INDUCTIVE ENERGY INPUT IN FLUIDIZED BEDS

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Abstract: *The energy input in fluidized beds is usually performed by convection. In this case, the fluid stream is heated through a heater before entering the fluidized bed chamber. This method has long heating and cooling time. Therefore the purpose of this work is to find out other energy input options in fluidized beds. Such as, the induction heating is suggested. In this case, the fluidizing gas is not the source of energy, but the electrically conductive inert particles (like iron hollow spheres) into the fluidized bed, in which an induction electromagnetic field is transferred. On the surface of these particles, the heat is released directly into the fluidized bed. Here, since the heat is emitted via a large overall surface of the bed material, a very high energy density and, finally, highly efficient heat transfer can be achieved. In this way, the energy efficiency of fluidized bed processes can be significantly increased.*

Keywords: FLUIDIZED BED, INDUCTIVE HEATING, DRYING, SPRAY LAYERING GRANULATION

1. Introduction

A fluidized bed is a state of a two-phase mixture of particulate solid material and fluid, which has various procedural advantages and is widely used in various applications like drying, granulation and coating. Furthermore, the fluidized beds have a very good heat and mass transfer, which play an important role in many industrial processes. Usually, the fluidized beds are heated by the hot fluidizing gas. In this case, the energy input is realized by convection. Due to the long heating and cooling time of this method and thus resulting energy losses, other energy input methods should be suggested for increasing the energy efficiency of fluidized bed processes. The inductive heating is a possible way to achieve this objective.

Here, the energy input is transmitted directly by non-contact heating of electrically conductive but chemically inert particles in the fluidized bed. For this purpose, an induction electromagnetic field is transferred in this particles leading to their heating, and thereby, the heat is released on the surface of these particles directly into the fluidized bed. This results in large heat transfer surface areas and very quick heating and cooling.

By induction, the energy conversion occurs mainly at the edge zones (surface) of the particle due to the skin effect. The term " skin effect" refers to the tendency for alternating current to flow mostly near the outer surface of an electrical conductor, e.g. iron balls. It takes place with high frequency alternating current and describes the appearance of the current density. Due to the fact that the electric current flows mainly at the "skin" of the conductor, the current density decreases towards the center and it is largest near the surface of the conductor. The higher the frequency is, the greater the skin effect. This is a positive characteristic of the inductive energy input. In this way, only the particle surface must be heated for heat transfer (Filtz and Birenbaum 1987, Rudnev et al. 2003).

The inductive heating is applied in various processes including annealing, bonding, brazing, forging, hardening, melting, plasma production etc.. The heating by induction offers very clear benefits in terms of reducing heat loss and energy consumption in comparison to conventional convective heating. Moreover, induction transfers more energy per square meter than the open flame, which leads to faster heating. Ultimately this improves both the throughput and the quality (EFD 2010).

These considerable advantages of induction can also be transferred to fluidized bed processes. By using induction, the bed material will be faster heated and faster cooled, resulting in high efficiency and better product quality. Therefore, the research strategy pursued here focuses on the application of induction technology in fluidized beds in order to lower energy costs and thus enhance the complete production profitability.

In previos own research studies it was shown how induction influensses the fluidization behavior (Idakiev et al. submitted). The presented contribution describes therefore the heating behavior. Both methods of energy input in fluidized beds (induction and convection) are shown and compared. In addition, the application possibilities of the inductive energy input are presented, e.g. drying of suspensions in inductively heated fluidized beds and fluidized bed granulation with conventional and inductive heating. The ultimate goal of this work is to reduce the energy consumption during particle formulation processes in fluidized bed apparatus.

2. Experimental setup

In this study, two cylindrical fluidized bed apparatus are used for experimental purposes. One is heated by induction. Therefore, the plant is equipped with an inductor with 9 windings, which generate the electromagnetic field in the fluidized bed, leading to heating of the electrically conductive particles in the fluidized bed chamber. The inductor is electrically powered by a generator from Hüttinger Elektrik GmbH + Co. KG (TruHeat MF 3040). It can transmit electrical power up to 40 kW and is made from copper of high purity and has a good electrical conductivity. In order to avoid heating of the copper, the inductor is cooled with water during the trials. In this manner, the electrical conductivity is kept stable. The schematic representation of this experimental plant and the illustration of the inductor surrounding the fluidized bed chamber are given in Figure 1. The 2nd plant used in this study is heated by convection, thus via the fluidizing gas, in which the benchmark experiments are conducted. It is electrically heated and has the same fluid bed distributor plate as the inductive fluidized bed apparatus. Also, the fluidized bed chambers of both experimental plants have the same inner diameter of 300 mm permiting reproducibility of the tests carried out.

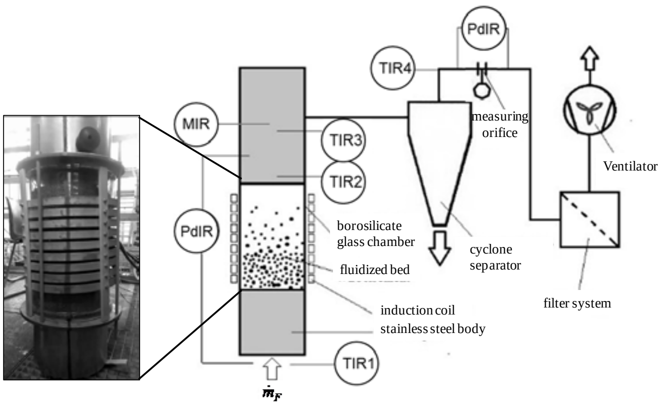

Fig. 1 *Schematic design and picture of the inductive experimental plans*

As an experimental material electrically conductive iron hollow balls (IHB) are used. Based on the production process of the company Hollomet GmbH nearly monodisperse particles of defined diameter with varying the particle layer thickness can be produced (Hollomet 2014). This allows to create particles with defined fluidization properties. Therefore, hollow balls of conductive material with wide-ranging properties can be manufactured enabling a broad range of possible fluidization of solid material.

The iron hollow balls used in this work exhibit a sauter mean diameter of 3.22 mm, an iron layer thickness of 120 μm, and an apparent density of 1774 kg/m³. In addition, the experimental material can be coated with kaolin to insulate the iron hollow balls in order to prevent possible electricity flows at higher energy input between the individual particles leading to local overheating and sparks on particle surface. The kaolin coated and non-coated iron hollow balls are shown in Figure 2.

Fig. 2 *Iron hollow balls (kaolin coated and non-coated)*

As an experimental material electrically non-conductive glass beads (GB) in diameter of 2.66 mm and with an apparent density of 2615 kg/m³ are used to study the heating behavior of mixtures of conductive and non-conductive materials. They have similar fluid dynamic properties (determined by similar Archimedes number, minimum fluidization and elutriation Reynolds numbers) as the iron hollow balls. The glass beads are meant to represent the product of a real process, e.g. moist bulk materials for drying processes or carriers cores for spray layering granulation processes. In this study, they are used as model substance for carriers cores, too.

In order to determine the impact of individual process parameters on the efficiency of the inductive energy input and the behavior of the fluidized bed, various parameters such as applied electrical power, air velocity, kaolin coating, ratio of iron hollow balls to non-conductive material were systematically varied. In the presented study, only the influence of the applied electrical power and the ratio of conductive to non-conductive material on the heating behavior will be discussed. The impact of the other parameters can be gathered from our previous research studies (Idakiev et al. 2015, Idakiev et al. submitted).

In further experiments, the drying of suspensions in inductive heated fluidized beds is investigated. Here, limestone powder as raw material for the preparation of suspension to be dried by induction is used. The solids content in the tested suspension is 20 % m/m. After reaching the desired process temperature, the suspension is sprayed for 2 hours on the surface of the inert particles (IHB) forming solid layers on their surface, which break by collision resulting in finely-dispersed particles.

Subsequently, the fluidized bed spray layering granulation with inductive energy input is studied. In these experiments, 30 % m/m sodium benzoate solution is sprayed for 2 hours after reaching the desired process temperature. The spraying takes place from below in the form of a bottom spray. As carriers cores for build-up of granules, glass beads in diameter of 2.66 mm and with an apparent density of 2615 kg/m³, having a good thorough mixing and fluidization with the IHB are used in this study.

3. Results and Discussion

In this section, the temperature response under inductive energy input are presented and discussed. The evaluation of fluidized bed processes such as drying of suspensions and spray layering granulation in inductive heated fluidized beds is given in this section, too.

3.1 Heating behavior

Figure 3 shows the effect of the induction heating on the temperature increase and decrease, respectively. In the induction trials, after a few seconds the gas outlet temperature has already achieved a steady-state value while in the convective one the achieving of the steady-state value takes significantly longer. This also applies for the cooling process. The figure 3 proves that the induction technology massively reduces heating and cooling times. Therefore, temperature gradients are much more controllable. This allows the treatment of heat sensitive materials or biological substances demanding quick heating and cooling.

Moreover, all conducted experiments show a similar time response of the temperature. Even at different induction powers, the heating and cooling occurs equally quick. The gas outlet temperature increases with the increasing energy supplied to the system. It is to be noted that not all of the supplied electrical power is transferred to the iron hollow balls, but a part of the energy is consumed by the water cooling of the inductor as well as heat losses to the environment. This is the reason, why in the induction experiment more electrical power (5.5 kW) should be applied to achieve the same steady-state gas outlet temperature than the experiment with convective heating (4.0 kW).

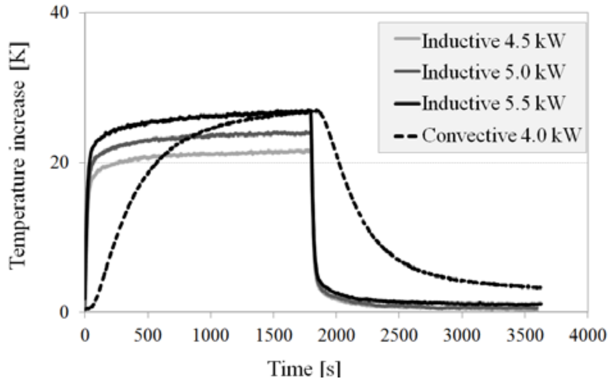

Fig. 3 *Influence of the energy input on the heating behavior*

Since the mixture ratio is an important parameter from the point of view of heating behavior, the necessary ratio of electrically conductive particles to bed material for efficient and uniform heating is investigated. The results thereof are presented in the Figure 4.

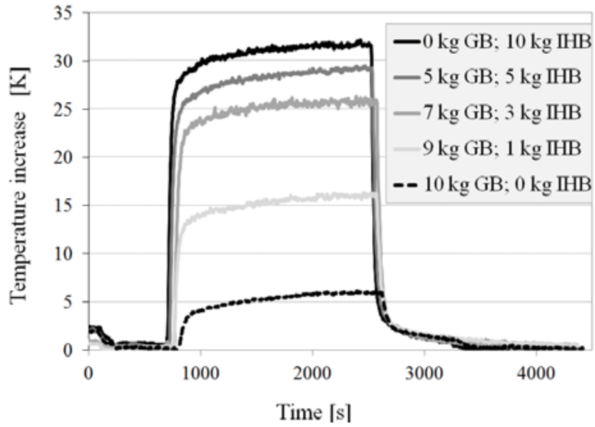

Fig. 4 *Influence of the mixing ratio on the heating behavior*

It can be seen an increase in temperature with the increasing proportion of iron balls. The greater number of electrically conductive balls is, the higher the surface of the particle collective on which the air can be heated. In the experiment, where the bed consist only of glass beads, therefore there are no conductive particles for the heat transfer, the slight increase in temperature can be attributed to the fact that the steel flanges of the fluidized bed chamber are heated under influence of the electromagnetic field and they release the heat to their surroundings. Figure 4 illustrates that even with a small mass fraction of iron hollow balls (30 %), a high temperature increase similar to that of bed consisting only of iron hollow balls can be achieved. Therefore, the mixing ratio of 1:0.43 GB:IHB is selected for the spray layering granulation experiments (10 kg bed mass consisting of 7 kg GB and 3 kg IHB).

3.2 Drying of suspensions with inductive energy input

The temperature curves during the heat-up and spraying phases of the drying process with inductive and convective energy input are illustrated in the Figure 5. The heat-up phase designates the time difference between the switching on the heating and reaching the steady state temperature, at which the temperature deviation from the average is less than 0.25 K.

The heat-up phase of inductive heating is several times shorter than that of convective heating. Furthermore, the gas temperature or the operating temperature can be controlled very well with the induction heating method, since with switching on the heating the heat is available immediately for the drying process and with switching off the heating the process temperature immediately sinks. Although the steady state temperature is reached in a few seconds, the spraying is conducted after 1 hour to ensure comparability of the both experiments.

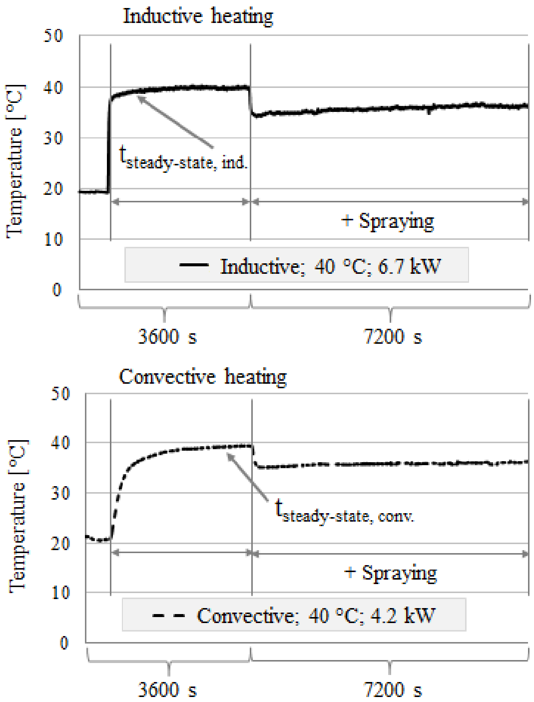

Fig. 5 *Temperature profile of suspension drying process*

Since the sprayed suspension is dried on the surface of the inert particles (IHB), it is important to know if some of solids adhere on the surface of IHB. As shown in Figure 6, no coating of the inert particles is observed, so that they are directly reusable. The scanning-electron-microscope (SEM) studies reveal that almost no differences exist in the surface structure of untreated IHB and IHB after the drying process (see Figure 6). Some pores are covered with limestone dust, but no homogeneous coating has been formed during the drying process.

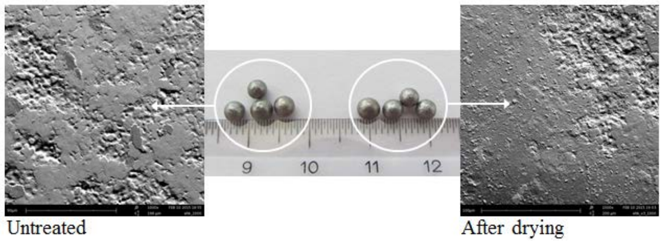

Fig. 6 *SEM images of iron hollow balls before and after drying*

To clarify the possible changes in the product quality through the drying process, the surface structure and the particle size distribution of the untreated and dried product are investigated. The SEM images and the graphical presentation of the particle size distribution are provided in Figures 7 and 8.

The SEM images clearly show that no marked differences between the individual samples can be identified. The particle structure of all products is characterized by angular, irregular but smooth surfaces (Figure 7). But the particle size is clearly influenced by the drying process. The convective drying yields a product with wide particle size distribution. In comparison, the inductive drying results in formation of particles with a very narrow size distribution (Figure 8), which is especially preferred in pharmaceutical applications, e.g. pharmaceutical powders for use in inhalation.

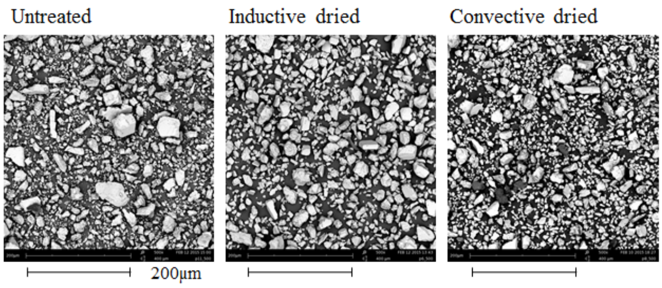

Fig. 7 *SEM images of limestone powder before and after drying*

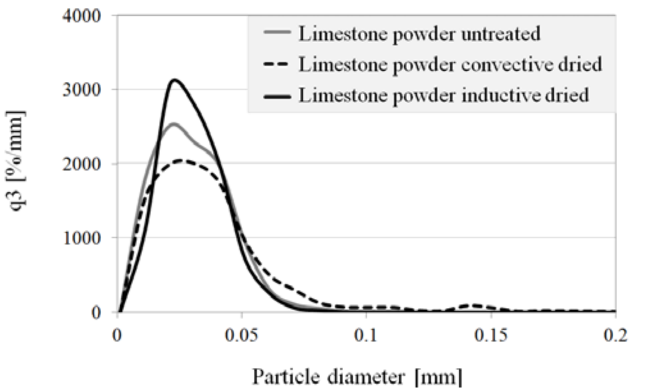

Fig. 8 *Particle size distribution of limestone powder before and after drying*

3.3 Spray layering granulation with inductive energy input

A comparison between the particle size of the untreated particles (IHB and GB) and that of the formed granules is given in Figure 9. The conductive particles as well as the carriers cores are simultaneously coated as illustrated by the SEM images in Figure 10 resulting in particle growth of both materials. It is important to note that the type of fluidized bed heating does not affect the particle growth. No differences between the inductive heating and convective one are observed.

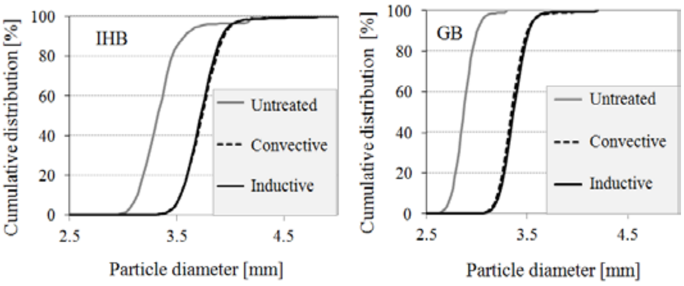

Fig. 9 *Cumulative distribution of IHB (left) and GB (right) before and after drying*

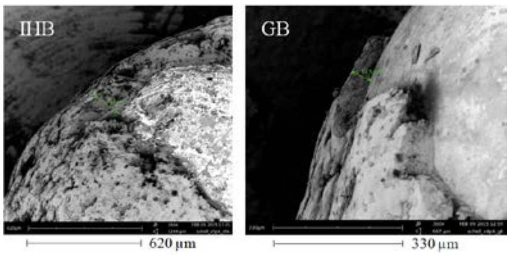

Fig. 10 *SEM images of coated IHB (left) and coated GB (right)*

To make a clear statement about the product quality of the produced granules, the morphology of the formed layer was investigated. For this purpose, the coating layer thickness and porosity of the obtained granules are measured using micro-computed X-ray tomography according to the method reported by Sondej et al. (2015). The 3D reconstruction of granule shells of glass beads is given in Figure 11. It was determined that by rising spray rate from 3.1 to 5.4 kg/h and constant temperature (55 °C) the coating layer thickness of granules is increased having a value ranging from 130 to 212 µm by inductive heating and from 169 to 243 µm by convective heating, respectively. By convective heating, the coating layer porosity also increases with increasing spray rate, so that it is 9.3 µm at 3.1 kg/h and 11.6 µm at 5.4 kg/h spray rate. Conversely, by inductive heating it decrease from 12.2 to 7.3 µm. Despite this difference, it could be concluded that the granules obtained from inductive and convective spray layering granulation do not differ essentially with respect to the product quality.

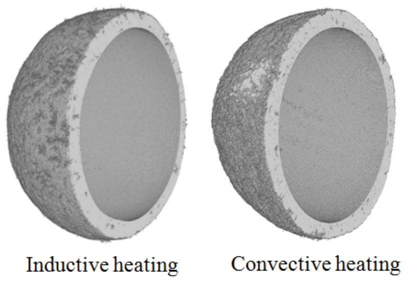

Fig. 11 *3D reconstruction of granule shells using micro-computed X-ray tomography*

4. Summary

In the presented study, the inductive heating is tested as an alternative to the convective heating in fluidized beds. In essence, this is attributable to the advantages that inductive energy input demonstrates, most notably in comparison with convective one. For example: very high heat transfer surfaces and energy densities due to the fact that the heat exchanger is the electrically conductive particles in the fluidized bed. Also invaluable here is the very quick time response, minimizing time and energy consuming heating and cooling times, and giving the possibility to precisely control the process. It is therefore the objective of the present study to apply the inductive energy input in fluidized beds in order to improve efficiency and enhance product quality.

From the investigation carried out, it can be concluded that the induction heating massively reduces heating and cooling times. The heating and cooling process is very fast, which is favourable for processing of heat sensitive materials or biological substances demanding quick heat treatment and short residence times.

Special attention was put on ways to find application of the inductive energy input in fluidized bed processes. Therefore, drying of suspensions and spray layering granulation are evaluated as possible application of inductive energy input in fluidized beds.

The inductive drying is characterized by a shorter heat-up phase in comparison with convective heating. The surface of the inert particles (IHB) is not affected by the inductive drying process. No undesired coating takes place during the drying, so that the iron hollow balls can be directly reused. From the point of view of product quality, the inductive and the convective drying can not be differentiated from each other. The inductive drying appears to be even more promising in regard to the narrow particle size distribution of the resulting product.

In view of spray layering granulation process, no differences between particle growth by inductive and convective heating are recognizable. The granules made by means of spray granulation with inductive and convective energy input show similar product properties like surface structure and layer morphology.

In summary, the results of the presented study clearly demonstrate the enormous potential of inductive energy input in fluidized beds. However, to use it in industrial applications as well as to bring fluidized bed apparatus with inductive heating to a marketable stage, further research effort is needed.

Acknowledgements

The project is funded by the Federal Ministry of Education and Research (BMBF) under the funding program “InnoProfile-Transfer”. The authors thank BMBF for the financial support as well as the master's degree students Ludger Schmidt and Stefan Helmeke for their experimental support. The authors would also like to convey thanks to Franziska Sondej for performing the micro-computed X-ray tomography measurements.

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