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Development of the Heat and Mass Transfer Model for Mixed-Flow Grain Dryer

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Abstract: A mathematical model of the coupled heat and mass transfer has been developed to calculate the drying process in a mixed-flow grain dryer. Periodical discharge operation of the dryer causes strong variations of temperature and moisture of the material. A series of quasi-stationary drying experiments have been carried out. These results are used to test and to improve the dryer model. The calculated results are in relative good agreement in the stationary operation period which is relevant for practice.

1. INTRODUCTION

Considerable amounts of agricultural crops, and more particularly grain, are dried artificially using near ambient or high temperature air in various grain drying systems. The need for storage over a long period of time after harvest requires an accurate control of the properties of the dried product (Aregba and Nadeau, 2007). The grain quality is a basic criterion for determining its subsequent usage and commercial value. Grain drying consumes more than 65 % of the total energy used for farm corn production (Brooker, *et al*., 1974). Worldwide mixed-flow dryers preserve large mass flows of grain, rice, and maize. Although this technology is widely used for hot-air grain drying there is, eminently against the background of increasing prices for fossil fuels, a need to optimize the dryer apparatus as well as the process control. The partly considerable fluctuations of the grain moisture content at the dryer entrance are still the major problem for quality assurance at hot-air drying. Dryers and control systems used so far are unable to equalize these grain moisture distributions during the drying process resulting in quality and economic losses due to under-drying or over-drying. The target of this work is therefore to develop a mathematical model for the heat and mass transfer in a mixed-flow grain dryer.

For the thin-layer drying of cereal grains a number of models are available in the literature. These can be empirical (see for example Jayas, *et al*., 1991), diffusional (Sokhansanj, 1987), or based on irreversible thermodynamics (Luikov, 1966, Mészáros, *et al*., 2007). Diffusion models are most common in the cereal drying literature, as they are more accurate than the empirical models, but without the complexity of thermodynamic models. Bruce (1985) looked at three models for the drying of grain up to 150 °C. He found that a diffusion-based model fitted the experimental data better than either of two types of empirical equations. In further development of the work, with Sokhansanj, it was found that the use of coupled partial differential equations to describe heat and mass transfer gave improved results on considering distributed moisture and lumped temperature (Sokanasanj & Bruce, 1986a, 1986b; 1987). A number of models have used experimental data for heat transfer coefficients and the specific area of the grains.

More extensive, however, is the mathematical modelling of deep-bed drying processes such as mixed-flow dryers where grain flow and air flow interact in different ways exchanging heat and masses. The influence of different forms of air ducts on the flows of grain and air through a mixed-flow dryer has already been studied by Klinger (1977). The dryer was assumed as a series of co-current and counter-current elements. The same modelling concept was applied by Bruce (1984) who successfully predicted the general behavior of the dryer and the influences of operating variables on dryer performance. In a dynamic form it has also been used in the development of an automatic dryer controller (McFarlane and Bruce, 1991). Cenkowski et al. (1990) experimentally investigated the airflow patterns in mixed-flow dryers. They revealed that about 30 % of the dryer shaft volume operates in a cross-flow configuration. Giner et al. (1998a,b) developed a two-dimensional model of the mixed-flow dryer including cross-flow elements. To calculate the grain drying process in each co-current, counter-current, and cross-flow element, however, an empirical model has been employed.

2. MATHEMATICAL MODEL

In order to predict the complex drying process in a mixed-flow dryer a mathematical model of the coupled heat and mass transfer has been developed at the Leibniz-Institute for Agricultural Engineering Potsdam-Bornim. The model consists of two parts: a thin-layer drying model for the heat and mass transfer within a single grain kernel (single grain model) and a drying model for the bed material (deep-bed model). For the single grain model it is assumed that the grain has the shape of a sphere which can be subdivided into up to ten shells, see (Mellmann, *et al.*, 2007). The differential equations for air flow and grain flow are coupled in the deep-bed model. Industrial mixed-flow dryers often work in a quasi-stationary record-by-record mode of operation. In this case, the grain is at rest during almost the whole drying time. The standing time between two discharges may reach several minutes whereas the discharge time – the period of time at which the discharge device is opened – amounts to few seconds. The grain is transported stepwise downwards the dryer shaft. At each discharge it is assumed that the grain bed moves in plug flow pattern. During the standing time the drying process can be considered as unsteady batch drying. The bed material is assumed to be a connection in series of single grain layers the drying behaviour of which is described by means of a single grain model (Farkas and Rendik, 1996; Ziegler, 1999). In this way the exit air of a certain layer is the inlet air of the next layer. Therefore, the drying process in a mixed-flow dryer can be simplistically described as follows:

1. Modelling of the drying behaviour of a single grain layer by heat and mass transfer in a single grain kernel,
2. Modelling the drying process of the grain bed using a connection in series of single grain layers.

The heat and mass transfer between air and grain as well as the balances of masses and energy at a finite volume element of the grain bed are schematically depicted in Fig. 1.

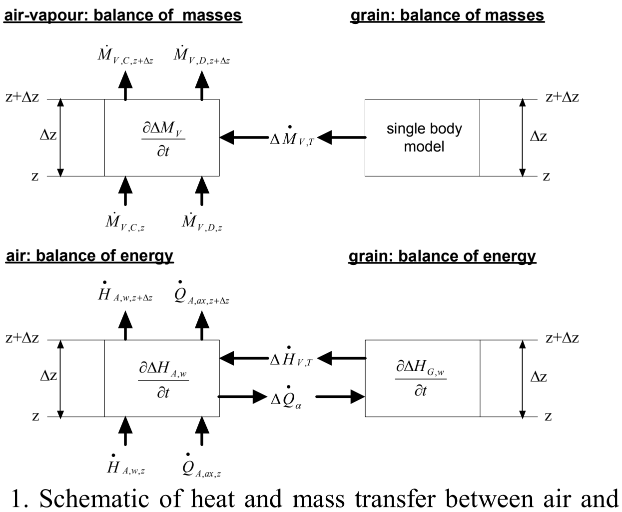

Fig. 1. Schematic of heat and mass transfer between air and grain at a finite volume element of the grain bed (deep-bed model)

The finite volume element represents a single grain layer in the dryer. Assuming an equal particle velocity profile over the dryer cross-section a one-dimensional model is applied to the mixed-flow dryer with the simplifying assumptions:

- the grain kernels are homogeneous and spherically shaped
- the bed is homogeneous with constant porosity
- grain and air move in plug-flow mode; wall effects are neglected
- grain kernels dry entirely within the falling-rate period, i.e. the internal resistance to moisture transport is dominating the drying process
- volume changes of the bed material during drying are negligible small
- the relation between air humidity and grain equilibrium moisture content at a certain temperature can be explained by sorption isotherms
- heat transport in radial direction is neglected (dryer walls are heat insulated and adiabatic)
- axial dispersion of water vapour, axial heat conduction within the void fraction, and heat conduction in the bed via particle contacts are neglected

The balance of masses of the moisture transported by the dry air around the finite volume element yields the differential equation

$$\psi \cdot \rho_{A,dr} \cdot \frac{\partial Y}{\partial t} = -w_0 \cdot \rho_{A,dr} \frac{\partial Y}{\partial z} - (1-\psi) \cdot \rho_{G,DS} \cdot \frac{\partial X}{\partial t} \qquad (1)$$

The last term in equation (1) describes the vapour transport from the grain kernels assembled in the volume element to the surrounding air. The temporal change of wet air enthalpy results from the energy balance around the finite volume element

$$\psi \cdot \rho_{A,dr} \cdot \frac{\partial h_{A,w}}{\partial t} = -w_0 \cdot \rho_{A,dr} \cdot \frac{\partial h_{A,w}}{\partial z} - \alpha \cdot A_v \cdot (\vartheta_A - \vartheta_G) - (1-\psi) \cdot \rho_{G,DS} \cdot h_V(\vartheta_G) \cdot \frac{\partial X}{\partial t} \qquad (2)$$

From the energy balance around the finite volume element of the grain bed, the temporal change of the enthalpy of the moist grain can be derived

$$(1-\psi) \cdot \rho_{G,DS} \cdot \frac{\partial h_{G,w}}{\partial t} = \alpha \cdot A_v \cdot (\vartheta_A - \vartheta_G) + (1-\psi) \cdot \rho_{G,DS} \cdot h_V(\vartheta_G) \cdot \frac{\partial X}{\partial t} \qquad (3)$$

The deep-bed model and the single grain model are coupled via the drying rate of the single grain layer dX/dt. The differential equation system (1-3) was numerically solved using a difference technique, see (Mellmann, *et al.*, 2007).

3. DRYER TEST STATION

To validate the mathematical model a semi-technical test station of a mixed-flow dryer has been constructed, see Fig. 2. The dryer plant consists of an air conditioning and conveying system (including two ventilators, a steam injection and three electrical heaters), two parallel vertically arranged mixed-flow dryer shafts, and a computer-based measuring and control system. One dryer shaft is used for drying experiments and the other for grain flow studies. The dryer shaft of about 2 m height and 0,6 m width consists of in total 12 inlet and 14 exit air ducts which are horizontally arranged across the dryer. The moist grain is feeded by an elevator into the hopper at top of the dryer. Following gravity the grain vertically passes through the dryer. A pneumatically operated slide bottom is used as discharge device for the dried grain providing an almost even grain flow over the cross-section. Temperature and velocity of the drying air are adjusted and held constant using control algorithms.

The drying air enters the inlet air box at the top of the dryer where it is distributed over the inlet air ducts. From the inlet air ducts it passes through the grain bed until it reaches the exit air ducts. The average length of an air streamline through the bed is approximately the distance between inlet and exit air duct. At the other side of the dryer the exit air is accumulated and transported through the exit air box. Via ventilator 2 the total exit air is conveyed to the outside.

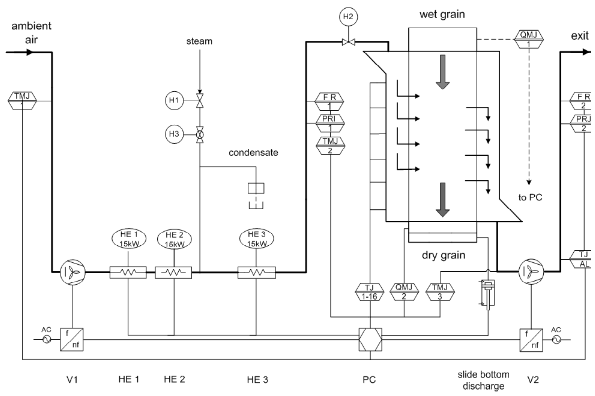

Fig. 2. Flow sheet of the mixed-flow dryer test station

The temperatures and relative humidity's of ambient air, drying air, and exit air are continuously measured using combined humidity-temperature sensors. Hot-wire sensors are employed to gauge the air velocities both in the drying air and in the exit air pipe. All temperatures at the dryer are detected with thermocouples. The drying air temperature is measured at two positions over the height in the inlet air box as well as in two inlet air ducts inside the dryer at the same positions. At each line of exit air ducts (7 in total) the exit air temperatures are detected within the dryer (almost in the middle) in order to obtain the temperature profile over the dryer height. In addition, the temperatures of the grain bed are determined at six positions over the height of the dryer shaft.

The grain moisture content at the dryer entrance (inlet m.c.) is measured using a grain moisture immediate-measuring system (Granomat, Pfeuffer). For that purpose, samples are taken from the wet inlet grain flow. The moisture content of the dried grain at the dryer discharge (outlet m.c.) is continuously detected with an on-line microwave moisture sensor (TRIME-GW, Imko) based on the time-domain-reflectometry. Additionally, samples are taken from each grain discharge to analyze the moisture content using both the Granomat and the reference technique (drying chamber, according to DIN 10350). The reference values were applied to calibrate the TRIME sensor as well as the Granomat measuring system. The masses of all inlet and outlet grain quantities are gauged using a balance. All measuring values are recorded by a computer who controls the dryer devices such as ventilators, heaters, air registers, and grain discharge device.

4. DRYING EXPERIMENTS

For the drying experiments a quasi-stationary record-by-record operation of the mixed-flow dryer test station was chosen. As drying bed material charges of farm-fresh wheat with initial moisture contents between 15 and 16 % w.b. were used. The grain mass flow rate varied between 100 kg/h and 200 kg/h. Drying air temperatures employed were 60°C and 70°C. The volume flow rate of the drying air was held constant corresponding to an air velocity within the void fraction of the grain bed of about 0.25 m/s. The standing time of the dryer was fixed to 5 minutes whereas the discharge time amounted to a few seconds depending on the grain mass flow rate. For example, to achieve a grain mass flow rate of 200 kg/h a grain mass of 16.7 kg per discharge has been adjusted according to the feed characteristic of the slide bottom.

In the following two drying experiments (No. 6 and 7) are considered as examples. The moisture content of the wheat amounted to 15.6 % w. b. and 15.3 % w. b., respectively. Besides the different grain mass flow rates of 100 kg/h and 200 kg/h applied the mixed-flow dryer was operated in two different ways in experiments 6 and 7. Experiment 6 was started with moist grain from the beginning whereas in experiment 7 an initial dryer filling of dried grain from test No. 6 was applied to save bed material and, thus, to be able to extend the stationary range of the drying process.

In Fig. 3 measured inlet and outlet grain moisture contents are shown in dependence on the drying time. As can be seen from the figure the outlet m. c. values follow different courses due to differences in operation.

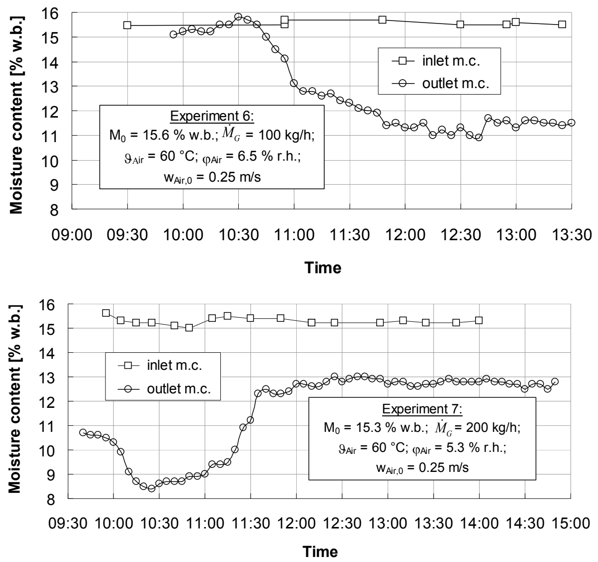

Fig. 3. Measured inlet and outlet grain moisture contents: a) experiment 6; b) experiment 7

Experiment 6 was started with moist grain. Therefore, the outlet grain moisture content is at the same level as the inlet moisture content at the beginning of the test at 09:55 when the discharge device was activated. From 10:30 the outlet moisture content is continuously falling until it obtains an almost steady value of about 11.5 % w. b. at 12:00. Against it, experiment 7 was started with dry grain bed material used as initial dryer filling. Therefore, the outlet moisture content measured at the beginning (at 09:40 the discharge system was started) is at a low level of about 10.8 % w. b. After it, the outlet moisture content decreases displaying that the initial dryer filling is over-dried followed by a period of continuous increase. From 11:40 when the moist inlet grain completely replaced the initial dryer filling the moisture content at the dryer discharge reaches an almost constant value of about 12.8 % w. b.

In Fig. 4 measured temperatures and relative humidity's of the total exit air for experiments 6 and 7 are depicted as a function of the drying time. In case of experiment 6 started with moist inlet grain from the beginning the total exit air temperature is continuously increasing until it attains a steady value of about 32 °C around 10:40. The relative humidity of the exit air is increasing for the first 20 minutes up to 86.4 % r. h. From 10:00 it is falling until it reaches almost constant conditions of average 57.4 % r. h. In case of experiment 7, however, the total exit air temperature and relative humidity are steeply increasing and decreasing from the start, respectively. This is due to the dry initial bed material passing through the dryer shaft. Both variables attain nearly constant values of 28.4 °C and 57.5 % r.h., respectively, from about 11:30.

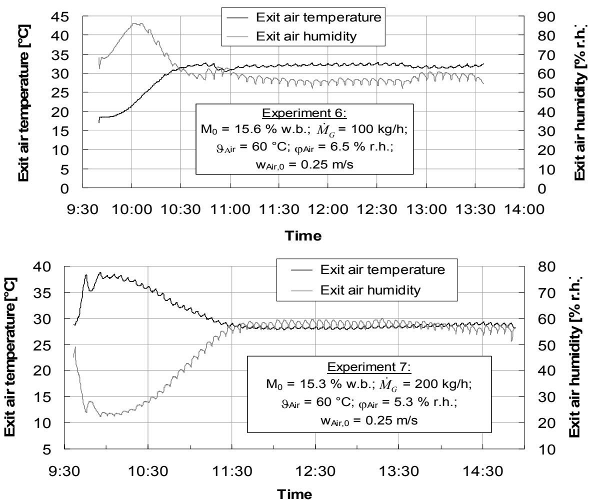

Fig. 4. Measured temperatures and relative humidity's of the total exit air: a) exp. 6; b) exp. 7

5. MODEL TESTING

For testing the mathematical model measuring results from experiment 5 were taken the operating variables of which are: inlet moisture content of wheat M_0 = 15.7 % w.b., grain mass flow rate $\dot{M}_G = 100$ kg/h, condition of drying air □$_{Air}$ = 70 °C / □$_{Air}$ = 2.9 % r.h., air velocity $w_{Air,0}$ = 0.25 m/s (within the void fraction). Similar as in experiment 6 moist grain was used as bed material from the beginning. The measured and calculated results of the grain moisture content at the dryer discharge are shown in Fig. 5 in dependence on the drying time. The outlet m. c. was continuously measured with the on-line microwave material moisture sensor. At 13:25 after a heating-up period of about 2 hours the discharge device was set into operation resulting in a decrease of the moisture content. For the next two hours the unsteady dried initial dryer filling was discharged leading to a strong fluctuation of both the measured and predicted grain moisture curves. From about 15:40 the mixed-flow dryer reached stationary operation. As can be seen from Fig. 5 model and experiment are in relative good agreement in this region.

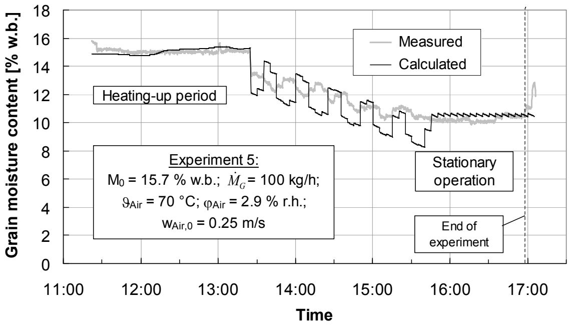

Fig. 5. Measured and calculated outlet grain moisture contents as a function of drying time

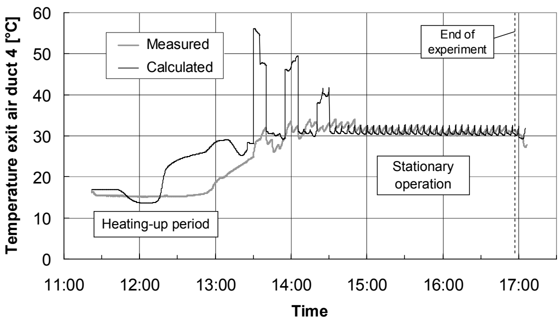

Fig. 6. Exit air temperatures measured within exit air duct No. 4 in comparison with calculated results as a function of drying time

In Fig. 6 measured and calculated results of the exit air temperature in the middle of the dryer (within exit air duct No. 4) are compared to each other. As can be seen from the diagram steady state is reached earlier in that case. This is due to the fact that the fresh grain has already displaced the initial dryer filling in the middle part of the dryer. In the stationary operation period model and experiment agree well with each other. At the beginning of the experiment, however, after the discharge device was started there are high fluctuations in the calculated values showing that the model reacts hyper sensitive to moisture flutuations caused by single discharges.

6. CONCLUSIONS

As the model testing revealed experimental and calculated results are in relative good agreement in the stationary operation period which is relevant for practice. However, further improvements of the model are necessary in order to more accurately predict unsteady reversing operation modes which may occur if for instance the inlet grain moisture content is intensely fluctuating or the type of grain, the grain mass flow rate, the air temperature, and other operation variables are changing. For example it is necessary to change to a two-dimensional approach for grain and air flow. Grain mass flow experiments will be carried out and a model for the solids transport will be derived to couple it with dryer model.

The target is to obtain a model with an accuracy required to be able to optimize the dryer apparatus as well as the model-based process control of mixed-flow grain drying.

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NOMENCLATURE

A_v	volumetric exchange area	m^2m^{-3}
h	specific enthalpy	Jkg^{-1}
H	enthalpy	J
$\dot{H}$	enthalpy flow	W
M	mass	kg
M	moisture content	% w. b.
$\dot{M}$	mass flow	kgs^{-1}
$\dot{Q}$	heat flow	W
t	time	s
w	air velocity	ms^{-1}
X	water content of solid	$kgkg^{-1}$ d. b.
Y	water content of air	$kgkg^{-1}$ d. b.
z	length coordinate	m

Greek Symbols

α	heat transfer coefficient	$Wm^{-2}K^{-1}$
ϑ	temperature	°C
ρ	density	kgm^{-3}
φ	relative humidity	% r. h.
ψ	porosity	-

Indices

A	air
ax	axial
C	convection
dr	dry
DS	dry substance
G	grain
i	at time step i
T	transfer
v	volumetric
V	water vapour
w	wet
z	in z-direction
0	initial, empty pipe
α	convective