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# Prediction of the solids mass flow rate in mixed-flow dryers

Mixed-flow dryers are delivered in various modes of recirculation or through-flow dryers and predominantly used for grain drying. To design and control the dryer, the knowledge of the solids mass flow rate or discharge rate is essential. Fundamentals for its calculation are not known from the literature so far. Hence, this work was aimed to derive appropriate fundamentals. Based on experiments on the discharge characteristic at a test dryer equipped with a discharge gate, equations for the solids mass flow rate for the continuous and the interrupted mode of operation were developed, respectively.

**Keywords**
Mixed-flow dryer, grain, solids mass flow rate, pneumatic discharge gate

**Abstract**
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Mixed-flow dryers are mainly used when large quantities of grain such as maize and rice have to be stored [1]. Small alterations in the grain characteristics or the process parameters have a big effect on the quality of the dried product. The development of mixed-flow dryers has occupied scientists for decades [2–4]. Although the process of hot-air drying has already been extensively investigated and the state of the art in convective grain drying, there still exists a very great potential for innovation in description of the process and, above all, in the structural design of the drying equipment used. In addition to the form and geometry of the air ducts for inlet and outlet and their layout in the dryer shaft to give the resulting airflow, the drying process is also determined by the design of the discharge device.

In order to discharge the dried grain various designs of thrust discharge gates are mainly used in mixed-flow dryers [1]. Newer dryers are mostly fitted with pneumatically driven discharge gates whereby the drive motor and extender wheel are replaced by a pneumatic cylinder. By means of the pneumatic cylinder the discharge gate is shunted at set intervals so far that the grain can run freely out of the discharge channel. Based on the size of the dryer cross section, several discharge channels are located next to each other in mixed-flow dryers. The opening area of the discharge channels varies between 30 and 40 % of the dryer cross section [1]. Discharge gate devices are mainly constructed with free outlet. The dried grain is collected in a funnel beneath the discharge and cyclically transported away.

For both the dryer design and also the regulation of the drying process the knowledge of the solids mass flow rate is of crucial importance. The solids mass flow rate is the main parameter in the dryer control. This signifies that the grain moisture at the dryer discharge is controlled by the retention time which for its part is inversely proportional to the solids mass flow rate. From the literature no method of calculation for the solids mass flow rate is so far known. For this reason the aim of this work was the derivation of basic calculations for mixed-flow dryers that are quasi-continuously operated in interrupted flow modus [5]. An analysis of the function and flow rate characteristics of the pneumatic discharge gate formed the basis of these experiments.

## Design and operation of the discharge device

The mixed-flow dryer used for the experiments at the Leibniz Institute for Agricultural Engineering Potsdam-Bornim (ATB) consists of a vertical drying shaft in which the inlet and outlet air ducts are arranged horizontally offset (**Figure 1**). The dry airflow is channelled by the inlet and outlet air ducts. The moist grain is filled into the dryer from above and flows by gravity vertically downwards. At the bottom of the dryer is situated a pneumatically driven discharge gate with which the solids mass flow rate can be controlled. Mixed-flow dryers used in industry operate in a quasi-continuous mode. This means that during the drying the load is still for most of the time and only in a short period in which the discharge gate is open does it flow vertically through the dryer shaft. This operation is selected to ensure the corresponding retention time for the grain in the dryer. But for the experimental examination of the discharge characteristics a continuous operating mode is an advantage [5]. In the mixed-flow dryer this is the case when the discharge is permanently open and there is a continuous flow of particles exiting the drier. Under these conditions the continuous discharge from a mixed-flow dryer

Fig. 1

*Photo of the experimental mixed-flow dryer (Photo: ATB)*

can be characterised as analogous to the solids discharge from a silo [6] for which the maximum discharge rate is reached.

For the interrupted solids discharge from the experimental dryer a pneumatically driven discharge gate was developed (**Figure 2**). The upper, fixed part of the discharge device consists of triangular profiles (yellow) which form several outlet funnels over the width of the dryer. The sliding floor operated by the pneumatic cylinder consists of individual square profiles (blue) which are welded onto a frame. The discharge gate devices of large-scale mixed-flow dryers are in principle similarly constructed whereby the number of slits is less, the width of the slits is larger and the slope of the funnel wall is flatter. For the experimental dryer a larger number of outlet funnels was chosen in order to achieve the most even distribution of the solids mass flow rate over the small cross-section of the dryer (0.6 x 0.4 m). The solids flow is improved by the comparatively steep funnel wall (small angle Θ). The small slit width w, however, limits the maximum usable grain size. In mixed-flow dryers the interrupted discharge is achieved by periodic opening and closing of the outlet funnel by means of the oscillating sliding floor.

The solids mass flow rate is controlled in practice by means of the time interval between two discharges, the so-called holding time ts. The holding time consists of the idle period between two discharge events tR and the discharge time $t_A$ [5].

$$t_S = t_R + t_A \quad \text{(eq. 1)}$$

The proportion $t_R/t_S$ to the total retention time corresponds thereby to the period of batch drying in the mixed-flow dryer.

## Flow rate characteristics and solids mass flow rate

The flow rate characteristics of discharge gate devices with free outlet are mainly determined by the discharge time. The discharge time $t_A$ corresponds to the time interval in which the particles flow through the discharge apertures. It depends on the design and dynamics of the discharge device [5]. The flow and discharge characteristic is thus a function of the form

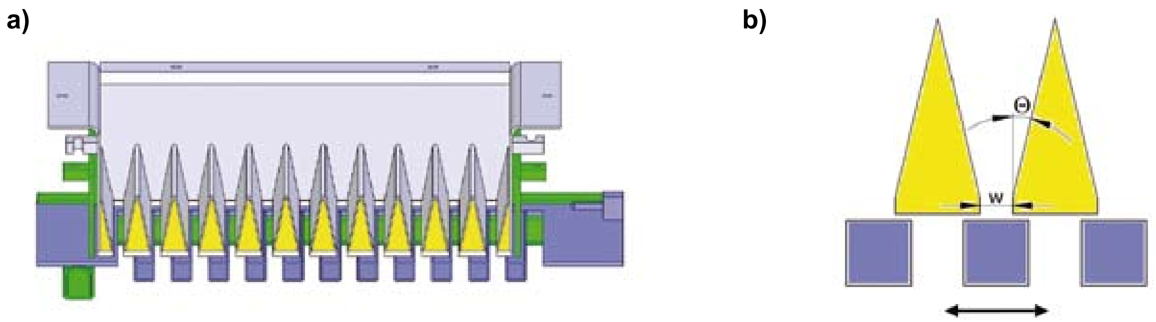
$$M_S = f(t_A) \quad \text{(eq. 2)}$$

In repeated experiments with wheat a linear correlation was always determined by (**Figure 3**)

$$M_S = a_1 \cdot t_A + a_2 \quad \text{(eq. 3)}$$

The coefficient $a_1$ in equation (3) has the dimension of a mass flow, the coefficient $a_2$ that of a mass. For the example of wheat the moisture 12 % w.b. (w.b. = wet basis, based on moist grain) gave the linear regression $a_1$ = 11.70 kg/s and $a_2$ = -0.9693 kg in the range of the discharge time between 0.7 s ≤ $t_A$ ≤ 2.0 s ($R^2$ = 0.9998).

Fig. 2




*(a) Schematic, (b) Construction element of the discharge device*

In addition to the investigations on discharge characteristics experiments were also carried out on continuous flow from the mixed-flow dryer modelled after the solids discharge from silos. For this purpose the discharge time $t_A$ was varied and the discharge mass flow $\dot{M}_{S,kont} = M_S / t_A$ measured. The results for the two wheat batches used with 12 % and 18.2 % w. b. respectively are shown in **Figure 4**.

As the graph shows, the solids mass flow rate rises continually with increasing discharge time and approaches asymptotically a maximum value. This maximum value corresponds to the achievable maximum discharge with unimpeded, continuous flow which is determined solely from constructional parameters and the solid characteristics. For wheat with 12 % w. b. moisture this value was determined by $\dot{M}_{S,kont}$ = 11.78 kg/s and for wheat with 18.2 % w. b. by $\dot{M}_{S,kont}$ = 11.97 kg/s. A comparison with the correlation (3) illustrates that the gradient a1 of the discharge characteristic approximately corresponds with the maximum discharge

$$a_1 \approx \dot{M}_{S,kont} \qquad \text{(eq. 4)}$$

In the literature different approaches are known to estimate the discharge mass flow rate from silos [6]. The British Materials Handling Board [7] specifies the following correlation for large grain, free flowing bulk solids in mass flow funnels with elongated, rectangular discharge apertures

$$\dot{M} = 1{,}03 \cdot \rho_S \cdot \sqrt{g} \cdot (L - k \cdot d_P) \cdot (w - k \cdot d_P)^{1{,}5} \cdot (\tan \Theta)^{-0{,}35} \qquad \text{(eq. 5)}$$

The derivation of this equation is based on the known discharge formula from Torricelli for the frictionless discharge of liquids out of an open container with an aperture at the base. Equation (5) is valid for L > 3 • w and for funnel inclination angles Θ < 45°. The form factor k is applied for spherical particles k = 1.6 and for non-spherical particles k = 2.4.

In contrast to a silo, the discharge device of a mixed-flow dryer has several parallel discharge funnels $N_{AS}$ (**Figure 2**). The length L approximately corresponds to the depth of the dryer shaft. The slit width w varies between 0.05 and 0.1 m. In equation (5) three parameters for solids are considered: the form factor k, the average particle diameter $d_P$ and the bulk density $\rho_S$. Cereal grains have an elongated form which is very similar to that of an ellipsoid.

When being discharged from funnels it is known that they orientate themselves to the mainstream and align their longitudinal axis mainly parallel to the funnel wall [8]. For this reason the grain thickness δ can be used instead of the average particle diameter $d_P$.

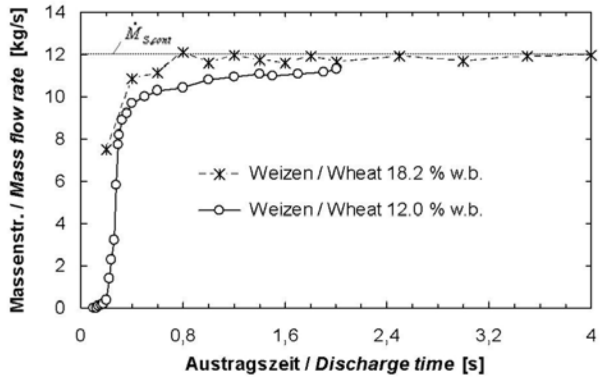
Applied to the mixed-flow dryer with a discharge gate device and open outlet, equation (5) is modified to

$$\dot{M}_{S,kont} = 1{,}03 \cdot \rho_S \cdot \sqrt{g} \cdot N_{AS} \cdot (L - k \cdot \delta) \cdot (w - k \cdot \delta)^{1{,}5} \cdot (\tan \Theta)^{-0{,}35} \qquad \text{(eq. 6)}$$

With the aid of equation (6) the maximum solids mass flow rate can be estimated for continuous flow from a mixed-flow dryer. This equation was tested with the experiments on continuous flow. The experimental dryer has $N_{AS}$ = 11 discharge slits with a length L = 0.6 m and a slit width w = 0.01 m. The inclination angle of the funnel wall is Θ = 13.4° (**Figure 2 b**). The grain thickness δ was determined from measurements by Regner [9] using the wheat variety Avalon to be δ = 2.7 mm. For the grain form k = 1.6 was assumed since the cut grain has an approximate circular form. Using the example of wheat with a moisture of 18.2 % w. b. and a bulk density of $\rho_S$ = 783 kg/m³, the maximum solids mass flow rate according to equation (6) is calculated as $\dot{M}_{S,kon}$ = 11.69 kg/s. This value matches very well with the measured values mentioned above.

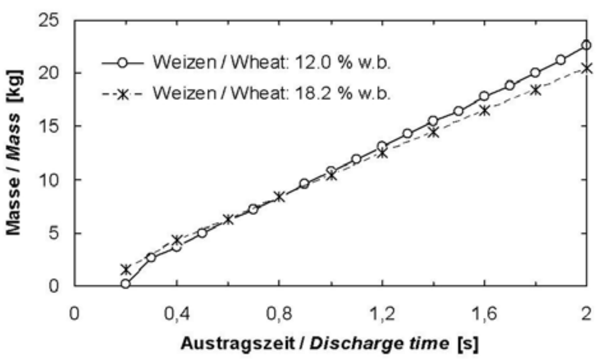
In practice mixed-flow dryers are operated discontinuously in so-called interrupted flow mode. For a known bulk mass $M_S$ which is discharged per opening cycle the solids mass flow rate is then calculated.

Fig. 4




*Solids mass flow rate at continuous flow versus discharge time measured for wheat*

Fig. 3




*Discharge characteristic of the test dryer measured for wheat*

$$\dot{M}_{S,\text{int}} = \frac{M_S}{t_S} \qquad \text{(eq. 7)}$$

Equation (7) is used within the industry for control of the mass flow rate whereby the holding time ts is varied. This non-linear relationship, however, adversely affects drier regulation.

When the discharge characteristic is known the use of equations (3) and (4) in correlation (7) results in the following statement

$$\dot{M}_{S,\text{int}} = \dot{M}_{S,kont} \cdot \frac{t_A}{t_S} + \frac{a_2}{t_S} \qquad \text{(eq. 8)}$$

With this approach (equation 8) and taking into consideration equation 6, the solids mass flow rate for the in practice discontinuous operation (interrupted flow) of mixed-flow dryers can be predicted. The term $a_2/t_S$ from the discharge characteristic takes into account the influences of the opening and closing events which have an effect on every individual discharge. For estimative calculations these can be disregarded.

As equation (8) illustrates, the solids mass flow rate in interrupted flow operation amounts to only a fraction of the maximum solids mass flow rate in continuous flow operation. Their correlation $\dot{M}_{S,\text{int}} / \dot{M}_{S,kont}$ thus corresponds to the proportion of the discharge time to the holding time $t_A / t_S = t_A / (t_R + t_A)$.

## Conclusions

Based on experiments on the discharge characteristic of a mixed-flow dryer with discharge gate device, the basis of calculation for the solids mass flow rate in continuous and interrupted flow operation were derived.

These can be equally useful for the dryer design and control of the drying process.

## Literature


[1] Mühlbauer, W. (2009): Handbuch der Getreidetrocknung. Clenze, AgriMedia Verlag

[2] Maltry, W. (1966): Einige Untersuchungen zur Aufklärung des Verhaltens von Getreide im Dächer-Schachttrockner. Archiv für Landtechnik 5, S. 223–264

[3] Klinger, J. (1977): Einige thermodynamische und strömungstechnische Untersuchungen zur Modellierung der Vorgänge in Dächerschachttrocknern für Getreidekörner. Dissertation. Technische Universität Dresden

[4] Cenkowski, S.; Miketinac, M.; Kelm, A. (1990): Airflow patterns in a mixed-flow dryer. J. Can. Agric. Eng. 32, pp. 85–90

[5] Mellmann, J.; Teodorov, T. (2011): Solids transport in mixed-flow dryers. Powder Technology 205, pp. 117–125

[6] Schulze, D. (2009): Pulver und Schüttgüter. Berlin, Springer Verlag, 2. Aufl.

[7] British Standards Institution (Ed.) (1987): Draft design code for silos, bins, bunkers and hoppers. Published by BSI in association with the British Materials Handling Board

[8] Markauskas, D.; Kačianauska, R. (2011): Investigation of rice grain flow by multi-sphere particle model with rolling resistance. Granular Matter 13, pp. 143-148

[9] Regner, S. (1995): Kernel mass related properties of cereal grains. Ph. D. dissertation. Swedish University of Agricultural Sciences, Uppsala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