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Application note

Real-time product moisture content monitoring in batch dryer using psychrometric and airflow measurements

Franz Román *, Oliver Hensel [1]

University of Kassel, Department of Agricultural Engineering, Nordbahnhofstr. 1a, 37213 Witzenhausen, Germany

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ABSTRACT

The possibility of a continuous monitoring of moisture content in batch dryers using air humidity was studied in a laboratory-scale test stand. Psychrometers formed by two K-type thermocouples, one of them kept moist, were installed at the system inlet and outlet to measure the increase in the humidity of the drying air. A grid measurement of air velocity at the inlet duct was used to estimate the airflow from a single measurement point. The sensors were connected to a data logger and this to a computer. An algorithm written in MATLAB allowed the retrieval of measured data from the data logger at specified time intervals and the calculation of the mass of water removed. Numerous drying trials have shown that this method can be suitable for drying monitoring. Errors in the calculation of final moisture content of less than 0.03 (dry basis) could be obtained. The difficulty in measuring wet-bulb temperature with sufficient accuracy over long periods was seen as the main obstacle for a reliable use of the method. Attention must be paid to different possible sources of error, which can be minimized by adequate sensor selection and location.

1. Introduction

Monitoring the moisture content of a product during drying is a complicated task. For convective batch dryers, the simplest, cheapest and most traditional method is to take a sample and determine its moisture content in an oven at a high temperature. Although this method can be very accurate, it is often of limited use since the results are obtained after some time, in many cases hours, which prevents a real-time monitoring of the process. Also, depending on dryer type, sample extraction might involve stopping the process which during commercial production is not advisable (Briens and Bojarra, 2010). In many cases, particularly but not only in small-scale facilities the moisture content is estimated by experience based on inspection of the product, which is inevitably subjective and inaccurate. There are also electrical methods for the measurement of solids' moisture content, which are based on the dependence of electrical resistance and dielectric properties of the material on its moisture content (Molnár, 2006). They are fast and in some cases the sensor probes can be introduced into the product bed for continuous monitoring at the measurement point. However they are restricted to a set of products like grain, wood and hay, their accuracy is dependent on many factors and they need to be calibrated for each product.

The methods mentioned above measure the moisture at a particular location in the dryer, and therefore by taking numerous measurements at different positions they are useful to determine the moisture profile resulting from spatially varying drying conditions in the product bulk. However, in many cases it might be useful to know additionally (or only) the average moisture content in the bulk and such methods are in this case less useful. An option to estimate the average moisture content of the bulk is through the monitoring of the product and/or the outflowing air temperature, since during most of the drying process both are cooled down due to water evaporation. At some point when the water content of the product reaches a critical point, the temperature of outflowing air and product will raise until it reaches the inlet air temperature, thus marking the end of the process. Because the bed temperature only begins to increase once surface moisture is lost from the particles, this type of temperature monitoring only provides information about bed moisture content late in the drying process (Chaplin et al., 2005).

Another possibility, and the one considered in the present study, would be to directly calculate the amount of water evaporated from the product. This can be done by precise and continuous measurement of air humidity before and after it passes through the product as well as of the airflow rate. Although the principle of this method is of course not new, no studies have been found to assess

* Corresponding author. Tel.: +49 5542 98 1649; fax: +49 5542 98 1520.
E-mail addresses: roman@uni-kassel.de (F. Román), agrartechnik@uni-kassel.de (O. Hensel).
[1] Tel.: +49 5542 98 1649; fax: +49 5542 98 1520.

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its accuracy and feasibility. Such a method was employed in some studies to follow the drying progress. However, in general the applicability of the method was not the topic of study and no estimation of its accuracy was obtained (Arinze et al., 1996; Godsalve et al., 1977). Correa-Hernando et al. (2011) developed three model-based methods for the supervision of a solar dryer, one of which was based on calculations from inlet and outlet air conditions and airflow rate. However, their results show a large difference between measured and calculated weight loss. Therefore, the objective of this study was to assess the applicability of air humidity and flow measurements to monitor the course of the drying process in batch dryers.

2. Materials and methods

2.1. Apparatus

An existing apparatus to measure the airflow resistance of bulks of agricultural products was modified and equipped with the necessary sensors. Fig. 1 shows a schematic diagram. The main parts of the apparatus are inlet duct, butterfly valve, centrifugal in-line duct fan, test column and outlet duct.

The entrance to the apparatus consisted of a round galvanized steel air duct with a diameter of 0.15 m and a length of 0.85 m. At 0.3 m downstream from the duct inlet a honeycomb flow straightener with tube diameter of 0.005 m and tube length of 0.05 m was installed to remove any tangential velocity components. The butterfly valve was installed immediately upstream of the fan in order to reduce the airflow to the desired test conditions. Below the perforated plate which formed the bottom of the test column, three additional perforated plates with a space between them of 0.05 m were installed to improve the flow uniformity after the change of direction in the plenum chamber. The test column had a height and a diameter of 0.6 m.

An Airflow TA-5 hot wire anemometer with a full scale accuracy of ±1% (FS of 15 m s^{-1}) in its analogue output was used to measure air velocity. The probe was placed at the duct centre and 0.4 m downstream of the flow straightener. To determine the airflow rate in the system from a single measurement point, the guideline VDI/VDE 2640 Part 3 (1983) was used, which details the procedures to determine the flow rate of gases in ducts of circular, annular and rectangular cross sections by means of grid measurements. For this, the circular cross section of the duct was divided in three concentric surfaces of equal area, and the circular line dividing again each surface in two equal areas (circular dotted lines in Fig. 2) was determined. Twenty-four measurement points in the centroid

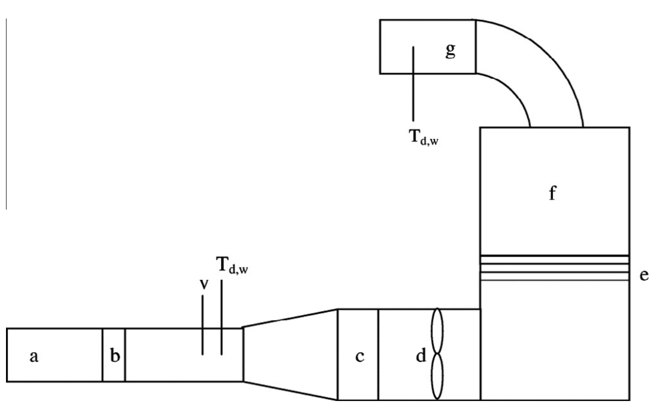

Fig. 1. Schematic diagram of test apparatus: (a) inlet duct, (b) flow straightener, (c) butterfly valve, (d) in-line duct fan, (e) perforated plates, (f) test column, and (g) outlet duct.

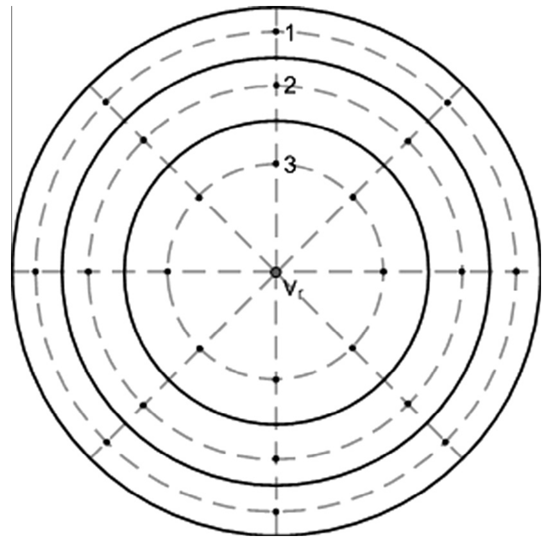

Fig. 2. Measurement positions for the grid measurement.

of twenty-four equal-area surfaces are thus established by the intersection of these lines and eight radial lines (straight dotted lines in Fig. 2) distributed around the circumference.

Since the measurements could only be done successively, and small, slow changes in flow rate cannot be excluded, a reference measurement v_r in the duct centre is taken immediately after each point measurement v_i. The influence of airflow fluctuation is taken into account by working with the velocity ratio v_i/v_r. To account for the effect of the duct wall on the velocity profile a correction is introduced. A reference factor is calculated from the measured data as follows:

$$\frac{v_m}{v_r} = \frac{\bar{v}}{v_r} - \left(\frac{\bar{v}_2}{v_r} - \frac{\bar{v}_1}{v_r}\right)\frac{k}{n} \quad (1)$$

where $\bar{v}/v_r$ is the mean of the velocity ratio over the twenty-four measurement points, $\bar{v}_1/v_r$ and $\bar{v}_2/v_r$ are the means of the velocity ratio in the first and second outermost concentric surfaces respectively, and k/n is a correction factor for the duct wall effect. Finally the airflow rate at a given time can be calculated as follows:

$$q_V(t_i) = \left(\frac{v_m}{v_r}\right) v_r(t_i) A \quad (2)$$

where $v_r(t_i)$ is a velocity measurement at the duct centre and A is the cross-sectional area of the duct.

To form a psychrometer two ungrounded type-K thermocouples with a probe sheath diameter of 3 mm were installed in close proximity to each other and 0.05 m downstream of the anemometer. One of them was kept moist by a cloth wick partly immersed in distilled water. Another such pair of thermocouples was installed in the outlet duct. Before the tests the thermocouples were calibrated in an ice water bath.

The thermocouples and the hot wire anemometer were connected to an Agilent 34970a data acquisition device and this was connected to a computer.

2.2. Algorithm

A program was written in MATLAB to communicate with the data acquisition device, retrieve the temperature and air velocity measurements at specified intervals, and perform the calculations to determine the mass of water evaporated. A flowchart of the program appears in Fig. 3.