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Characteristic drying curves for cellulosic fibres

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Abstract

The tray drying of cellulosic fibres from citrus fruits has been studied here, for hot air drying at dry-bulb temperatures from 40–80 °C, a wet-bulb temperature of 40 °C, and a cross-stream air velocity of 1.3 m s^{-1}. It appears that a single characteristic drying curve may be adequate to describe the drying behaviour of the fibres, whether the fibres are mixed with water or with hibiscus extract. The amount of hindrance to moisture movement seems to be small relative to many other materials, and the characteristic curve has the approximate form $f = \Phi^{0.5}$. Comparison of the characteristic curve with the normalized drying rates measured by previous workers suggests that the characteristic curve remains applicable for sugar beet fibres dried in hot air over a wider range of temperatures, from 130 to 183 °C. The importance of the basic cellulosic component in the fibres in controlling the drying behaviour may explain the absence of any significant difference between the normalised drying rates for sugar beet fibres and those for citrus fibres. In the context of drying the fibres by other methods, including spray drying, compared with the tray drying used here, the absence of substantial additional hindrance to the movement of moisture caused by the extract (compared with water) may be useful.

Keywords: Tray drying; Fibre; Cellulose; Plant materials; Characteristic drying curve; Drying kinetics

1. Introduction

The by-products of processing fruits and vegetables, such as skins, pips and peels, can cause significant environmental problems, such as biochemical oxygen demand, nutrients and eutrophication. However, these by-products also contain significant amounts of fibres, which can be valuable nutritional supplements for human consumption. There are two basic types of fibres, including insoluble fibre, which consists of hemicellulose, cellulose and lignin and which is found in beans and fruits with edible seeds, and soluble fibre, which is found in all fruit and vegetables. Examples of soluble fibre include gums and pectin [1]. The benefit of insoluble fibre is that water binds to it, giving the fibre a bulking effect and improving the efficiency of the gut and colon, while the beneficial effects of soluble fibre include an increase in the growth rate of natural bacteria in the digestive tract, improving the process of digestion [2].

Drying improves the shelf life of dietary fibres [3]. The drying of cellulosic fibres from wood for paper [4,5] and for fibreboard [6] has been extensively studied. Bernardo et al. [7] studied the drying of sugar beet fibres with hot air or superheated steam, but only mass–time curves were presented with a scale that does not enable the drying kinetics behaviour to be adequately assessed or inferred. Steam condensation on cold feed material was found to increase the drying time significantly. The drying of fruit pulps, including mango, West Indian cherry and avocado, in a pilot-scale spouted bed was investigated by Medeiros et al. [8], together with standard mango pulp and mango pulps modified by altering the concentrations of reducer sugars, lipids, fibers, starch and pectin. However, it is difficult to extract the drying kinetics for the materials on their own from the overall drying behaviour that was observed. Pronyk et al. [9] have investigated the drying of foodstuffs, inclduing sugar beet pulp, with superheated steam and air at temperatures between 130 and 157 °C. The shapes of the drying curves for beet do not appear to differ greatly with temperature over the temperature range studied for air, but there are differences in shape within the curves for superheated-steam drying. Hence, for air but not for steam, there appears to be a characteristic drying curve for this material over the studied temperature range.

Approaches to correlating or estimating the drying behaviour of different materials include the concept of a characteristic drying curve by van Meel [10] that has been reviewed by Keey

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[11], Fickian diffusion models [12], reaction engineering style approaches [13], models based on a shrinking wet core [14] and models based on convective and diffusive moisture transport processes [15]. Despite its empirical nature, the concept of a characteristic drying curve remains an effective one for interpolating the drying behaviour of a large number of different materials [16], since many of the weaknesses in the assumptions made in applying the concept cancel each other out to a large extent [17]. This work has investigated the drying behaviour of edible fibres in a cross-circulation air flow, comparing the behaviour of citrus fibres with those from sugar beet found in previous work.

2. Experimental equipment and method

The drying tunnel used for these studies is shown schematically in Fig. 1. The air velocity through the working section of the tunnel is 1.3 m s^{-1}, as measured by a Solomat hot-wire mean-flow anemometer, model number MPM 500e. Regulating the flow of steam to a finned heat exchanger is used to control the dry-bulb temperature of the air, while the wet-bulb temperature is controlled by regulating the injection rate of steam through a four-port injection system. The temperatures are measured with standard platinum 100 Ω resistance thermometers. The total mass of the sample was measured using a platform balance, with a capacity of 200 kg and a resolution of 5 g. The mass was transmitted through a RS 232 interface to a computer to estimate the average moisture content of the sample.

Round aluminium pans of 180 mm diameter and height 40 mm were used to contain the samples. The dried samples consisted typically of 50 g of coarse cellulosic fibre from the peel of citrus fruit (oranges) and 250–280 g of liquid (either water or hibiscus extract with a solids concentration of 11.3%). The layer thicknesses were 10–12 mm. Dry and wet-bulb temperatures of 80 and 40 °C, respectively, 60 and 40 °C, and 50 and 40 °C were used.

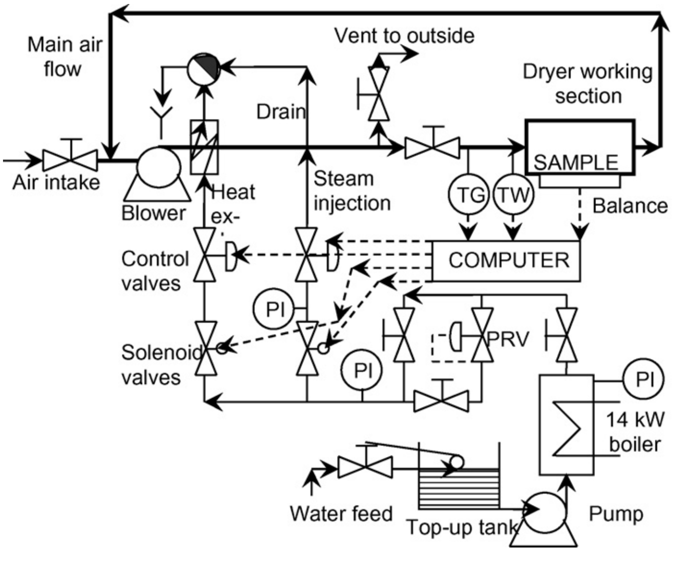

Fig. 1. Schematic diagram of drying tunnel.

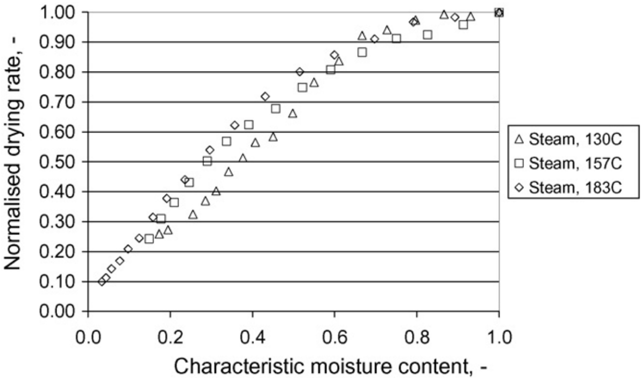

Fig. 2. Normalised drying curves for sugar beet fibres in superheated steam (from [9]).

3. Results and discussion

The drying rates measured by Pronyk et al. [9] for sugar beet in superheated steam (Fig. 2) and hot air (Fig. 3) have been normalised. The normalisation yields a more singular characteristic curve in hot air (Fig. 2) than for hot air (Fig. 3). From the current work on citrus fibres, the drying rates of fibres and water, and fibres and hibiscus extract, are shown in Figs. 4 and 5, respectively. Allowing for what appears to be greater scatter in the drying rate results for fibres and hibiscus extract, the combined curves for the normalised drying rates for hot air drying (Fig. 6) show no evidence of any systematic differences, either between

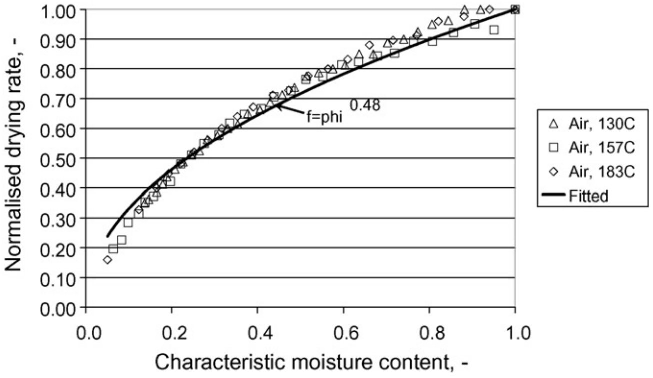

Fig. 3. Normalised drying curves for sugar beet fibres in hot air (from [9]).

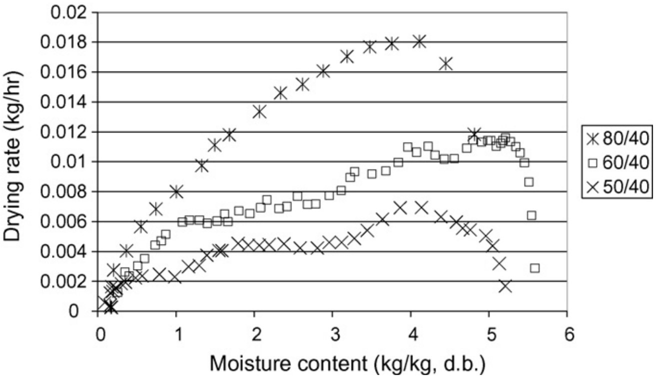

Fig. 4. Drying curves for citrus fibres and water in hot air (this work).

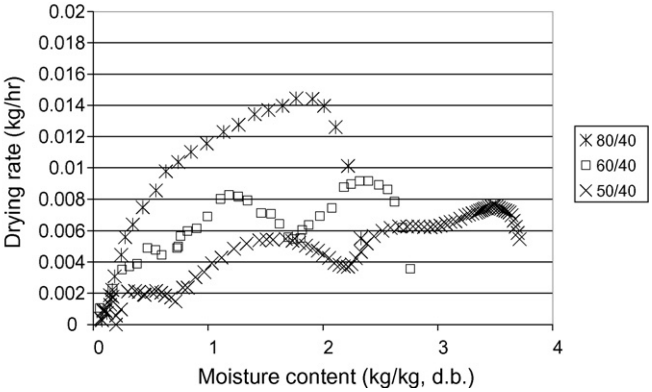

Fig. 5. Drying curves for citrus fibres and extract in hot air (this work).

the normalised drying rates for sugar beet fibres and those for citrus fibres, or between citrus fibre and water and citrus fibre and extract. The absence of any apparent difference between the normalised drying rates for sugar beet fibres and those for citrus fibres may be a reflection of the importance of the basic cellulosic component in the fibres in controlling the drying behaviour, so that the source of the cellulose (sugar beet or citrus) does not have a substantial effect on the drying behaviour. The small difference between the normalised drying rates between citrus fibre and water, and citrus fibre and extract, may reflect the low solids content of the hibiscus extract and the small difference between the extract and water in terms of the overall drying behaviour. It is also noticeable that, allowing for the lower initial moisture contents in the drying of citrus fibre and extract compared with the drying of citrus fibre and water, the drying rates are not very different either. For example, the drying rate at a moisture content of 2 kg kg^{-1} is around 0.014 kg h^{-1} for both citrus fibre and water (Fig. 4) and citrus fibre and extract (Fig. 5). The absence of substantial additional hindrance to the movement of moisture caused by the extract (compared with water) is significant and may be important in the context of drying the fibres by other methods, including spray drying, compared with the tray drying used here.

The shape of the characteristic drying curve in Fig. 6 is concave downwards. This situation is suggestive of the curves predicted by wetted surface models [11], despite these models being most appropriate, in theory, for very thin samples (less than 2–3 mm), compared with the 5–10 mm thick layers used here. It may indicate that the resistance to moisture transport from the fibres is relatively small compared with many other materials. The shape of the normalised drying curve also follows the behaviour seen by Pronyk et al. [9] for sugar beet in hot air. Keey [16] has commented that "*a value of 0.6 for n* (in $f = \Phi^n$) *describes the through-circulation drying of thin mats of loose wool fibers*", which may be relevant to this work in the sense that wool fibers are similar in shape but not composition to these cellulosic fibres.

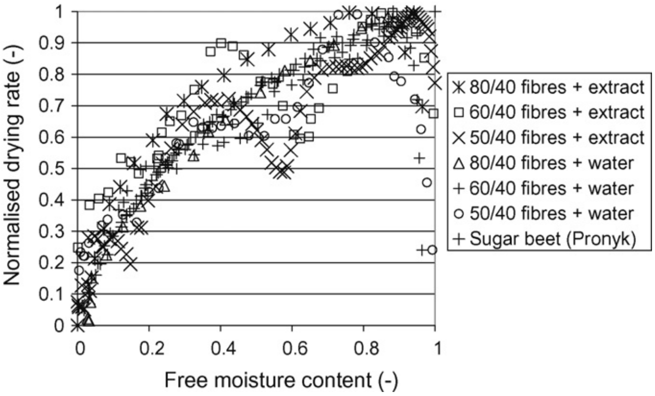

Fig. 6. Normalised drying curves for all fibres in reply to: hot air (this work and [9]).

Suzuki et al. [14] have also commented that "*In the limit of the slow drying of a thick material, a single linear characteristic curve* ($f = \Phi$) *is found.*" Such a linear falling rate curve has been found for many materials [16], including for sugar beet pulp by Salgado et al. [18] at air temperatures of 45–90 °C, air velocities from 0.5 to 1.5 m s^{-1}, and layers that were 1–20 cm thick, which were generally deeper than the layer used here. Increasing the bed thickness, as in the work of Salgado et al. [18] compared with the work here, is likely to lead to a decreasing extent to which the drying curve is concave downwards. For deeper beds, a reason for the suggestion that the drying curve becomes more linear, or concave upwards, is that the drying process is then more greatly limited by the moisture movement through the bed of solids rather than the moisture transport within the fibre material itself. This limitation leads to a drying process that is characterized by a receding evaporative interface. Such a concave upwards curve was found by Hallström and Wimmerstadt [19] for the convective drying of nitrogen–phosphorous–potassium fertlizer granules. They interpreted the drying process for these fertilizers as involving moisture vapour diffusion through a dry outer shell, with the outer shell extending into the core as drying proceeds. Hence, the concave downwards shape of the drying kinetics curve here for the thin layers is consistent with the linear falling rate curve of Salgado et al. [18] for sugar beet in deeper layers.

Some indication of the ultimate experimental uncertainities can be seen in Fig. 5 from the scatter in drying rates. The apparent waves, and this scatter, arise from the differentiation in moisture contents to extract the drying rates, and it appears to be of the order of ±0.001 kg h^{-1}, in terms of the drying rates themselves, and up to ±0.1 in terms of normalised drying rates. The scatter, to some extent, is almost inevitable [11] and this phenomenon is discussed in Keey [11,16] as a difficulty that arises in differentiating mass–time drying curves. While it does not invalidate the interpretation of the drying behaviour, it does introduce some uncertainty into the interpretation of the drying behaviour. Here, it means that there is some uncertainty, as has just been quantified, in the conclusion that a single characteristic curve represents all the drying behaviour in hot air.

4. Conclusions

The drying behaviour of citrus fibres appears to be described, to a significant extent, by a single characteristic drying curve of the form $f = \Phi^{0.5}$, whether the fibres are mixed with water or with hibiscus extract. The amount of hindrance to moisture movement seems to be small relative to many other materials. Comparing the characteristic curve with the normalized drying rates measured by previous workers [9] suggests that the characteristic curve remains applicable for sugar beet fibres dried in hot air over a wider range of temperatures, from 130 to 183 °C. The source of the cellulose (sugar beet or citrus) does not seem to have a substantial effect on the drying behaviour, as indicated by the absence of any significant difference between the normalised drying rates for sugar beet fibres and those for citrus fibres. The absence of substantial additional hindrance to the movement of moisture caused by the extract (compared with water) is significant and may be important in the context of drying the fibres by other methods, including spray drying, compared with the tray drying used here.

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