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The Power-consumption-controlled Extruder: A Tool for Pellet Production

P. KLEINEBUDDE, A. J. SØLVBERG AND H. LINDNER

Department of Pharmaceutics and Biopharmaceutics, Christian-Albrechts-University, Gutenbergstraße 76/78, 24118 Kiel, Germany

Abstract—Based on the assumption that there is a link between power consumption of an extruder and pellet properties, a control circuit for power consumption was developed. Powder and granulation liquid are feeded separately into a twin-screw extruder. The power consumption is controlled by varying the pump rate at a given powder-feed rate; consequently each level of power consumption results in a specific water content of the extrudate for a particular formulation. The shape of pellets depends almost entirely on the level of power consumption irrespective of formulation. The size of dry pellets is additionally affected by a shrinking factor which depends on the water content. The power-consumption-controlled extruder is an appropriate tool for the production of pellets. The system is able to adapt the water content for a formulation automatically.

The fraction of liquid phase in extrudates has a high impact on pellet properties, especially with regard to their shape (Lövgren & Lundberg 1989; Pinto et al 1992; Baert et al 1992a), and the amount of liquid needed to produce spheres of comparable shape is highly dependent on the formulation (Harrison et al 1985; Bains et al 1991; Eerikainen 1991). Each formulation exhibits a suitable working range of liquid contents for producing pellets (Kleinebudde 1993). Using water as granulation liquid the fraction of liquid phase can be estimated by the water content.

Consequently, it is more sensible to adjust the liquid content within the working range than to compare different formulations at the same liquid content. One approach for this was presented by Le Doeuff et al (1992), who used a penetrability coefficient as one factor in a factorial design. The quantity of water for granulation was adjusted according to the consistency of wet mass.

Another approach presented here is based on the fact that the water content of the extrudate influences power consumption or torque of the extruder (Harrison et al 1985; Gamlen & Eardley 1986; Baert et al 1991, 1992b) and the power consumption can be related to pellet qualities. Baert et al (1992a) showed a relation between power consumption and the formation of good pellets in terms of shape. Bains et al (1991) extruded different binary mixtures of barium sulphate and microcrystalline cellulose. They showed that similar power consumption led to similar pellet qualities independent of the respective water content.

When working with existing methods, a suitable water content has to be determined in preliminary studies before extrusion. The first objective of this study was the creation of a power-consumption-controlled extruder which adjusts the power consumption to a preset value by varying the water content of the extrudate. The second objective was to examine the hypothesis that power-consumption control is a tool for the production of similar pellets in terms of shape and size.

Correspondence: P. Kleinebudde, Department of Pharmaceutics and Biopharmaceutics, Christian-Albrechts-University, Gutenbergstraße 76/78, 24118 Kiel, Germany.

Materials and Methods

Materials

The ingredients selected for this study were microcrystalline cellulose (Avicel PH 101, FMC Corporation, Philadelphia, USA) and lactose monohydrate (Lactose D 20, Meggle, Wasserburg, Germany). Demineralized water was used as granulation fluid.

Extrusion system

The extruder used in these studies was a co-rotating twin-screw extruder (ZE 25 × 18 D, Berstorff AG, Hannover, Germany). Extruder and dosage systems have been described in detail by Kleinebudde & Lindner (1993). The axial-mounted die plate was mounted directly in front of the screws. The plate contained 48 holes of 1 mm diameter and 2·5 mm length. Dry powder was fed by a powder feeder (Type T 25, K-Tron-Soder, Niederlenz, Switzerland). Granulation liquid was pumped by a membrane dosage pump (Type

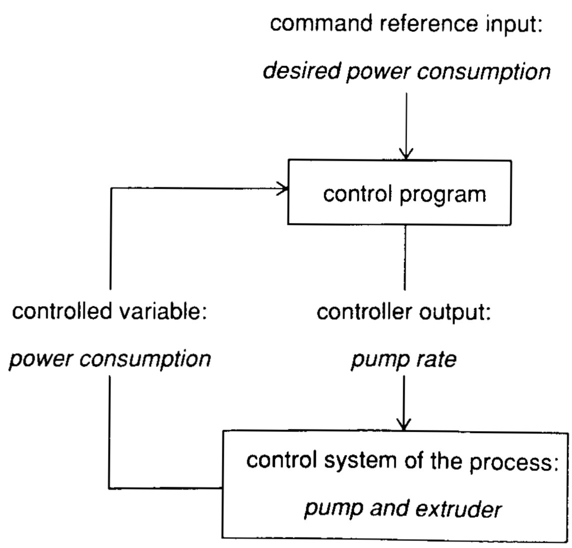

FIG. 1. Scheme of control circuit of the extrusion system.

Gamma 4, ProMinent, Heidelberg, Germany) via a dosage valve into the extruder barrel. Extruder and dosage pump were connected to a personal computer via an analogue-digital converter (DT 2814, Data Translation, Marlboro, USA). Power consumption was recorded and monitored every two seconds.

A programme (Turbo Pascal 6·0, Borland, Munich, Germany) was written for the generation of the power control circuit. The circuit is schematically shown in Fig. 1. The desired and the actual values of the power consumption were compared at 30-s intervals. If the power consumption was too high the pump rate was increased leading to a higher water content. The rate of changing the pump flow depends on the difference between desired and actual value. The control interval was found to be suitable for the given extrusion conditions (length of the extruder barrel, screw speed and powder feed rate).

Experimental plan

Four power consumption levels, 180, 210, 240 and 270 W were chosen for the tested formulations. Five different binary mixtures of microcrystalline cellulose and lactose containing 10, 30, 50, 70 and 90% (w/w) of microcrystalline cellulose were investigated. For each mixture two blends were prepared and extruded at each power consumption level. Extrusion of blends was performed in a randomized order. The sequences of the four experiments for each blend were also randomized.

Production of pellets

The moisture content of the ingredients was measured with an infrared balance (Type 1212 MP, Sartorius, Göttingen, Germany). The formulations were based on dry powders, corrected for their moisture content. Batch size for each blend was 4 kg of dry powder.

Extrusion was started after a warming cycle of the extruder at 100 rev min^{-1} for 30 min. Powder feeder, water pump, data acquisition and power control were started simultaneously. Powder feeder rate was adjusted to 25 ± 1 g min^{-1}. The extruder was operated at a speed of 60 rev min^{-1} during production. The experimental run started when the power consumption reached a constant level. Then, extrudate was collected until 400 g was produced. The data for power consumption of the extruder drive were processed after the experiment. From the data collected during the time span of production the means and coefficients of variation were calculated.

For determination of the moisture content of the extrudate, samples (5–10 g) were taken at the beginning, middle and end of the experimental run. The moisture content was calculated by the loss of drying at 105°C for 24 h.

The extrudate was spheronized immediately following extrusion. The spheronizer (type 320 S, Nica AB, Mölndal, Sweden) was operated for 5 min at a rotational speed of 800 rev min^{-1} (radial velocity 13·4 ms^{-1}). A sample of 20 g wet pellets was taken and stored in a tightly closed container for image analysis. The remaining pellets were dried for 20 min at 50°C in a fluid-bed drier (TR 2, Glatt AG, Binzen, Germany).

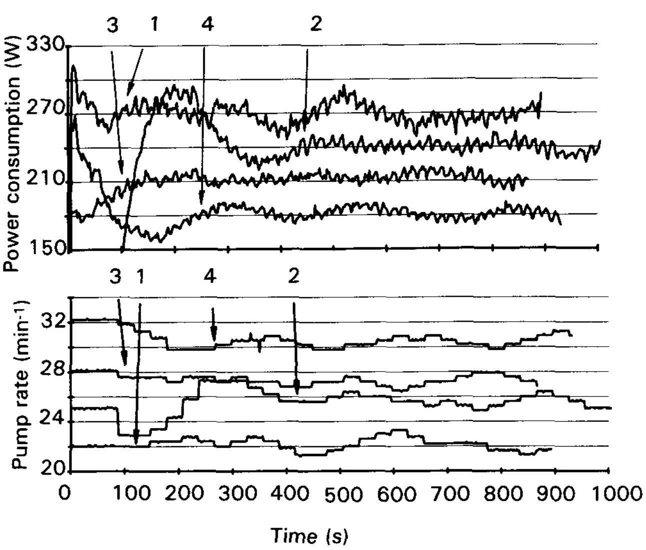

FIG. 2. Power-consumption/time and pump-rate/time profiles of runs 1 to 4 for binary mixture containing 30% microcrystalline cellulose.

Characterization of pellets

The fines of the dried pellets were quantified and separated using a 500-μm sieve. The remaining pellets were analysed in terms of size and shape using an image analysis system (Leco 2001, Leco Instruments, St Joseph, USA). All investigations were performed according to a standardized method described by Lindner & Kleinebudde (1993). The pellets were placed on an illuminated desk. The image was taken by a macro camera. Magnification of the system was adjusted to 50 pixels per particle resulting in 50–70 pellets per field. A minimum of 600 pellets was analysed for each batch. The data were processed externally using a spreadsheet program (Excel 4·0, Microsoft GmbH, Unterscheißheim, Germany). The mean values, standard deviations and coefficients of variation were calculated for the following parameters: length (longest of eight measured feret diameters), width (shortest feret), aspect ratio (ratio of length to breadth) and projected area. (Ferets, named after the French mathematician who first described them, are straight-line measurements made between tangents at various angles; the 2001 measures eight ferets at 0, 22.5, 45, 67.5, 90, 112.5, 135 and 157.5°).

For image analysis of wet pellets the analysis procedure had to be modified. The wet pellets were sieved using a 710-μm sieve to free them from fine particles. The pellets were put on a glass plate lying on the illuminated desk. Analysis of the pellets was performed immediately after preparation. Nine fields were inspected for each batch. The glass plates with the wet pellets were transferred into an oven and dried at 50°C for at least 12 h. The dried pellets were analysed again. The shrinking factors (SF) were calculated as percent decrease for the parameters described above.

Results and Discussion

Extrusion

The first objective of this work was to develop an extruder with power consumption control. It was possible to fulfil

Table 1. Results for the two blends containing 30% microcrystalline cellulose.

Run	Mean power consumption (W)	Coefficient of variation for power consumption (%)	Deviation between desired and measured power consumption (%)
1	269·4	3·08	0·22
2	241·4	2·32	0·58
3	212·7	1·97	1·29
4	181·9	2·64	1·06
5	276·2	4·13	2·30
6	240·6	2·33	0·25
7	211·3	2·7	0·62
8	179·6	2·67	0·22

this objective satisfactorily. Batchwise coefficients of variation for the data of power consumption varied between 1·65 and 4·26%. The mean of coefficients of variation for all 40 experiments was 2·50%. The absolute deviation of mean values for power consumption from the desired values was always less than 2·5% without any tendency in one direction. The mean deviation was 0·69%. No correlation between power consumption level, variation in power consumption during an experiment and deviation from the desired value could be observed. Fig. 2 shows the power consumption-time-profiles and pump rates for four experiments containing 30% microcrystalline cellulose. The arrows mark the start of the experimental runs. The power consumption data for these runs (1–4) and their replications (5–8) are listed in Table 1.

The system was able to adapt the pump rate until the desired power consumption was reached. The four different levels are clearly differentiated. The curves do not overlap during the experimental time. However, differences between the levels ought to be greater than 30 W to avoid overlapping. All curves show oscillations, principally two oscillations with different periods. The range of the oscillation with higher frequency is of the same size as that obtained when working with normal extrusion equipment. The superimposed oscillation of lower frequency is caused by the power consumption control circuit. The same period of oscillation can be observed for pump rate. The response of the system to a change in pump rate is slow and depends on the screw speed. The higher the screw speed, the lower the passage time of the material through the extruder (Kleinebudde & Lindner 1993).

In Fig. 3 the water content, aspect ratio and length are plotted against power consumption. The measured absolute water contents of the extrudates varied between 20·0 and 58·9%. The mean of the differences between the two runs of each factor-level combination was found to be 0·39%. This means that for a given formulation and a given level of power consumption the water content of the extrudate is constant. For each formulation the water content decreases with increasing power consumption. When the power consumption was increased from 180 to 270 W the water content decreased between 3·5 and 6·6% for the formulation. Compared with the total variation in water content the working range for a particular formulation is small. For each power consumption level the water contents of the different

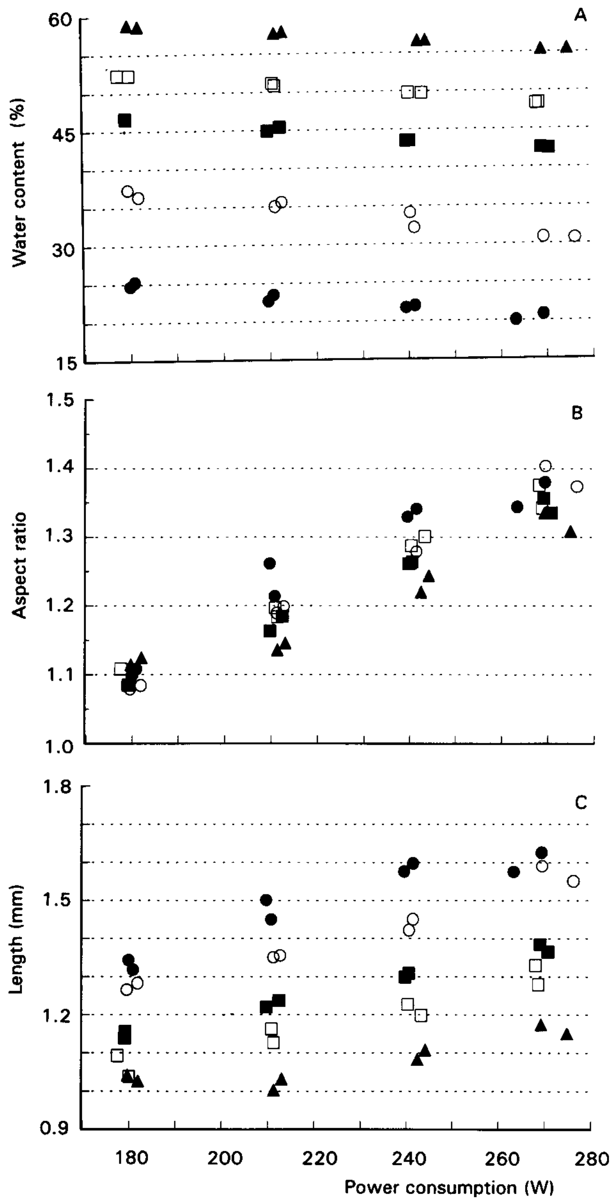

FIG. 3. Water content (A), aspect ratio (B) and length (C) vs power consumption for formulations containing 10% (●), 30% (○), 50% (■), 70% (□) and 90% (▲) microcrystalline cellulose.

formulations are clearly distinct, indicating different working ranges. The amount of microcrystalline cellulose has a strong influence on the position of the working range on the water content scale. Changing the amount of microcrystalline cellulose from 10 to 90% raises the water content by about 35%.

Extrusion at a particular power consumption allows the system to find the working range for a formulation. The level of power consumption identifies a desired location within the working range. The power control system is able to run into stable conditions in terms of power consumption. As a consequence the water content of the extrudate results from the experimental setup and is highly dependent on the respective formulation.

Pellets

The second objective of this study was to show that extruding at the same level of power consumption results in pellets with similar properties. This approach is valid for different formulations independent of the particular water content. In this context the properties of particles that are of interest are size and shape.

Due to the amount of data from image analysis, not all the data is presented here. The most important findings are given in Figs 3 and 4, using the length as the compared parameter; the same dependencies were valid for other size parameters such as area or feret diameter.

The shape of pellets can be described using the aspect ratio. In Fig. 3B mean values for aspect ratio are plotted against power consumption. There is an evident positive correlation between aspect ratio and power consumption. The lowest values for aspect ratio are obtained at the lowest power consumption level. At this level, the smallest variation for the data of the 10 batches occurred. An influence of formulation on aspect ratio can be seen for the levels 210 and 240 W.

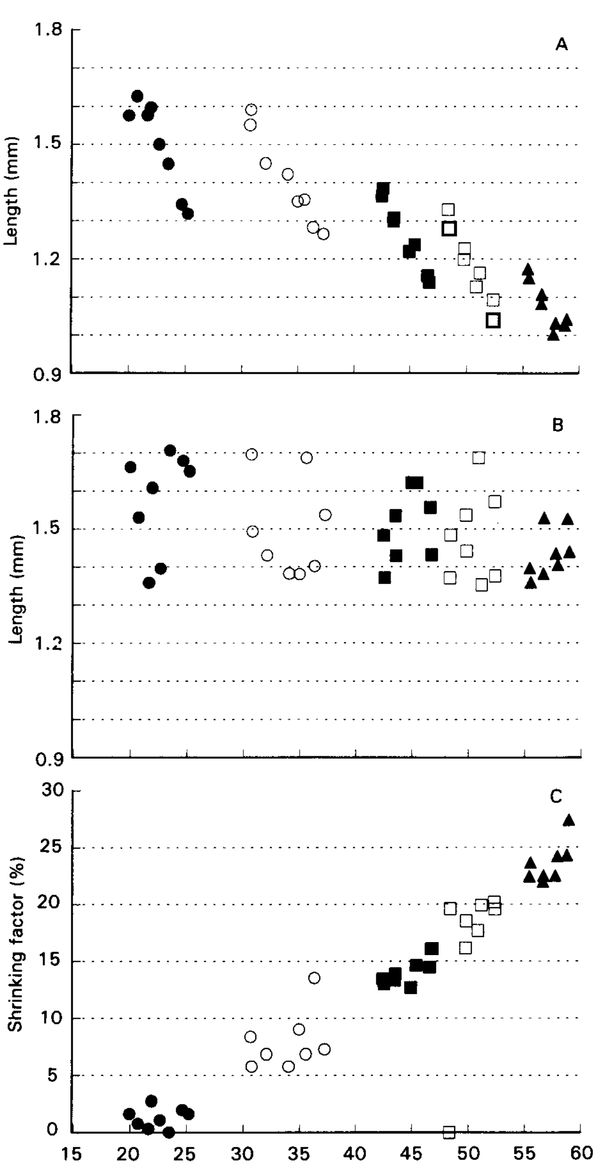

FIG. 4. Length of dry pellets (A) and wet pellets (B) and shrinking factor (C) vs water content for formulations containing 10% (●), 30% (○), 50% (■), 70% (□) and 90% (▲) microcrystalline cellulose.

The length of the pellets is influenced by both power consumption and formulation (Fig. 3C). Shortest pellets are obtained for low power consumption and high microcrystalline cellulose content. For all formulations, higher power consumption led to longer pellets. In Fig. 4A the length of dry pellets is plotted against the water content of the extrudate. For each formulation the same trend can be observed. However, larger amounts of microcrystalline cellulose led to smaller pellets at higher water contents. Compared with the data of dried pellets, different behaviour can be observed for wet products. Fig. 4B shows the results of the image analysis of wet pellets. There is no clear relationship between length and either water content or formulation. Length of wet pellets varied between 1·35 and 1·71 mm, while data for the dry products were between 1·00 and 1·63 mm. From these data, shrinking factors can be calculated (Fig. 4C). There was correlation between water content of extrudate and the shrinking factor. A high initial water content implies a substantial shrinking during drying. Shrinking factors can be observed for all size parameters.

The rheological behaviour of the extrudate is a key variable of the extrusion process (Harrison et al 1987; Fielden & Newton 1992). A coherent interpretation of the actual results is possible on the assumption of the following hypothesis. For constant extrusion conditions, rheological behaviour is related to the power consumption. The rheological properties of the extrudate are important for the spheronization step. Under constant spheronization conditions, extrudates with similar rheological behaviour will result in similar products. In the current experiment, different formulations were extruded at the same power consumption levels. For a particular power consumption level similar rheological behaviour and consequently comparable pellets in terms of shape and size were expected. For shape, this assumption is verified by the data and the size of the wet pellets was independent of the respective formulation. The size of the dry product was affected by the different extent of shrinking according to the initial water content.

From the current results on binary mixtures of microcrystalline cellulose and lactose it is evident that a certain power consumption during extrusion leads to pellets of similar shape. For the comparison of different formulations it is necessary to fix the power consumption rather than the water content of extrudate. Validity of the results has to be proved by the extrusion of formulations with different compounds.

The power-consumption-controlled extruder is a helpful tool in the development and production of pellets. For the development of pellets this process is able to compare different formulations on a rational basis. In production it may prove to be effective when reproducible results in continuous extrusion are required.

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