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Factors influencing the drying of prunes 1. Effects of temperature upon the kinetics of moisture loss during drying

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The kinetics of the drying of prunes (*Prunus domestica*) have been investigated as a function of temperature (70–100°C). The variety of plum used was D'Agen. The prunes were dried in an oven under exhaust conditions resulting in a constant relative humidity during drying (70–80%). It was found that simple first-order kinetics fitted the experimental data well. This is consistent with a diffusion-controlled process through the fruit matrix. The activation energy plot was found to be non-linear with a much higher activation (80 kJ mol^{-1}) at the lower temperature end. This indicates a more hindered path for diffusion of the water through the matrix. This is consistent with what is known about the temperature dependence of cell rupture and disturbance of structure in such a material. In addition, estimates of diffusion of water through the food matrix are much slower than the self-diffusion coefficient of water across the entire temperature range. This also emphasises the hindered nature of the process.

INTRODUCTION

Fruit has been dried as a means of preservation for thousands of years and dehydration is therefore probably the oldest method of preserving foodstuffs. Many fruits are conventionally dried by the sun; however, some are commercially dried at elevated temperatures. For example, prunes are processed by the drying of plums (*Prunus domestica*) in drying tunnels at temperatures of approximately 75–85°C because of their large volume to surface area ratio. The major prune producers in the world include USA and France (Bousigon *et al.*, 1988). Australia has an increasing prune industry producing currently up to 4500 tonnes of dried product per year in NSW, Victoria and South Australia (Dried Fruits Research and Development Council, 1992). The majority of the produce is for domestic consumption.

Prunes are traditionally dried to about 18% moisture content, which has sufficiently low water activity to avoid problems of microbial spoilage allowing long-term storage of the fruit. These fruits are then rehydrated (in Australia to 35–40%) prior to packing and sale. Drying costs therefore make up a significant percentage of the total cost of production. In Australia, current estimates are that drying is about 30% of production costs (DFRDC, 1992).

It is known that the air-drying of foodstuffs is dependent on simultaneous water migration through the food matrix and evaporation from the surface (Bushra Al-Duri & McIntyre, 1992). The mass transfer is controlled by the water concentration gradient across the food. The temperature gradient between the fruit surface and the drying atmosphere and the relative humidity (and hence air velocity) are all likely to affect the evaporation process. A range of fruit and vegetables has been extensively studied; however, there has been relatively little work on the kinetics of drying of tree fruit such as prunes (McBean *et al.*, 1966; Ponting & McBean, 1970; Adams & Thompson, 1985; Halbwachs, 1987; Weitz *et al.*, 1989; Barbanti *et al.*, 1994, 1995). The last major study of prune processing in Australia was carried out (McBean *et al.*, 1966; Ponting & McBean, 1970) in the 1960s. One exception has been a project in France (Bousigon *et al.*, 1988; Centre de Recherche sur la Technologie de Sechage, 1988) which has led to the development of a new type of drier utilizing moving conveyors to transport the fruit through the drying tunnel. In addition, work by Barbanti and co-workers

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has focused attention on differences in the rate of drying between cultivars (Barbanti *et al.*, 1994) and some processing parameters (Barbanti *et al.*, 1995). In particular, there have been few recent studies of the kinetics of dehydration of prunes from a physicochemical point of view.

The present work is the first paper in a major study of drying of prunes looking at the processing parameters that affect the rate of moisture loss from the surface of a drying plum, such as temperature, control of relative humidity, air-flow characteristics or the effect of any pre-treatment such as dipping. In addition, the effects of drying upon aspects of the chemical composition (volatiles and important flavour components such as sugars) are also under investigation. The overall aim of the project is to identify the major factors influencing the rate of drying and from these results to devise a physical model for the drying process. It is also the intention to utilize the new knowledge to improve the cost-effectiveness of commercial drying of prunes in Australia. The current paper deals with preliminary experiments highlighting the effect of temperature upon the drying of prunes.

MATERIALS AND METHODS

A fan-forced convection heating chamber was used for the drying experiments. This was made with modifications from a commercial oven. The exhaust system of the oven was arranged such that the relative humidity in the oven during the experiments was approximately constant (about 70–80%) as measured by a relative humidity probe (Vaisala, Finland). The temperature control was better than ±0.5°C. In each experiment 50 plums (variety D'Agen) were placed on trays and placed into the pre-heated oven at time $t = 0$. Kinetic samples were obtained by removing five plums at a given time and taking the average weight loss. The organization of plums upon the tray was such that it minimized artefacts due to temperature differences in various parts of the drying space. In addition, any plums that split during drying were discarded from the kinetic calculations, the additional error and uncertainty in the weight loss being undesirable. An equilibrium sample was taken at 18–24 h, depending on the temperature. Preliminary experiments had determined the equilibrium moisture content. Plums were weighed before the experiment on a top pan balance and after sampling. Experiments at each temperature were carried out several times to check for reproducibility and the results averaged.

RESULTS AND DISCUSSION

Figure 1 shows curves for the rate of loss of water as a function of temperature. These are mean values taken from at least three experiments for each temperature. The standard deviation for each value was better than 5%. The figure is notable in that there appears to be a substantial difference between 70°C and the higher temperatures. It was found that the equilibrium amount of water loss was the same for all temperatures within experimental error (71 ± 2.5%).

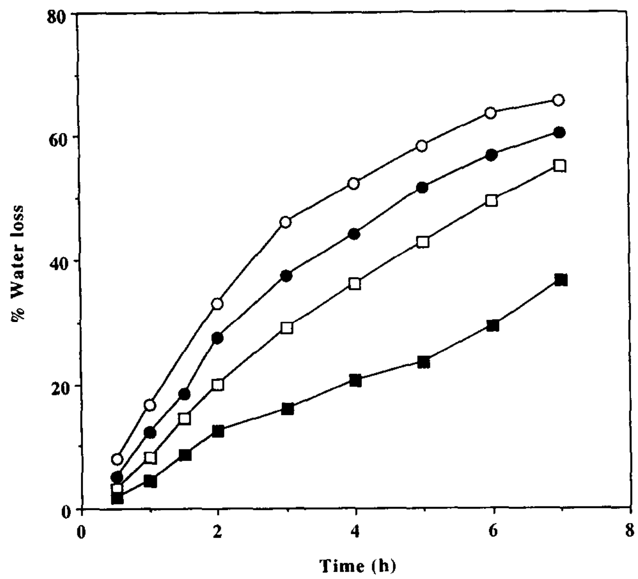

Fig. 1. Rate of water loss from D'Agen prunes as a function of temperature (°C). ■, 70°C; □, 80°C; ●, 90°C; ○, 100°C.

It has been shown previously that the drying of foodstuff fits first-order kinetics (Diamante & Munro, 1991, 1993) and that a plot of the form:

$$\ln[W_\infty/(W_\infty - W_t)] = kt \quad (1)$$

where W_∞ and W_t are the water loss of the plum at equilibrium and after drying time t, respectively, results in a good straight line with slope k (first-order rate constant). This is a very simple approach but an attractive one as the rate of drying can be characterized by a single number. It has also been shown that this first-order kinetics is consistent with diffusion-controlled processes. For example, Spiro and co-workers have carried out (Spiro & Jago, 1982) extensive studies on the extraction of solubles from tea and coffee and have shown that the rate-determining step is likely to be diffusion of components through the food matrix. The situation with the air-drying of fruit is somewhat different. The heat transfer step in the evaporation under the humidity conditions of these experiments means that evaporation is probably also going to be a controlling factor.

Figure 2, therefore, fits kinetic drying data to a first-order kinetics plot of the type given in Equation 1. For all temperatures studied, good linear fits were obtained with excellent correlations. All plots also had an intercept c, not predicted by the first-order model, that was always small and negative. This is in contrast to results from extraction kinetics from foods such as tea (Price, 1985). In these cases, a positive intercept was generally obtained. This was explained in terms of the washing off of an amount of soluble component from the surface of

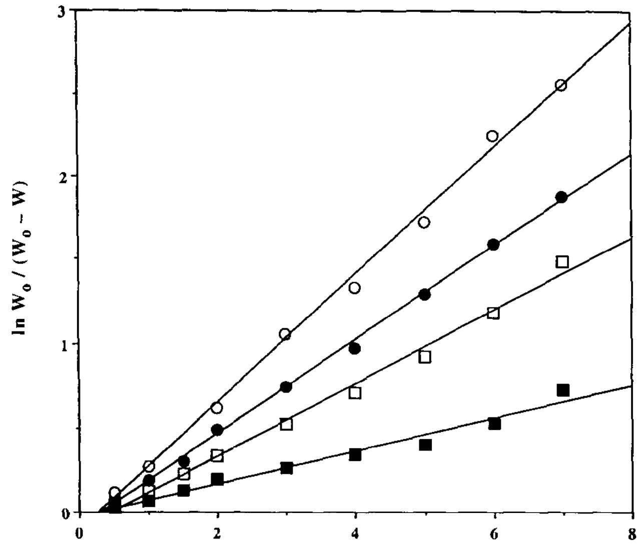

Fig. 2. Plots for the average rate of moisture loss from D'Agen prunes expressed as a first-order rate process. Symbols as for Fig. 1.

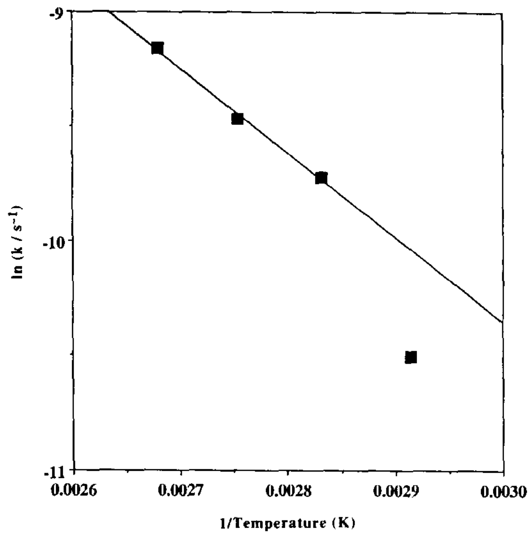

Fig. 3. Temperature dependence of rate of prune drying expressed as an Arrhenius plot.

the food immediately on immersion in the extracting medium. In the present case, the negative intercept may be interpreted as evidence for a lag time in drying (under these conditions of approximately 10–15 min). This would be due to the mass of cold fruit having to be heated up from room temperature before the onset of water loss.

There is clearly a marked increase in the rate of water loss above 70°C. This is likely to be due to the poor efficiency of cell wall rupture at this temperature (Binkley & Wiley, 1978). This would result in slower diffusion of the water to the surface because of the more tortuous path encountered. The fact that the water loss process is more hindered at the lower temperature is clearly illustrated by an Arrhenius plot of the data (Fig. 3). A good straight line is observed in the range 80–100°C with an activation energy of 31 kJ mol^{-1}. However, over the range 70–80°C, a value of nearly 80 kJ mol^{-1} is found. The activation energy for the self-diffusion of water (Easteal *et al.*, 1989) within this temperature range is 12–16 kJ mol^{-1}. This also indicates that the water loss process is a hindered one with a tortuous path within the food matrix. This is supported further by estimating the water diffusion coefficient within the drying plum. If diffusion of water through the food matrix is rate limiting then its value (D_{food}) is related to the observed rate constant by $k_{obs} = 12D_{food}/r^2$, where r is the radius of the food particle (Spiro & Selwood, 1984). This yields a value of 0.8×10^{-5} cm^2 s^{-1} at 80°C. This is assuming a spherical plum (2.5 cm radius) and ignores the effect of change in size during drying. This approximation, although simplistic, is eight times smaller than the self-diffusion of water at the same temperature (Easteal *et al.*, 1989) and indicates that the water is not freely able to move through the fruit but is hindered. This is curious in a food with such a high moisture content and is being investigated further through nuclear magnetic resonance (NMR) imaging work.

The activation energy results suggest that there may be a threshold temperature for efficient commercial drying (the actual temperature may vary because of the difference in conditions between the laboratory scale and those used in the industry). Most commercial prune driers do in fact use temperatures around the 80°C mark (Barbanti *et al.*, 1995). The benefits of using higher temperatures in terms of increased rates are clearly illustrated.

Because of the seemingly obvious benefits of using higher temperatures to dry at a faster rate, it is interesting to investigate whether a two-phase temperature regime could decrease the overall drying time. There is a clear precedent for this twin-drying regime in the literature. It has been suggested in order either to drive off

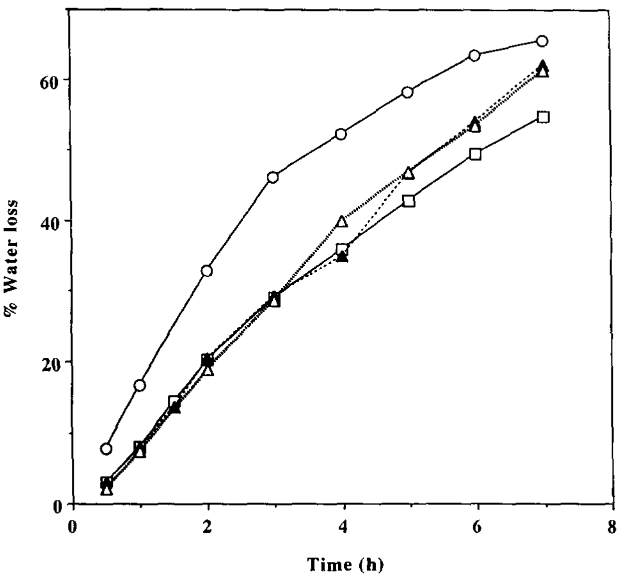

Fig. 4. Comparison of rate of moisture loss by two methods. (a) Single temperature: □, 80°C; ○, 100°C. (b) Dual temperature regime: ▲, experiment T1 (see text); △, experiment T2.

the difficult last 5–10% of moisture (Adams & Thompson, 1985; Barbanti *et al.*, 1995) by using a higher temperature, or using a higher temperature (e.g. 100°C) first to drive off the first 50% of water and then lower the temperature (e.g. to 70°C) to complete the process. This latter cycle has the advantage that low moisture plums are more susceptible to burning at higher temperatures. To test this former idea plums were: (1) first dried at 80°C for 4 h, then the temperature was increased to 100°C (experiment T1); and (2) first dried for 3 h at 80°C and then dried at 100°C (experiment T2). These results are shown in Fig. 4. Although only preliminary experiments have been completed during the current season, it is clear that this twin-temperature regime has an effect. In both experiments T1 and T2, after 7 h of drying under the twin regime, the plums had lost an amount of water that was only 2–3% less (60% compared with 63%) than the case with 7 h of drying at 100°C under a single temperature regime (7 h of drying at 80°C loses 52% of moisture). It is interesting that it makes little difference if the temperature is increased after 3 or 4 h of drying.

CONCLUSIONS

Temperature is an obvious parameter determining the rate of drying of prunes. The experiments here have shown that the kinetics may be fitted to a simple first-order process but that the temperature dependence may be more complex. The difference in activation energy between two temperature regimes would appear to indicate different rate-limiting obstacles to be overcome. This may be because of the poor efficiency of cell rupturing at the lower temperatures (70°C). This is known from other work. It would be interesting to test out this idea by drying plums at different temperatures and looking at changes in cell structure using electron microscopy. In addition, NMR diffusion measurements of water in plums at different stages of drying would be useful to see if the diffusion of water is restricted or hindered. These aspects are currently under investigation.

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