas flow dynamics and bulk solids drying in vertical fluidized bed systems. The fluidized bed system technology processes, mathematical methods, as well as stages of experiments carried out in the virtual laboratory are described in detail. Fluidized bed behaviors in varied heated air flow rates are described. An algorithm for the operation of the virtual unit is presented including modules containing mathematical models of complex heat transfer systems, gas flow dynamics and control of the drying process, as well as interaction with expandable databases with information on the physical and chemical properties of feed materials, purge gases, and ready-made design solutions. The process of comparing the results obtained in the virtual and real low-temperature simulation models is described.

1. Introduction

The design and reconstruction of a fluidized bed apparatus is a complex and laborious process. A significant number of complex calculations based on the reference and experimental data is required to find an optimal mode and adapt the fluidized bed apparatus (FBA) to the real operating conditions. The main goal pursued by the designer is the search for the FBA optimal geometric characteristics, types of gas flow for drying purposes and the quality of the finished product. A virtual laboratory complex designed to model the FBA behavior and operation and perform a pre-design study is described below.

2. Fluidized bed technology

A fluidized bed apparatus is basically a cylindrical column of the required diameter, shown in Figure 1. The FBA housing chamber 1 is made of heat-resistant steel which can withstand high temperatures and aggressive gases. Through air duct 2, a forced draft fan generates air or gas flow into the lower part of the FBA. Perforated plate 3 with many holes of a certain diameter (see Figure 2) helps produce even pressure and ensures uniformity of the fluidizing gas distribution in the FBA working area 4. With the help of a special dispenser 5 consisting of a screw feeder, raw material is supplied to the FBA from the charging hopper for drying purposes. It forms working layer 6 on the perforated distribution plate 3. The hot gas or air pumps through the spaces between solid particles. Each particle comes in direct contact with and becomes uniformly surrounded by the hot gas or air. The particles which were stuck together begin to disintegrate promoting their intense chaotic movement in zone 4. This creates a state of fluidization where the particles are suspended in what appears to be a boiling bed of liquid, the modes of which are mainly as follows: bubbling; turbulent-inertial; and slugging [1,2]. Various modes of the FBA operation are possible. Any of the modes under consideration allows to remove moisture from the particles and evacuate it with the exhaust gas through channel 7. The dry material enters hopper 8 through the outlet duct, and can be forwarded to the next stage of the technological process or used as a finished product.
To avoid entrainment of some particles from zone 4, plate 9 is installed. It resembles in design the distribution plate in Figure 2.

3. Mathematical models

The fluidization process within the FBA involves complex processes of gas flow dynamics and heat transfer. A set of heat and mass balance equations is calculated in real time. These equations are based on the laws of conservation of mass and energy.

Balance calculations estimate the most important operating characteristics for the dryer: heat consumption per kilogram of evaporated moisture, the amount of dry air or gas supplied to the unit, change in the heat transfer agent properties.

The mass and heat balances for the simplest case of continuous drying of moist material with heated air is the following. It is believed that the material to be dried and the heated air consist of a dry part and moisture. For continuous dryers, the mass balance is calculated for the hourly consumption of air, moisture, and material. Calculation of the material balance for an intermittent batch dryer is based on its complete operating cycle.

The input-output material balance calculation for a continuously operating dryer with single use of air looks as follows:

\[ L_{v,1} + G_{v1} + G_{v1} = L_{v,2} + G_{v2} + G_{v2}, \]

where \( L_{v,1}, L_{v,2} \) is the amount of inlet and outlet air flow in the fluidized bed apparatus, kg; \( G_{v1}, G_{v2} \) the amount of moisture contained in the material before and after drying, kg; \( G_{v1}, G_{v2} \) the amount of moisture before and after drying, kg.
The heat balance estimated during the design stage of the dryer, kW, analytically determines the flow rate of the heat transfer agent as well as the main thermotechnical indicators of the process:

\[ Q + Q_{\text{add}} + L_1 I_1 + Gc_1 t_{\text{in}} + Wc_{\text{moist}} t_{\text{in}} = L_2 I_2 + Gc_2 t_{\text{in}}^2 + Q_{\text{loss}}, \]

where \( Q \) is the amount of heat transferred from the air from the heat exchanger, kW; \( Q_{\text{add}} \) the amount of additionally supplied heat to the heat exchanger, kW; \( L_1, L_2 \) inlet and outlet air flow rate of the fluidized bed apparatus, m\(^3\)/h; \( I_1, I_2 \) enthalpy of the inlet and outlet air, kJ/kg; \( G \) the amount of the product to be dried, kg; \( c_1 \) and \( c_2 \) specific heat capacity of the product before and after drying, kJ/(kg\(\cdot\)\(^\circ\)C); \( t_{\text{in}}, t_{\text{in}} \) inlet and outlet product temperature, \(^\circ\)C; \( W \) the amount of the evaporated moisture, kg/h; \( c_{\text{moist}} \) specific heat capacity of the moisture, kJ/(kg\(\cdot\)\(^\circ\)C); \( Q_{\text{loss}} \) external heat loss, kW.

The rate of drying moist material with heated air depends on the intensity of the external and internal heat and mass transfer. External heat and mass transfer is understood as a set of processes contributing to heat transfer to the material and absorption of moisture evaporated from its surface. The intensity of these processes as applied to convective drying depends on the operating parameters of the heat transfer agent (heated air or gas), i.e. its temperature, relative humidity and flow rate.

In some cases, heat transfer and moisture movement within the material (internal heat and mass transfer) significantly affect the drying rate since they control the amount of moisture supplied to the surface. Heat and moisture transfer within the moist material as well as the nature of changes of its physical and mechanical properties in the process of drying are determined by its colloidal-physical and water-binding properties. The process of removing moisture from bulk material occurs when its connection with the skeleton of the material’s physical structure is broken, which requires a certain amount of energy. Therefore, the classification of water-binding capacities should take into account the value of this bond energy.

The amount of heat transferred from the gas to the bed depending on the residence time in the apparatus is described by the following expression:

\[ Q = \alpha_\Sigma \left( T_z - \frac{T_w + T_x}{2} \right) S \cdot t, \]

where \( \alpha_\Sigma \) is a heat transfer coefficient by convection, radiation and thermal conductivity, W/(m\(^2\)\(\cdot\)\(^\circ\)C); \( T_z \) gas temperature, \(^\circ\)C; \( T_w, T_x \) the initial and final temperature of the feed material, respectively, \(^\circ\)C; \( S \) cross-section area of the bed, m\(^2\); \( t \) particle residence time in the apparatus, sec.

The value of coefficient \( \alpha_\Sigma \) is determined by the expression:

\[ \alpha_\Sigma = \alpha_{\text{conv}} + \alpha_{\text{rad}} + \alpha_{\text{cond}}. \]

The convective heat transfer component can be determined by the dependence

\[ \alpha_{\text{conv}} = 0.142 \left( \frac{10.57}{\lambda} \right) w^{0.8} p^{0.43} c^{0.43} (1 - m_{\text{cm}})^{0.133} \left( d^{0.2} n^{0.37} m_{\text{cm}}^{0.8} \right), \]

where \( \lambda \) is thermal conductivity, \( w \) speed, m/sec.; \( p \) pressure, Pa; \( c \) heat capacity, kJ/(kg\(\cdot\)\(^\circ\)C); \( m_{\text{cm}} \) porosity near the heat exchange surface; \( d \) particle diameter, m; \( n \) kinematic viscosity, m\(^2\)/sec.

The radiation heat transfer coefficient is calculated by the formula:

\[ \alpha_{\text{rad}} = \sigma \varepsilon_{\text{giv}} \left( \frac{T_w + T_x}{2} \right) + T_x^2 \left( \frac{T_w + T_x}{2} + T_x \right), \]
Conductive heat transfer between a surface area unit and the fluidized bed depends on the particle relative surface area

\[ \alpha_{nd} = 8.95k / d (1 - m_{cm})^{2/3}. \]

A temperature increase in the fluidized bed apparatus has a double effect on the intensity of the external heat transfer. First, there is a change in the thermophysical properties of the dispersed material and fluidizing agent. Second, the mechanism of energy transfer becomes more complicated. Radiative transfer, the role of which in low-temperature systems is negligible, becomes essential. The main feature of the process of energy transfer in the form of electromagnetic radiation is optional presence of a medium necessary for wave propagation.

The interaction of radiation with matter is a very complex process depending on a number of factors. It is realized by three independent physical mechanisms: scattering, absorption and radiation. The first two cause attenuation of incident radiation; the latter enhances it.

To determine the total pressure loss, taking into account the maintenance of the bed in a fluidized state, we suggest the following dependence:

\[ P = \left( \frac{f}{F} \right)^2 \cdot \left( \frac{w}{F_c} \right)^2 \cdot \frac{\rho}{2} \left[ \left( 1 + 0.707 \sqrt{1 - \frac{F}{f}} \right)^2 + \left( 1.7 - \frac{F}{f} \right)^2 \right] + H_0 g \left( \rho_p - \rho \right) (1 - m_0), \]

where \( f \) is the area of the bottom plate of the fluidized bed apparatus, \( m^2 \); \( F \) open area of the perforated plate (total hole area), \( m^2 \); where \( F_c \) is the ratio of the hollow area of the plate \( m^2 \); \( H_0 \) height of the fixed bed, \( m \); \( g \) acceleration of gravity, \( m/s^2 \); \( m_0 \) bed porosity at rest.

The presented models form the basis for the virtual laboratory setup.

4. Virtual laboratory setup

A virtual laboratory setup is a software package developed in C ++ language. It allows to carry out research without direct involvement with a real apparatus or stand. As a rule, the virtual laboratory combines a machine model for dynamic simulation and a shell including the necessary methodological support for the experiment. The dynamic model is formed from a set of control elements which are used to adjust specific input parameters and read the experiment’s output parameters thereby simulating physical processes.

Modern computer graphics is used to create highly realistic three-dimensional models of virtual laboratories, machine tools, instruments and other objects. The harmonious combination of textures of materials and lighting, as well as the option to move the camera in three-dimensional space, ensures the most complete experience of virtual reality. Several modules of the virtual laboratory are designed in the Visual Basic.NET environment.

The virtual laboratory setup we created is based on the work described in [2-4]. First of all, the laboratory is focused on studying the drying process of bulk materials entering the fluidized bed apparatus; gas flow patterns in fluidized beds depending on the composition of the material and the nature of the air flow formed by high-pressure draft fans. The virtual unit has many windows, some of the main ones are shown in Figures. 3 and 4. During operation, other windows displaying the settings of ventilation, heating and filtration units, bulk solids, etc. open. In real time, it is possible to adjust the diameters of the holes in the distribution plate, shown in Figure 2, increase performance of the draft fans, change the heat transfer agent in the heat exchanger, the degree of inlet gas purity, etc.
Of particular value are three expandable databases containing information on the physical and chemical properties of feed materials, purge gases, and complete designs. There is a log where operation of each unit is registered. It contains information about the operating modes of each unit, adjustable values and results obtained.

5. **Operation algorithm**

As a preliminary step, before starting the systems in the virtual laboratory, one must enter initial data including:

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**Figure 3.** Window displaying an arrangement of forced draft fans, heat exchangers and filters.

**Figure 4.** Window displaying an arrangement of fluidized bed apparatuses.
1. Selection of a drying technology;
2. Selection of the initial physical and chemical parameters of the purge gas;
3. Selection of the heat transfer agent parameters via the heat exchanger;
4. The choice of bulk material and its properties;
5. Description of the FBA geometric characteristics and components;
6. Setting of the values for the high-pressure draft fan and filters;
7. Setting the residence time in the FBA for the bulk material.

FBA startup sequence:

1. Initial loading of the prepared bulk material until the required layer height is formed;
2. Heating up the heat exchanger, if necessary. Purge gas with the required physical and chemical properties from other manufacturing processes (for example, waste gas from boiler houses, thermal power plants, metallurgical and chemical industries, etc.) can be used.
3. Taking readings from virtual temperature sensors installed on the surface of the heat exchanger;
4. Opening valves on gas ducts using virtual actuators;
5. Smooth start of draft fans;
6. Taking readings from virtual temperature sensors installed on the surface of the heat exchanger, the suction and discharge pipes of the draft fan and the FBA inlet duct;
7. If the system parameters for some reason do not comply with the required ones (e.g. purge gas inlet temperature is lower than necessary), the virtual controller sends a signal to the actuator of the heat exchanger balancing valve to increase the heat transfer agent flow rate; consequently, it begins to circulate more intensively and the gas temperature increases.
8. Blowing gas through the layer of bulk material in the FBA. The layer warms up, “boils” in the gas flow, and the process of removing moisture from the bulk is initiated;
9. Taking readings from the virtual sensors of gas temperature, pressure and humidity installed inside the FBA;
10. Registration of indicators of each procedure and all measured and controlled parameters in the electronic log.

6. Results and validation of the model adequacy
As already mentioned, the physical parameters of the purge gas, the heat transfer agent in the heat exchanger, etc. are recorded during the experiments. The most significant results of an experiment are modes of the fluidized bed, which can be bubbling, turbulent-inertial or slug as well as assessment of the bulk solids at the inlet and outlet. In most cases, the gas flow rate is high producing a turbulent gas flow within the FBA.

The results obtained in the virtual laboratory were compared with the data from the real low-temperature simulation model, shown in Figure 5. Regarding the gas flow dynamics, the following parameters varied in the real model: flow rate, velocity, pressure, air and water temperature, design parameters of the FBA components, the type and mass of the loaded material, and flow intensity of the heat transfer agent in the heat exchanger. Figure 6 shows the research results obtained from a physical low-temperature simulation system and mathematical models. Three experiments were carried out independently of each other in a virtual laboratory setup and a low-temperature simulation model with different gas flow modes. Each experiment lasted 1 hour. The results were compared using the Reynolds number. The discrepancy between the results was no more than 4%. 
As seen in Figure 6, the mathematical model of the virtual laboratory quite satisfactorily describes real processes running in the low-temperature simulation model. The transfer of the results produced by the mathematical model to real systems is based, on the one hand, on an additional provision about the similarity of complex systems [5,6]. On the other hand, results for individual elements can be transferred through the criterion of gas-dynamic similarity, i.e. through the Reynolds number, which shows a relationship between the rates of ongoing processes and the geometric parameters of the connected elements and the properties of the environment. This task is very important in the synthesis of bulk solids drying systems.

Some important points are not elaborated on in this article; they require further research which will be presented in subsequent publications.
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