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Inductive heating of fluidized beds: Drying of particulate solids

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ABSTRACT

The present research work deals with drying of particulate solids in inductively heated fluidized bed. Capillary-porous and non-porous solids are dried by inductive and convective (benchmark experiments) heating. The influence of both heating types and test materials on the drying rate and the product moisture content is discussed. The conducted drying trials present very similar drying rates and product moisture contents under the same drying conditions by both energy input methods in fluidized beds. Moreover, it was demonstrated that this novel method for energy input in fluidized beds allows rapid heating and cooling and therefore enables considerably more controllable temperature profiles. In this way, the costly and time consuming start-up processes in batchwise fluidized bed processing can be shorten. This study therefore clearly points out the enormes potential of inductive energy input in fluidized beds.

1. Introduction

Fluidized bed technology is widely used in various industries such as the pharmaceutical, food chemistry and environmental technology sectors. Its advantages lie, among other things, in an intensive heat and mass transfer, a targeted temperature control and a compact construction volume [1,2]. In most cases, the energy input to a fluidized bed is realized by a convective heating of the fluidizing medium or in combination with contact heat transfer. In the present paper, a novel method for energy input into fluidized bed apparatus for drying of solid materials is presented. The inductive energy input offers an alternative for the convective heat transfer in fluidized beds. Here, the heat source are electrically conductive particles (e.g. iron hollow balls IHB) in the fluidized bed to which energy is transmitted contact-free via an alternating electromagnetic field.

On the surface of the inert particles (IHB) the heat is released directly into fluidized bed. Since the heat is dissipated to the fluidized material through a large total particle surface, a very high energy density and finally a highly efficient heat transfer can be achieved. In this way, the energy efficiency of fluidized bed processes can be increased. Of particular interest is the fast and precise temperature control during the inductive heating of fluidized beds. This is especially important for batch processes in fluidized bed apparatuses. In previous work, the behavior of fluidized bed with inductive heating was investigated by Idakiev et al. [3]. In this paper, this novel technology for energy input in fluidized beds is used to dry particulate solids. The drying of capillary-porous and non-porous solids with convective (benchmark experiments) and inductive energy input is studied and compared with each other with respect to moisture content of the product and the drying rates.

2. State of the technology

Due to their numerous advantages, the fluidized bed technology has gained significant importance in the last century in many industrial processes. To date, a large number of publications and patents on fluidized bulk materials can be found. To the ever-increasing application areas of fluidized bed technology, belong processes such as drying, molding, granulation, agglomeration or combustion [1,2].

Drying is the oldest known method for removing a liquid from wet bulk materials [4]. Already in the older Stone Age, people have dried food to store it for a long time. In 17th and 18th century various substances were usually dried by hot air or smoke. In the 19th century the drying by vacuum or by spraying was developed. A century later, the drum dryer and vacuum-freeze dryer were invented. But the drying has been greatly developed after the Second World War [5].

Today there are many processes to dry solids, suspensions or solutions. For example, drum drying, spray drying, flash drying, drying by microwave, freeze-drying and other [6].

The individual types of dryers can be divided according to different characteristics (dominant heat transfer mechanism, type of product to be dried, pressure in the apparatus, operation and others). In many cases the required heat is supplied by convection. In these dryers, the solid particles are dried using a hot continuously flowing gas stream. In contact drying, heat is transferred through the wet material from heated surfaces by conduction [7]. Freeze-drying and vacuum-freeze drying are often used for drying of heat-sensitive materials. These methods ensure gentle drying of the goods and increase the quality of the dried product. However, their use is not wide-spread because of

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their equipment and operation cost [8]. Heating by infrared radiation enables to reduce the drying time, since the heat of the heating element is transferred directly to the particle surface without that the ambient air is heated in the apparatus [9]. Another approach is microwave drying, as microwaves can penetrate the material to be dried and in this way the heat is generated directly in the solid [10]. Nevertheless, this type of drying is rarely used in the industry due to the high operating costs, compared to convective or contact drying.

Fluidized bed apparatuses are often used for convective drying owing to the excellent mass and heat transfer for instance in drying of solids, granules, pharmaceutical and agricultural materials and foodstuffs such as peas, beans, vegetable and onion dices, coffee and other [11]. Fluidized beds are particularly advantageous due to the simple solids handling through the fluid-like behavior, intensive solids mixing and the resulting uniform temperature distribution, large exchange surface between solid and gas and high heat transfer value between solid and gas [1]. In most cases, the heat required for the drying process in fluidized beds is provided by means of a preheated fluidizing gas. Moreover, additional thermal energy can be inserted to the process by either immersed heating elements, e.g. steam-heated tubes, or by heating of the fluidization chamber wall. Due to contact of particles with heated surfaces additional heat transfer is available leading to process intensification, i.e. higher drying rates due to increased heat transfer area. Lower gas inlet temperature is requested, which is preferable for heat-sensitive products. However, limited number of tubes, influence on flow field and fouling are subject to the limitations of the process intensification by contact heating [12]. An alternative method of providing the required heat to fluidized beds is inductive heating. First studies on the inductive energy input into fluidized beds by Stresing et al. [13] have found that the method of non-contact heating of inert particles by electromagnetic alternating fields in fluidized bed apparatuses is possible. In their work, iron hollow balls (IHB) were used as electrically conductive inert particles in the fluidized bed apparatus submitted to an external electromagnetic field. The heat released by the skin effect on the surface of the iron particles is transferred convectively to the fluidizing medium. Skin effect is a tendency for alternating current to flow mostly near the outer surface of an electrical conductor, such as iron balls. It describes the appearance of the current density and occurs with high frequency alternating current. Due to this effect, the current density is largest near the surface of the conductor and decreases towards the center. This is because electric current flows mainly at the “skin” of the conductor. This effect is greater with increase of the frequency. This is a desired effect by the inductive energy input and it is beneficial, because only the particle surface must be heated for heat transfer [3]. Energy losses were reported. Furthermore, it has been found that very fast heating and cooling can be realized [14]. In Idakiev et al. [15]., the influence of the electrical power supplied to the generator and the bed composition on the heating behavior of an inductively heated fluidized bed has been examined and compared with a convection-heated fluidized bed plant. It has been shown that the magnitude of power has no significant effect on the response time of the inductive heating. A higher proportion of inert particles yields higher gas outlet temperatures, since a larger surface of the iron particles for the heat transfer with the fluidizing medium has been available. The authors also reported on the efficiency of the inductive energy input (percentage of the electric power injected via the generator transferred to the fluidizing medium by the IHB) of about 70%. Furthermore, Roßau [16] has found out that the increase of induction power may yield changes in the fluidization behavior in a bed consisting of inert iron particles due to orientation along field lines. These changes in the fluidization behavior observed by Roßau [16] were prevented by coating of iron hollow balls with kaolin or use of pulsed induction power as described in Idakiev et al. [3]. Higher induction powers also have led to stronger fluctuations of the bed pressure drop. With increasing gas velocity these fluctuations have been smaller. Furthermore, smaller iron hollow balls have influenced the fluidization behavior of the fluidized bed more strongly, because a greater surface area for interaction with the magnetic field is available [3].

Idakiev et al. [17] have presented a model for the calculation of heat transfer in an inductively heated fluidized bed. This model allows the calculation of the particle, gas and wall temperature at a certain introduced energy. The authors performed experiments at various mass of the bed, gas velocity and induction power. The calculated temperatures are in very good agreement with the experimentally measured values.

An alternative approach to inductive energy input into a fluidized bed has been shown by Latifi et al. [18]. The authors have used an inductive heated fluidized bed mini-reactor, having a reaction zone with a diameter of 0.025 m and a length of 0.3 m, which has been designed and built for solid-state reactions up to 1500 °C. The fluidized bed chamber of this reactor has consisted of an aluminium oxide tube, which has been externally surrounded by a copper coil with 8 windings. Inside, inductively heated steel bars have been installed. In these tests, up to 1500 °C process temperatures could be obtained a few seconds after switching on the electromagnetic alternating field. Again, the short warm-up and cool-down have been observed using the induction heating.

Use of IHB for heat transfer is beneficial in terms of very large surface area for heat transfer, co-fluidization with product (moving transfer area), possibly self-cleaning via particle-particle collisions, combining advantages of heating elements and inductive heating. In view of these benefits, use of IHB offers bright prospects for process intensification by induction heating.

First results for drying of a porous material using inductive heating were presented by Roßau [16]. The drying process could be accelerated considerably by increasing the induction power. Intensification of the drying process particularly in the first drying stage has been also reported by increase of the inert particle mass mainly due to the increasing surface area for heat transfer. Based on these first experiences for drying capillary porous bulk materials an in-depth study of drying of a non-porous bulk material is presented in this contribution. The product moisture content and the drying rates for a strongly capillary porous bulk material and a non-porous bulk material are investigated. Variations of the gas mass flow and the process temperature are discussed. In addition, a direct comparison of the drying process with convective and inductive energy input to the fluidized bed is made.

3. Experimental setup

This section describes the configuration of the cylindrical fluidized bed apparatus. The properties of the used electrically conductive iron hollow balls and wet solid particles to be dried are presented. In addition, this chapter gives a description of the experimental procedure and the experiments carried out with the corresponding varied parameters.

3.1. Experimental apparatus

For the experimental investigations of drying of particulate solids by inductive heating a cylindrical fluidized bed apparatus was used with a bed diameter of 200 mm.

This plant was designed and built based on the results of previous work and offers a variety of precise measurement capabilities. The plant makes it possible to heat the fluidizing medium both inductively (by addition of IHB) and convectively (via an upstream electric heater), which leads to a reliable comparison between the two types of heating or drying methods, respectively. The setup of the fluidized bed apparatus is presented schematically in Fig. 1.

Air was used as fluidization medium in all experiments. Ambient air can be drawn in either by suction blower, pressure blower or with both of them simultaneously. The drying experiments shown in this paper have been carried out exclusively in suction operation so that the gas