Comparison of two paddle wheel geometries within the filling chamber of a rotary tablet press feed frame with regard to the distribution behavior of a model powder and the influence on the resulting tablet mass

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ABSTRACT

Objective: The purpose of this study was to compare the influence of two different paddle wheel geometries on the distribution behavior of a model powder within the filling chamber of a modified feed frame of a rotary tablet press. Moreover, both paddle wheels were compared regarding their influence on the resulting tablet mass during the tableting process.

Significance: Insights are provided regarding the influence of the paddle wheel geometry on the powder distribution to optimize the die filling process.

Materials and methods: Avicel PH 102 served as model powder. A laser triangulator was used to scan the powder surface level within the feed frame and, combined with the determination of the angle position of the paddle wheel, an in-house written software was used to calculate the powder surface profiles and filling levels. Two experimental setups, one based on the filling chamber filled with a defined amount of powder (offline) and one using the filling chamber during tableting (inline) were applied.

Results: Both paddle wheel geometries caused a significantly different distribution behavior of the powder within the filling chamber. The tablets obtained with the round rod filling wheel showed significantly higher tablet masses and significantly lower standard deviations. The inflow of powder into the filling chamber appeared to be improved with the round rod filling wheel.

Conclusions: Under the applied experimental conditions, the round rod filling wheel showed obvious advantages compared to that with flat rods in terms of the uniformity of tablet masses and the extent of die filling.

Introduction

Tablets are the most common solid dosage forms for oral delivery of therapeutic substances and are nowadays produced almost exclusively with high-speed rotary tablet presses, which are able to produce more than a million tablets per hour under optimal process conditions [1,2]. Because of the high-quality requirements for tablets, the optimization of individual production processes with regard to the uniformity of the product is of considerable interest to the industry, as the uniformity of quality-relevant parameters assures that all tablets meet the requirements.

An important process step in the production of tablets is the uniform filling of the dies, in which the powder is compressed [3–6]. Independent of the individual extent of die filling, the distance between the upper and the lower punches within the compaction station is usually kept constant for all dies during production [7]. Those dies, which are filled to a higher extent with powder than other dies, the compression force is accordingly higher. Therefore, numerous quality-relevant parameters are affected, if variations during the filling process of the individual dies occur [3,8–16].

Frequently, the deviation of the die fillings and thus the standard deviation of the tablet masses increases with increasing tableting speed and is often rate-limiting for tablet production [16]. In addition to the tableting speed, the flowability of the powder is a major influencing factor regarding the uniformity of the die filling process [4,5,6,17]. Therefore, during formulation, development attention has to be paid to formulate a powder blend that shows suitable flow characteristics.

In rotary tablet presses, the filling of the dies is carried out by feed frames. In addition to the tableting speed and flow behavior of the powder, the performance of the filling system is considered to be an additional main influencing factor in terms of the uniformity of the die filling process [3,5,10,12,13,15]. Feed frames usually possess one or more chambers containing rotating paddle wheels, which supply the powder to the dies as evenly as possible. In addition to the supply of the powder to the dies, the rotating paddle wheels are intended to improve the flowability of the powder to optimize the die filling process [3,5,6,14,18–20]. Surprisingly, only few studies have been published with regard to the influence of the paddle wheel geometries on the powder distribution within the feed frame chambers or the influence of different paddles on the die filling process. It is known that the rotational speed of the paddle wheels may affect the tablet masses and their uniformity [16]. In one study, the influence of certain paddle wheel geometries on die filling based on computer simulations was investigated [18]. However, computer simulations...
may differ from the real processes because both the distribution behavior of powders and the dynamic processes within the feed frames are very complex. Because the paddle wheel geometry might be an important factor influencing the homogeneity of the tablet masses, in this study two different paddle wheel geometries were examined regarding their influence on the distribution behavior of a model powder within the filling chamber of a feed frame as well as their influence on the resulting tablet masses.

For the investigation of the distribution behavior of the model powder within the filling chamber of the feed frame, which results from the rotational movement of the respective paddle wheel, a self-developed measuring device was applied to visualize changes of the powder surface level within the filling chamber based on an optical triangulation method [21,22]. Although the conditions in the feed frame appear challenging for optical measurements, there are already examples for a successful application of this technology under similar conditions [23]. Furthermore, in a previous study conducted by the authors, a good reproducibility of the measurements with this device has already been shown [22].

Materials and methods

Materials

For all experiments in this paper, Avicel PH-102 (FMC BioPolymer, Wallingstown, Ireland), referred to Avicel throughout this paper, was used as model powder. In the literature, Avicel is described as a reference standard for a powder with flow behavior between acceptable and poor during high-speed direct tableting [24]. Consequently, plain Avicel tablets show a higher standard deviation with regard to their tablet masses compared to excellently flowing powders, and thus, it is well suited as a model powder for the present study. The effect of a variation of the paddle wheel geometry on high standard deviations of Avicel tablet masses is expected to be better detectable than on low standard deviations observed with tablet masses of excellently flowing powders.

Methods

Experimental equipment

Instrumented feed frame. The instrumented feed frame used in this study is based on a 3-chamber feed frame (Fill-O-Matic®), Fette Compacting, Schwarzenbek, Germany) [22]. The feed frame possesses a distributor chamber (located above a filling and dosing chamber) which attenuates effects of the powder pressure resulting from powder inside the hopper above the feed frame on the die-filling area. Within the distributor chamber, a distributor wheel moves powder through an orifice inside the partition plate, which separates the distributor chamber from the dosing and filling chambers to the filling chamber in which a filling wheel is located. To simplify the experimental setup and thus the correlation between the measured powder filling level inside the filling chamber and the resulting tablet masses, the dosing chamber was closed by an acrylic lid and therefore excluded from all experiments in this study. The filling chamber was equipped with one of the two filling wheels, either the flat rod filling wheel or the round rod-filling wheel (Figure 1). These paddle wheels are compared in this study. For the determination of the powder-filling level within the filling chamber, a distance sensor was mounted to a linear precision stage to detect the powder surface level via laser triangulation through a window placed inside the ceiling of the filling chamber. An incremental rotary encoder mounted to the driving shaft of the feed frame was used to determine the angular position of the filling wheel inside the filling chamber. Further information on the instrumentation of the feed frame and the placement of the acrylic lid can be found in a previous study [22].

Applied software. Data acquisition and evaluation of the powder surface within the filling chamber were performed by an in-house written software based on LabVIEW (National Instruments, Austin, TX). The software used for data acquisition recorded the powder surface level data of the laser triangulator and the filling wheels’ angular position data of the encoder synchronously at a frequency of 2 kHz and stored the information in a subsequently created raw data file. Further information on the data acquisition may be found in previous work [22].

The software used for data evaluation consists of two algorithms, which were optimized for each of the investigated filling wheels. For the experiments containing the round rod-filling wheel, the round rod algorithm was used; for the experiments containing the flat rod-filling wheel, the flat rod algorithm was used.

Both algorithms return the powder surface level data in a format that corresponds to one (or multiple layered) complete filling wheel revolutions, which are referred throughout the paper as ‘powder surface profiles’, as they represent only a cross-section of the total powder surface, that is, only the distance of the powder surface to the ground plate of the filling chamber at the respective monitoring position. If the output is a powder surface profile of several revolutions, it corresponds to the arithmetic mean of the powder surface profiles of the individual paddle wheel

Figure 1. Images of the filling chamber of the feed frame; (a) round rod filling wheel with a total of 16 rods (paddles), which are alternately drawn high or low and (b) flat rod filling wheel with a total of 12 rods (paddles), which do not differ geometrically. The dosing chamber is deactivated by an acrylic lid.
Design of experiments

Offline determination of the powder distribution within the enclosed filling chamber. To investigate the influence of the filling wheel geometry on the distribution behavior of Avicel in the filling chamber, a response surface experimental design was developed with the software Design expert® (v. 8.0.7.1, Stat Ease, Minneapolis, USA), which contains the categorical factor filling wheel geometry as well as the numerical factors powder mass (within the enclosed filling chamber), filling wheel rotational speed and sensor position for monitoring the powder surface. The factor powder mass was adjusted to three levels (38, 46, and 54 g of Avicel), the factor filling wheel rotational speed to 5 levels (20, 40, 60, 80, and 100 rpm) and the factor sensor position to 3 levels (45, 59, and 74 mm distance to the center of the filling wheel rotational axis). Of each experimental run, 30 subsequent filling wheel revolutions were recorded and the filling level generated via the algorithms described in “Experimental equipment” section was used as a response. The design matrix evaluation of the response surface quadratic model may be found in the Supplementary data section.

Experimental runs with the same factor level of powder mass were carried out in a standardized sequence without refilling the chamber with powder at each experimental point of measurement. The sequence started at the lowest level of the rotational speed. Subsequently, the paddle wheel was accelerated to the next higher level until the highest level of the rotational speed was reached. At each level of the rotational speed, the laser was shifted along all positions for monitoring before the paddle wheel was accelerated to the next higher level.

The feed frames’ filling chamber was enclosed for these offline experiments by closing all orifices, namely the dosing chamber, the partition plate orifice, the sealing segment and the outflow orifice with lids (Figure 1). The enclosure of the chamber was necessary to keep the factor level powder mass constant during the experiments. Further information regarding the enclosure of the filling chamber, the filling process with the respective amount of powder and the experimental sequence can be found in previous work [22]. In the present study, a rotary tablet press (Fette 102i, Fette Compacting, Schwarzenbek, Germany) was used. In the offline experiments, the tablet press only served as a power unit to drive the filling wheel in the feed frame.

Tableting experiments with inline monitoring of the powder surface level within the feed frame. To investigate whether the geometry of the filling wheel affects the resulting tablet mass, an OFAT experimental design was selected that covers only the process parameter filling wheel geometry (round rod or flat rod filling wheel geometry). The tableting experiments were carried out on the rotary tablet press Fette 102i (Fette Compacting, Schwarzenbek, Germany) at a turret speed and a filling wheel speed of 60 rpm. The press was equipped with 30 pairs of punches (8 mm diameter, faceted). A 12 mm filling cam was used to slide the lower punches downwards for filling the dies with powder. The filling depth adjustment was set to the minimum level of 0.5 mm (11.5 mm final filling depth). During commercial tablet production, a scraper behind the feed frame collects and transports excessive powder into a channel within the die table, which redirects the powder into the feed frame with a lifter. In the present experimental setup, a scraper behind the feed frame removed excessive powder from the tableting process by moving protruding powder through a pipe into a collecting container. This modification from the commercial production process prevents protruding powder from an increase of the extent of die filling and/or the powder filling level inside the filling chamber behind the monitoring position of the powder surface level. By adjusting the compression rolls located within the compression station of the tablet press, a punch distance of 2.7 mm in the compression station was reached, resulting in a sufficient tablet hardness, providing an adequate mechanical stability of the tablets for the collection and weighing procedure. Previous experiments showed that the filling chamber is considerably full under the chosen experimental conditions on a 102i tablet press. To achieve a lower filling level within the filling chamber, the partition plate orifice through which the powder flows into the filling chamber was downsized by attaching a stable adhesive tape (Figure 2). The purpose of downsizing the partition plate orifice was to increase the influence of the filling wheel on the filling process of the dies by preventing a nearly filled up filling chamber and thus an oversupply of powder from overlapping effects of the wheel geometry on the die filling process. However, without downsizing the partition plate orifice and with an accessible dosing chamber which both affect the powder behavior within the feed frame, the influence of the filling wheel geometry on die filling may be reduced and therefore the possible application of the developed model on commonly used feed frame setups is limited because the obtained results are affected by the use of only one chamber on the bottom stage of the feed frame and the downsized partition plate orifice. The feed frame configuration with the enclosed dosing chamber was only investigated for scientific purposes in the present study because the dosing chamber with its dosing wheel is an essential component of the feed frame and is of particular importance for the manufacturing of tablets.

Before starting each tableting run, 2 kg of Avicel were filled inside the hopper above the feed frame. After starting the tableting process, samples of the tablets were collected with cups every
20 s and weighed immediately after completion of the experiment with an analytical balance (Mettler Toledo, Columbus, USA). 10 tablets per sample point were weighed and the mean and standard deviation were calculated.

The powder surface within the filling chamber was monitored continuously over the entire experimental run time by laser triangulation at a single measuring position, located at 59 mm from the center of the filling chamber. Both, the experiment containing the round rod filling wheel as well as that containing the flat rod filling wheel were carried out in triplicate.

Results and discussion

Offline determination of the powder surface profiles within the enclosed filling chamber

The surface analysis of the Avicel powder with the laser triangulator allowed the generation of surface profiles with both paddle wheel geometries. The comparison of these powder surface profiles indicate that the different paddle wheel geometries cause significant differences in the distribution behavior of the powder within the filling chamber of the feed frame (Figure 3).

The powder surface profiles obtained with the round rod filling wheel show a wavy-shaped powder surface. This shape is caused by the eight low-drawn round rods which plow through the powder. Therefore, the round rods increase the powder surface height resulting from their displacement volume and thus increase the determined powder-filling level to higher values. These round rods cause powders to accumulate in front of the rods until the rods finally plow through the powders, by which the powders are partially pushed forward. The powders thereby move into the direction of the rotational movement of the filling wheel, whereby the supply of powders for the die filling process is ensured. By increasing the speed of the round rod filling wheel, a change of the shape of the powder waves to a more symmetrical form and a broadening of the powder waves may be observed in the powder surface profiles (Figure 4).

As already shown with the flat rod-filling wheel in previous studies [22, 25], the powder accumulates in front of the pushing paddles and forms a heap that rises toward the paddle (Figure 3). This accumulation of powder causes an increase of the powder availability for die filling within the paddle wheel interspaces into the direction to the pushing paddles. Thus, an inhomogeneous provision of the powders for die filling occurs while the paddle wheel interspaces move across the die filling area. In the interspace area in front of the pushing paddle, comparably more powder is available, while within the interspace area behind the previous paddle less powder and/or probably less dense powder is present [22]. This factor of inhomogeneous powder distribution in the interspaces is likely to influence the uniformity of the die-filling process, as the final filling of a die is presumably lower when leaving the filling area, if it was mainly exposed to the front area of an interspace during its filling whereas the filling of a die which predominantly took place in a rear interspace area with high powder availability might lead to a higher filling. However, no investigations on individual die filling processes were performed in this study but a combined evaluation of compression forces and corresponding powder surface profiles or paddle constellations related to individual die filling processes is conceivable. The powder surface profiles of both paddle wheel geometries show that differences in the powder filling levels between the individual paddle wheel interspaces in the flat rod profiles and slight differences in the powder wave heights of the round rod profiles are detected via the averaged paddle wheel revolutions. These inhomogeneities are probably caused by manufacturing inaccuracies of the paddle wheels, which were already discussed in previous work [25]. The impact of an inhomogeneous powder supply during die filling, because of powder distribution inhomogeneities within the interspaces or between the interspaces, on the standard deviation of the tablet masses should be investigated in further studies.

Influence of the rotational speed, the paddle wheel geometry and the powder mass on the offline determined filling levels within the enclosed filling chamber

Despite the significantly different powder surface profiles of the two paddle wheels, which reflect the different effects of the paddle wheels on the powder, the respective resulting filling levels are rather similar (Figure 5). The corresponding ANOVA (please refer to the Supplementary data section) shows that the response ‘filling level’ is influenced by all investigated factors (p < .05), namely the geometry of the paddle wheel, the rotational speed of
Figure 3. (a) Illustration of the round rod positions at 45 mm distance (inner dots) and at 59 and 73 mm distance (outer dots) to the center of the rotational axis applicable to (b), (c), and (d). Paddles drawn high are marked with an x whereas paddles drawn low are marked with an y. (b–g) mean powder surface profiles \( n = 30 \) obtained over 30 s of monitoring 54 g of Avicel within the enclosed filling chamber of the feed frame at 60 rpm paddle wheel speed. Mean powder surface profiles were obtained at (b) 45 mm, (c) 59 mm, and (d) 73 mm distance to the center of the filling chamber in experiments with the round rod filling wheel and at (e) 45 mm, (f) 59 mm, and (g) 73 mm distance to the center of the filling chamber in the offline experiments with the flat rod filling wheel. The height of the filling chamber was 15.3 mm. The bands around the average profiles represent the standard deviations of the layered profiles.
the paddle wheel, and the amount of powder within the filling chamber of the feed frame.

With both paddle wheel geometries an increase in the rotational speed leads to an increase in the filling level at the measuring position located at a distance of 73 mm from the center of the filling chamber. This is mainly the result of the centrifugal forces which cause a radial displacement of the powder to the edge region of the chamber. An increase in the powder mass within the filling chamber leads to an increase of the filling level at all three measurement positions regardless of the paddle wheel geometry. At 45 mm distance from the chambers’ center, the filling level does not fall below approximately 4.2 mm if the chamber is equipped with the round rod filling wheel, whereas with the flat rod filling wheel implemented, the filling level does not fall below approximately 1.2 mm. This discrepancy in the maximum drop of the filling level is probably caused by the different distances of the paddles to the ground plate and the plowing behavior of the round rod paddles. A residual powder layer remains on the bottom of the chamber which is not captured by the paddles. Additionally, the round rod paddles might lead to a minor centrifugal shift of powder because of the plowing behavior of these paddles compared to flat rod paddles.

Inline monitoring of the powder filling level within the tableting process and effect of the filling wheel geometry on the resulting tablet mass

The inline monitoring of the powder surface profiles during the tableting process with the flat rod filling wheel mounted results in a significantly lower filling level of the filling chamber than in previous experiments, in which the partition plate orifice was not downsized (Figure 6) [25]. This downsizing thus effectively leads to a reduction of the powder flow into the filling chamber and thus to a reduction of the chambers’ filling level. In contrast to this significantly reduced filling level with the flat rod filling wheel, the inline monitoring with the round rod filling wheel showed a comparably high filling level despite the identical downsizing of the partition plate orifice (Figure 6). The filling process of the filling chamber, that is, the inflow of powder into the filling chamber through the partition plate orifice appears to be improved if using the round rod filling wheel instead of that with flat rods, because the filling levels determined in the offline experiments with both paddle wheels at 60 rpm paddle wheel speed showed a significantly lower difference between the filling levels (Figure 5(b vs. e)) compared to those determined in the inline experiments (Figure 6(a vs. b)). The cause for the improved filling process of the

Figure 4. Mean powder surface profiles (n = 30) obtained over 30 s of monitoring 46 g of Avicel at a distance of 73 mm to the center of the rotational axis at (a) 40 rpm and (b) 80 rpm rotational speed with the round rod paddle wheel mounted and (c) 40 rpm and (d) 80 rpm with the flat rod paddle wheel mounted within the enclosed filling chamber.
chamber could not be identified so far. A possible cause might be the higher number and lower displacement volume of the round rods compared to those of the flat rods. The round rods act at shorter intervals on the powder whereby the powder inflow might be improved and/or additional space for the succeeding powder might be available.

The comparison of the resulting tablet masses of the two tabletting experiments shows that the choice of the filling wheel significantly affects both, the absolute tablet masses and the relative standard deviation of the tablet masses over the entire time course of the experiments. In the case of the round rod-filling wheel, the absolute masses of the produced tablets are significantly higher while the relative standard deviation of the tablet masses is significantly lower (Figure 7). The powder thus appears to be more uniformly available for die filling if the round rod filling wheel is mounted. Additionally, the flow behavior of the powder appears to be of advantage for the die filling process, as the dies were filled to a higher extent, which is reflected by the higher tablet masses. Possibly, the plowing behavior of the round rod filling wheel reduces cohesive forces within the powder, so that it flows better into the dies. However, the increased tablet masses might also result from the higher powder filling level within the filling chamber or from a combination of the mentioned phenomena [17].

The filling level, the tablet masses and the relative standard deviation of the tablet masses undergo a pronounced and simultaneous trend change at approximately 200 s after starting the tabletting experiments, which illustrates the relationship between these factors (Figures 7 and 8). With both paddle wheels, a decrease of the filling level may lead to a decrease of the absolute tablet masses with an increase of the relative standard deviation of the tablet masses. During the course of the experiments, the tablet masses are reduced to a less extent if the round rod filling wheel is installed compared to the tablet masses of the experiments with the flat rod filling wheel (Figure 7(b)). At the end of the experiments, because of the diminishing pressure of the remaining powder in the hopper, the powder transfer into the filling chamber and thus the powder availability for die filling decreases, which becomes apparent as a decrease in the filling level in all tabletting experiments (Figure 8). With regard to the resulting tablet masses, a decrease of the filling level within the filling chamber appears to be better compensated by the round rod filling wheel.

Figure 5. Filling levels determined offline within the enclosed filling chamber at the three measurement positions for monitoring at a distance of (a) 45 mm, (b) 59 mm, and (c) 73 mm from the center of the chamber for the experiments carried out with the round rod-filling wheel and at a distance of (e) 45 mm, (f) 59 mm, and (g) 73 mm from the center of the chamber for the experiments carried out with the flat rod-filling wheel. Means ± SD, n = 30.
The relative standard deviation of the tablet masses obtained with the flat rod filling wheel varies over the time course of the experiments, while that of the experiments with the round rod filling wheel keeps relatively constant (Figure 7(a)). The cause of these variations has not yet been investigated. However, one possible cause might be the varying overlapping of the flat rod paddles with the dies during the individual die filling processes. Accordingly, the powder availability during die filling probably differs depending on whether the die is covered by a flat rod during filling, or if a critical part of the filling process takes place within the paddle wheel interspaces with high or low powder accumulation.
Conclusions
The analysis of the powder surface profiles measured in the enclosed filling chamber of the feed frame clearly showed that the choice of the paddle wheel geometry has a significant influence on the distribution behavior of powders within the filling chamber. The filling level, the tablet masses and the relative standard deviation of the tablet masses underwent a simultaneous trend change within the tabulating experiments, which illustrates the relationship between these factors. With both paddle wheels, a decrease of the filling level within the feed frame may lead to a decrease of the absolute tablet masses with an increase of their relative standard deviation. A significant influence of the paddle wheel geometry on both the tablet masses and their uniformity was observed. The tablets obtained with the round rod filling wheel showed significantly higher masses and a lower standard deviation compared to tablets obtained with the flat rod filling wheel under the same process conditions. Thus, the application of the filling wheel with round rods may contribute to a more uniform and more effective die filling process compared to the flat rod filling wheel. Additionally, the inflow of powder into the filling chamber through the partition plate orifice appeared to be improved if using the round rod filling wheel instead of that with flat rods. An identification of the cause of this phenomenon might provide useful information for the optimization of the powder availability for the die filling process.

In the present study, only one powder was examined. To investigate the individual behavior of various powders in the filling chamber, the powder surfaces of these powders need to be compared with each other. The results might allow to adapt different wheel geometries to the individual requirements of these powders.

In addition, a correlation of the powder surfaces with the corresponding compression forces during tableting might be useful to understand the variation of the filling of the individual dies.

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Disclosure statement
No potential conflict of interest was reported by the authors.

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