

The drying behaviour of fresh and candied carambola under natural convection

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Sankat, C.K. and Balkissoon, F. 1994. **The drying behaviour of fresh and candied carambola under natural convection.** *Can. Agric. Engr.* 36:165-174. Fresh and candied carambola (also known as five-finger, star fruit or kamaranga) slices of 10, 20, 30, and 40 mm thicknesses were dried in single layers under natural convection conditions at 40, 50, 60, and 70°C. Total soluble solids (TSS) content of fresh and candied slices were 7.5 and 49.1 °Brix, respectively. The simplified solution of the diffusion equation for a slab was used to model the drying behaviour which was found to be entirely in the falling rate period. Drying constants were established for a first and second falling rate period as a two-period model best fitted the data. The drying rate of carambola slices was influenced by air temperature and slice thicknesses and mathematical relationships were established between the drying constants and these variables. Candying of fruit slices reduced the drying rate, especially at 70°C due to case-hardening. Best drying conditions appear to be 60°C using 10-20 mm thick slices.

Des tranches de Carambolas frais et confits d'une épaisseur de 10, 20, 30, et 40 mm ont été séchées en couche mince par convection naturelle à 40, 50, 60, et 70°C. La teneur en solide soluble total (TSS) des tranches de carambolas frais et confits étaient respectivement 7.5 et 49,1 °Brix. Nous avons utilisé pour modéliser le séchage la solution simplifiée de l'équation de la diffusion dans une tranche infinie qui a monté que nous étions bien dans la période de séchage ralenti. Nous avons établi les constantes de séchage pour la première et la deuxième période de séchage ralenti puisque c'était le modèle à deux périodes de séchage qui correspondait le mieux aux résultats obtenus. Comme le taux de séchage des tranches de Caramboles était influencé par la température de l'air et l'épaisseur de la tranche, nous avons établi une relation mathématique entre le taux de séchage et ces constantes. Le **confisage** des tranches de fruit diminue le taux de séchage, spécialement à 70 °C à cause du dépôt de sucre en surface les meilleures conditions de séchage sont une température de l'air de 60 oC pour des tranches de 10 à 20 mm d'épaisseur.

INTRODUCTION

The Carambola (*Averrhoa carambola*) also known as the five-finger, star fruit, or kamaranga is a unique tropical fruit with considerable potential both for the fresh and processed fruit market. Berry et al. (1977) described the fresh fruit as one with an apple-like texture and an unusual flavour described as slightly apple-like, slightly pear-like with a tinge of pineapple. Both sweet and sour varieties of carambola are generally available. Joseph and Mendonca (1989) characterized sour varieties as those with a juice TSS (Total Soluble Solids) of 3.4 - 5 °Brix, TTA (Total Titratable Acidity) of 0.57 - 0.80% (expressed as oxalic acid) and a pH of 2.25 - 2.53. Sweet varieties had a juice TSS of 4.0 - 8.4 °Brix, TTA of 0.09 - 0.20% with a pH of 2.75 - 4.04. While there are a

few reports on the preservation of fresh carambola, there is little technical information on the processing of the fruit. Siddappa (1959) reported that carambolas which were candied in sugar solutions (initially at 33 °Brix and raised finally to 72 °Brix) and then air dried in the shade were of good quality. Berry et al. (1977) noted that air dried carambola had a pleasant, chewy texture, somewhat like a prune or raisin with a sweet-sour, unique aromatic flavour. Campbell and Campbell (1983) reported that both sliced and blended carambola, air dried at 60°C for 10, 12, and 24 hours, had excellent colour, texture, and flavour. Watson et al. (1988) noted that dried and sugared carambolas are prepared in China with the products being very acceptable.

In the Caribbean, small scale processors may use natural, open air, or solar assisted drying systems to prepare dried, candied carambola slices. Such simple drying systems, as described by Sankat and Rolle (1990) use natural convection for crop drying.

The objectives of this study therefore were to investigate the drying behaviour under natural convection conditions of fresh and candied carambola slices with a view to determining the factors which influence rates of drying.

MATERIALS AND METHODS

Drying of fresh fruit slices

Fruits at the mature green, colour break stage and of the sweet variety were washed and cut into transverse sections of 10, 20, 30, or 40 mm thickness. The average surface area of the freshly cut, star shaped sections was 1700 mm². It was expected that moisture loss in drying would occur principally from these cut surfaces rather than from the thick, waxy skin surrounding the fruit. Fruit sections of similar thickness were placed in single layers into pre-weighed wire baskets of 0.09 m² surface area. For 10 mm thick slices, 12 slices were used per tray, averaging 279 g initial mass, whereas for the 40 mm thick slices, six pieces were used per tray, averaging 392 g initial mass. After determining the initial masses of the baskets of fruits using an Ohaus Electronic Balance (Model #4000 GT-New Jersey) with a sensitivity of 0.1 g, the baskets of different fruit slices were placed in a Blue M, Stabil-Therm natural convection oven (Model #OV-18SA-Illinois) previously set at either 40, 50, 60, or 70°C. Assuming this to be a sensible heating process of ambient air (30°C, 75% RH), the corresponding initial relative humidity (RH) values of the heated air in the oven as determined from the psychro-metric

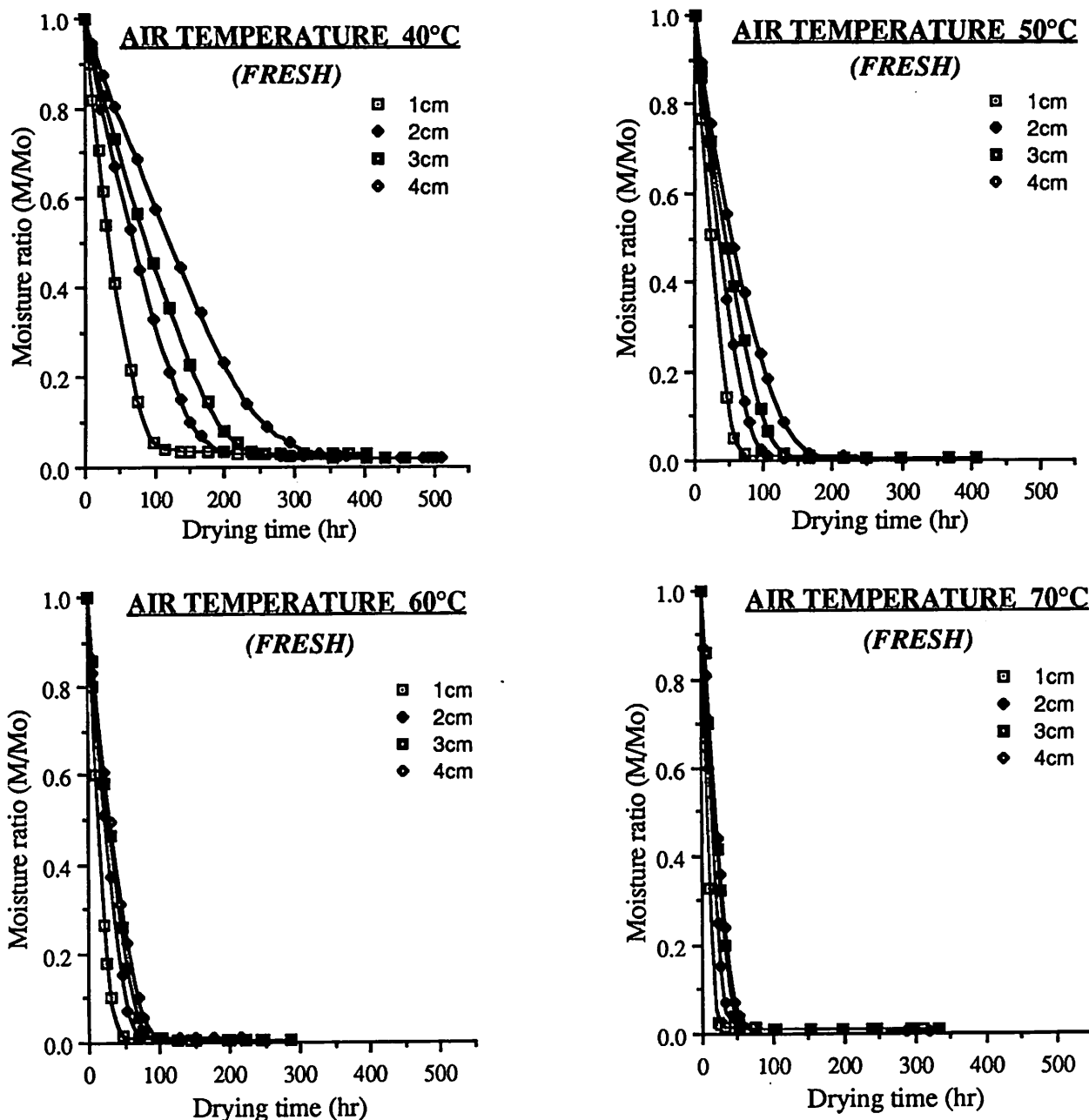


Fig. 1. Drying curves for fresh carambola slices at 40, 50, 60, and 70 °C.

chart were 43%, 22%, 17%, and 11% at 40°C, 50°C, 60°C, and 70°C, respectively. Baskets were weighed at 6 h intervals, approximately. Drying was allowed to progress until fruit and basket masses were constant. For 40 mm thick slices, total drying time ranged from 287 to 484 h at 70°C and 40°C, respectively. On completion of drying and on attaining equilibrium, the moisture contents of the dried samples were determined by the vacuum oven method (AOAC 1984) using a Cole Parmer Vacuum Oven (Model #6002, Cole Parmer Co., Philadelphia, PA). All moisture content determinations are given on a percent dry basis, except where otherwise noted i.e. $100 \times \text{kg H}_2\text{O}/(\text{kg DM})$ where DM is the dry matter content of the sample.

Candying of fruit slices

Before drying as previously described, fresh carambola slices were candied through a slow process, as described by CARIRI (1989). Cut slices of 10, 20, 30, or 40 mm thickness were initially immersed in a sugar solution of 30 °Brix. At two day intervals, the sugar solution strength, as measured by a refractometer, was increased by 10 °Brix, to a final 50 °Brix solution, and fruit sections were left to equilibrate for 4 days. After this time, fruit sections were removed, drained, and then dried in wire baskets by natural convection as previously described. Drying times ranged from 386 to 960 h at 70° and 40°C, respectively, for nominally 40 mm thick slices.

RESULTS AND DISCUSSION

Drying and drying rate curves

The mean moisture content of fresh fruit slices prior to candying or drying or both was 1270.0% dry basis (92.7% wet basis), while the TSS content was 7.5 °Brix. After the candying process, the TSS value of the osmotic dehydrated fruits increased to 49.1 °Brix, while the moisture content of such fruits decreased to an average value of 98.8% dry basis (49.7% wet basis). These fruits were then dried.

Drying curves for 10, 20, 30, and 40 mm thick fresh carambola slices and at 40, 50, 60, and 70°C are shown in Fig. 1.

Similar curves for candied fruit slices are shown in Fig. 2. In these curves the moisture ratio M/M_o is plotted against drying time:

where:

- M = variable moisture content (% dry basis),
- M_o = initial moisture content (% dry basis), and
- t = drying time (h).

These curves show that carambola slices dry very slowly under natural convection, particularly at 40°C. The moisture content of fresh and candied carambola slices at all four

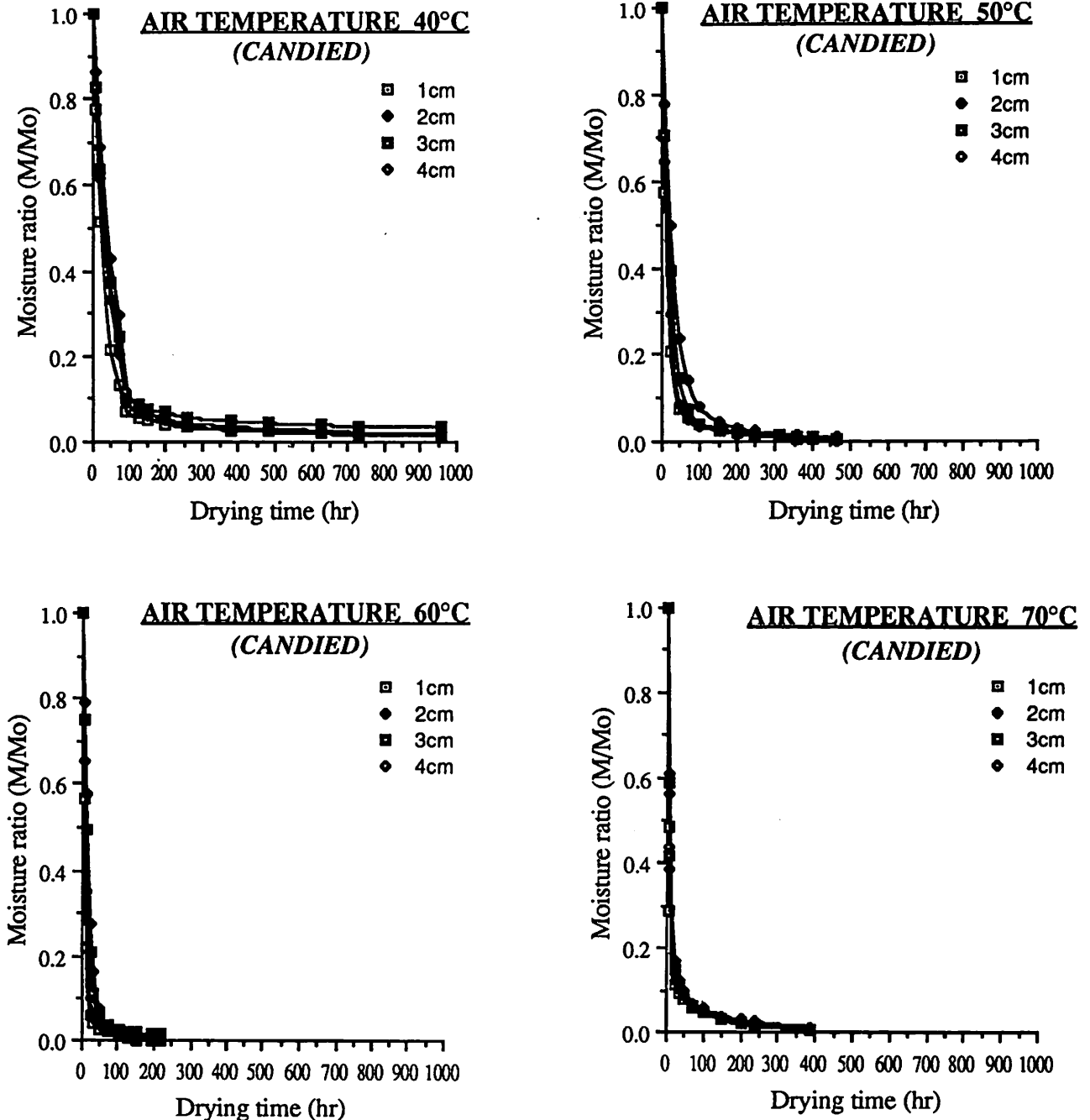


Fig. 2. Drying curves for candied carambola slices at 40, 50, 60, and 70 °C.

temperatures fall steadily to a value of $M/M_o < 0.05$, and then there is a marked levelling or very slow drying period, as the moisture content approaches equilibrium. As the drying air temperature is increased to 70°C, the drying curves become much steeper, indicating increased drying rates at the higher temperatures. As expected, the thinnest carambola slice (10 mm thick) dried most rapidly, with this effect being most noticeable at the lowest temperature, i.e. 40°C, and for fresh fruit slices.

The effects of drying air temperature and slice thickness on the drying rate of fresh and candied carambola slices are shown in Figs. 3 and 4, respectively. These figures, obtained from the slopes of the drying curves, show that as the moisture content is lowered in the drying process, the drying rate falls. The figures also demonstrate the effectiveness of increased air temperature on the improvement in the drying rate. For example, for 20 mm thick fresh slices, the initial drying rates (i.e. the rates at the very beginning of the drying process) were 0.15, 0.19, 0.28, and 0.42 kg H₂O/(kg DM•h) at 40, 50, 60 and 70°C respectively, while for candied fruits the corresponding values were 0.02, 0.05, 0.10 and 0.08 kg H₂O/(kg DM•h), respectively. It is apparent that the initial drying rates of fresh slices were 3-7 times greater than that of candied slices. This must be attributed to the initial moisture content of fresh carambola slices which was approximately twice that of the candied slices when compared on a wet basis, as well as to the barrier presented to moisture diffusion due to the sugar coating on the candied slices. As the thickness of the fresh and candied fruit slices increased from 10 mm to 40 mm, drying rates as observed in Figs. 3 and 4 decreased with the drying rate curves shifted downwards for each drying air temperature investigated.

An examination of Figs. 3 and 4 indicates that the drying of both fresh and candied carambola slices under natural convection occurs almost without exception in the falling rate period. This is a somewhat surprising result particularly for slices from the fresh fruit having a high moisture content and exposing a moist front to the drying air. It was thought that a constant rate of evaporation of water from this surface would prevail at least for some period of time. These results show that for both fresh and candied slices, that the rate at which moisture becomes available to the drying surface and

thus available for evaporation falls with time. The drying rate therefore appears to be internally controlled with diffusion being the moisture movement mechanism.

Modelling the drying behaviour

For drying in the falling rate period only and as used by Saravacos and Charm (1962) for fruit and vegetable dehydration, the simplified solution of the diffusion equation for a slab may be used:

$$\ln \left(\frac{M - M_e}{M_o - M_e} \right) = \left(\frac{-\pi^2 D t}{4L^2} \right) \quad (1)$$

where:

- M_e = equilibrium or asymptotic moisture content (% d.b.),
- D = coefficient of internal diffusion (m²/h), and
- L = half thickness of the slice (m).

The usual assumptions in this solution are: (1) the initial moisture distribution is uniform; (2) the diffusivity is constant, and (3) the resistance to moisture removal from the surface is negligible compared to the resistance to internal diffusion (Chirife 1971).

Henderson and Perry (1976) used the semi-empirical relationship to describe drying in the falling rate period:

$$\ln \left(\frac{M - M_e}{M_o - M_e} \right) = \ln A - Kt \quad (2)$$

where:

- K = drying constant (h⁻¹), and
- A = constant.

From Eqs. 1 and 2, the drying constant K is related to the diffusion coefficient by:

$$K = \left(\frac{\pi^2 D}{4L^2} \right) \quad (3)$$

Fresh fruit slices

An examination of the drying rate curves for the fresh fruit slices shows that the falling rate drying may be better de-

Table I: The effects of slice thickness and temperature on the presence of two drying rate constants (K) for fresh carambola slices dried under natural convection

Slice Thickness (mm)	Drying constant, K (h ⁻¹)															
	First falling rate K_1								Second falling rate K_2							
	Temperature (°C)								Temperature (°C)							
	40	r^*	50	r	60	r	70	r	40	r	50	r	60	r	70	r
10	0.034	0.97	0.066	0.96	0.103	0.96	0.170	0.98	0.018	0.98	0.022	1.00	0.024	0.99	0.012	1.00
20	0.016	0.98	0.043	0.95	0.064	0.95	0.100	0.99	0.031	1.00	0.018	0.96	0.022	0.97	0.012	1.00
30	0.010	0.99	0.044	0.91	0.047	0.96	0.083	0.96	0.026	0.99	0.012	0.96	0.035	0.96	0.015	0.99
40	0.007	0.99	0.025	0.95	0.047	0.94	0.073	0.98	0.025	1.00	0.022	0.94	0.029	0.99	0.014	1.00

* r is the correlation coefficient

scribed by two periods, a first and second falling rate period, separated by a critical moisture content M_c , after a drying time t_c has elapsed. This is illustrated in Fig. 5 for drying at 60°C and shows that for each slice thickness and under a particular drying condition, two drying constants K_1 and K_2 may be determined from regression analysis. Values of K_1 and K_2 and the correlation coefficients r which were obtained are given in Table I. The values of r obtained from the regression analyses using two falling rate periods were much better than if only a single falling rate period was considered. When using a single falling rate model, the calculated mean r value for each of the 16 lines (4 temperatures x 4 slice thicknesses) and as obtained from the regression analyses

was 0.95 with a range of 0.82 - 0.98. However, when two falling rate periods were used, the calculated mean r value (for $16 \times 2 = 32$ lines) was 0.97 with a range of 0.91 - 1.00, thus providing a better fit to the data.

An examination of Fig. 5 will show some non-linearity in the drying of the fresh carambola slices in the first falling rate period. This may be due to the nature of the material being dried and that the diffusion coefficient is not constant (Chirife 1971) as assumed in the theoretical solution of Eq. 1. Karathanos et al. (1990) stated that K may vary considerably with moisture content. The K values given can therefore be used to describe an average drying behaviour over the moisture content range investigated.

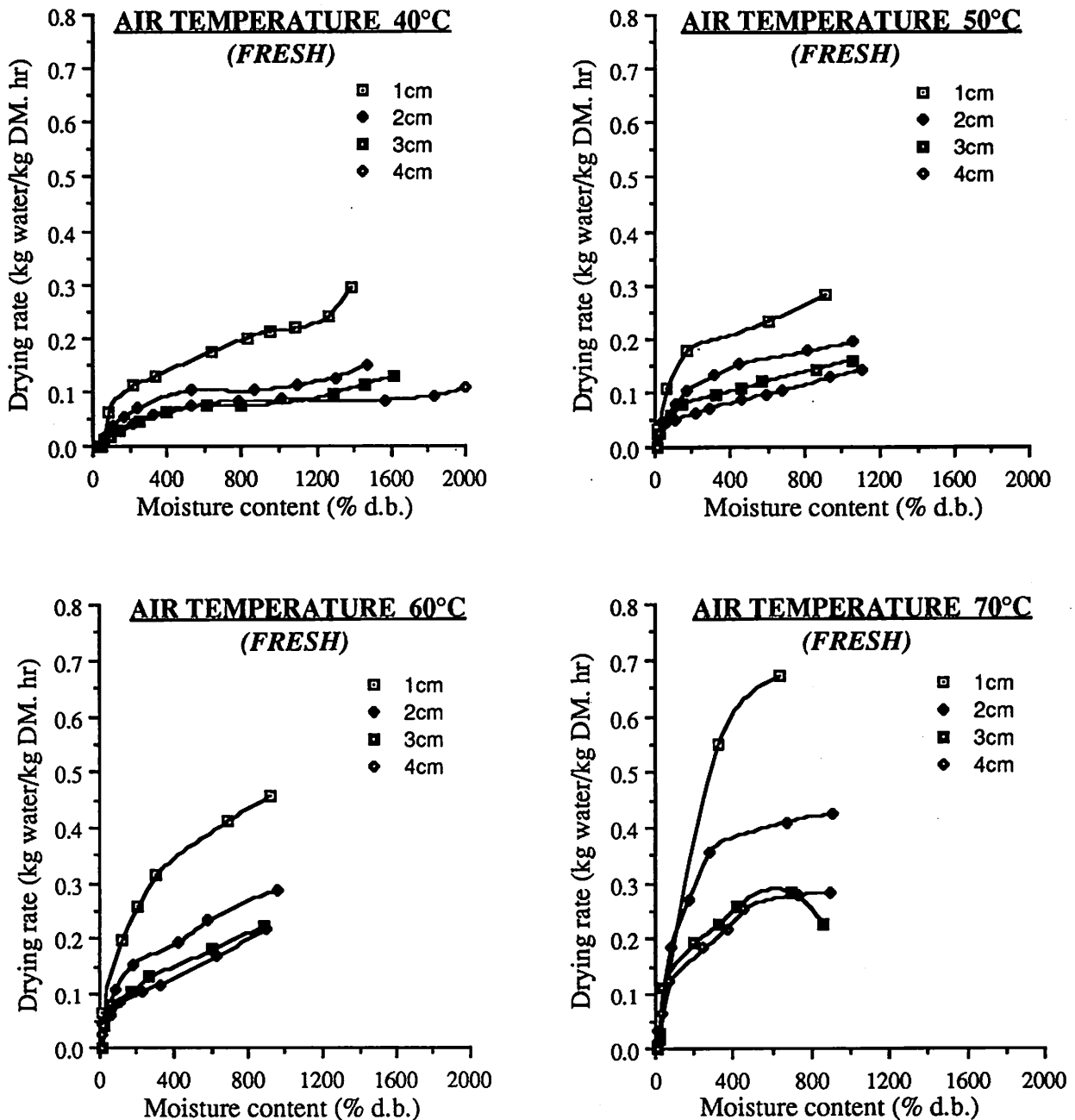


Fig. 3. Drying rate curves for fresh carambola slices at 40, 50, 60, and 70 °C.

These results for the drying of fresh fruit slices show that in the first falling rate period, the time when most of the drying occurs, the drying constant K_1 is very strongly influenced by the drying air temperature, T , and this increases exponentially with increases in the air temperatures as shown in Fig. 6, for each slice thickness. Since drying is diffusion controlled and temperature dependent with K_1 being directly related to D (Eq. 3), this behaviour is expected. A relationship of the form:

$$K = ae^{bT} \quad (4)$$

has been used (Nellist and O'Callaghan 1971) to relate K_1 to the drying air temperature, T . Values of a and b (constants) and r from a linear regression analysis carried out on the available data ($\ln K_1$ vs T) are given in Table II. Figure 6 also shows the influence of slice thickness on the drying constants with the trend being for such values to be lower as the slice thickness is increased.

In the second falling rate period, representing the final period of drying of fresh fruit slices, values of K_2 are expected to be much lower than K_1 , with the exception of

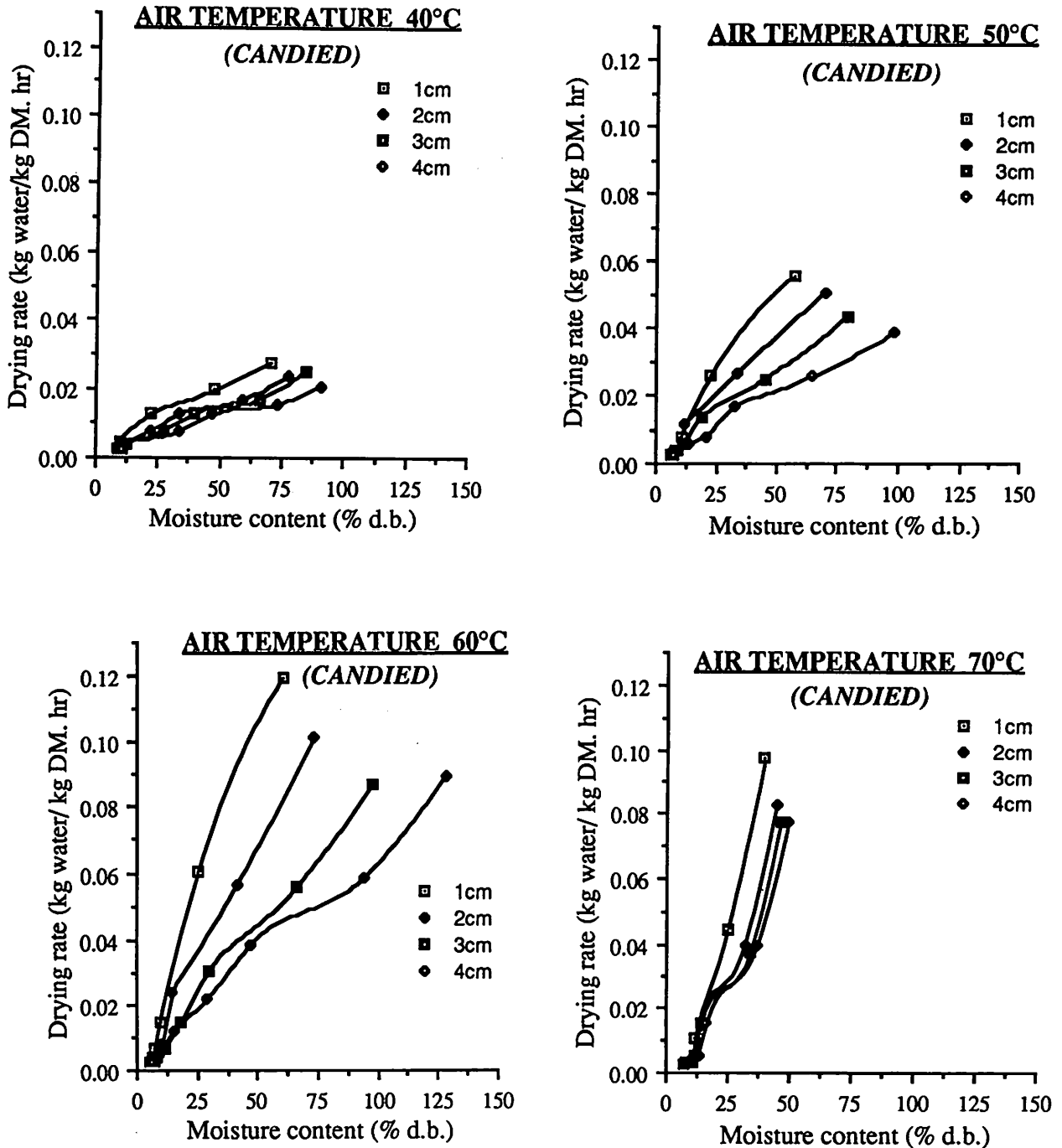


Fig. 4. Drying rate curves for candied carambola slices at 40, 50, 60, and 70 °C.

drying taking place at 40°C (Table I). The strong, positive influence of drying air temperature on the K values, as observed in the first falling rate period is also not observed. In fact, at 70°C, values of K_2 are the smallest compared to all the other temperatures. Two explanations are possible:

- (1) At 40°C, total drying time was as much as 21 days under natural convection and the drying time was therefore very slow, particularly in the 2nd falling rate period with a relatively high apparent equilibrium or asymptotic moisture content, averaging 40.9%. At this low temperature and slow rate of drying, it is quite possible therefore that there was some degree of dete-

rioration of the slices as a result of decay with a resultant loss in dry matter in this period, leading to a higher apparent K value.

- (2) As previously stated, at 70°C, the drying rate in the first period was the highest, and this could have resulted in case-hardening of the surfaces of the fruit slices, inhibiting further moisture removal, and hence the lowered K_2 values. Cruess (1958) noted that fruits case harden (searing over the surface) if the drying air relative humidity is so low and the temperature too high that the moisture is removed more rapidly from the surface than it diffuses from the interior of the fruit.

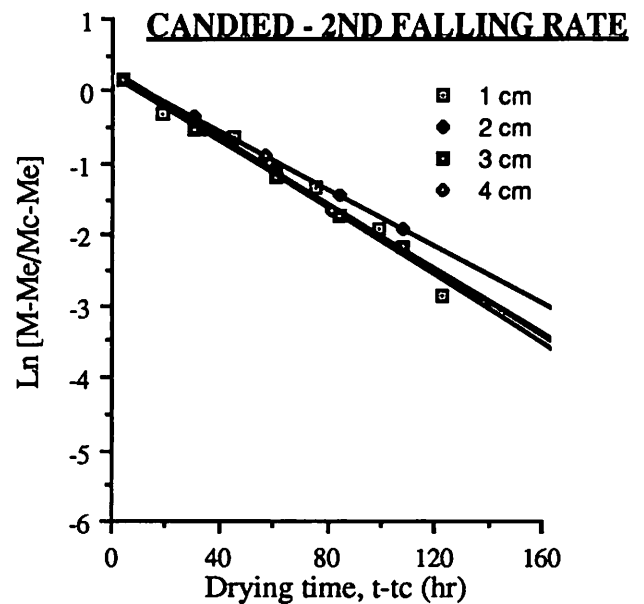
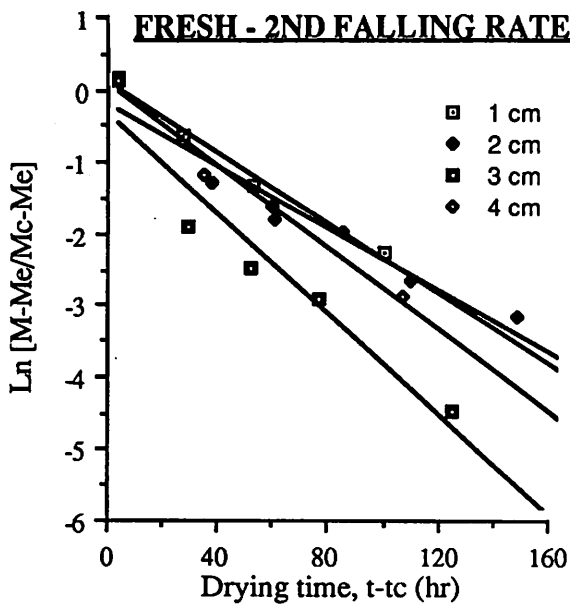
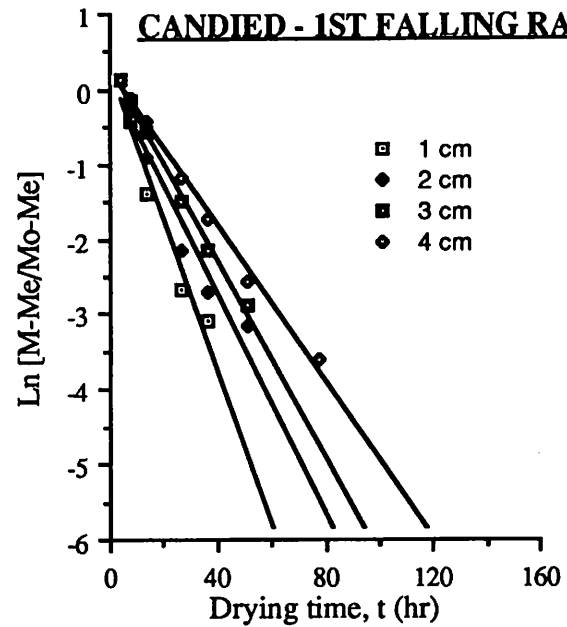
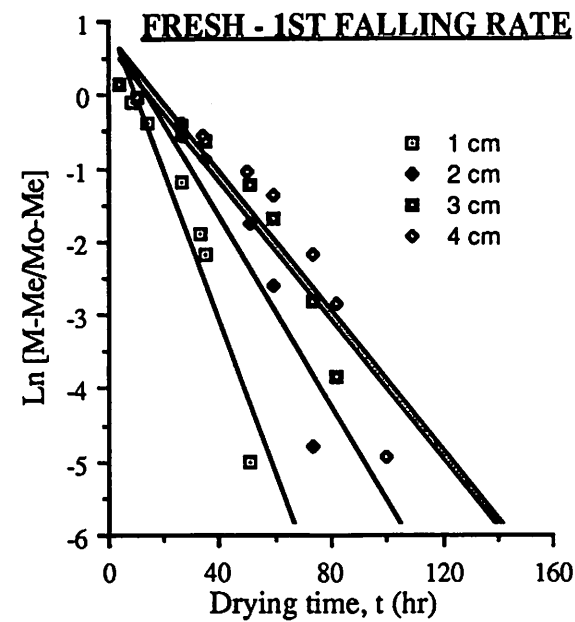


Fig. 5. First and second falling rate periods of drying at 60 °C for fresh and candied carambola slices.

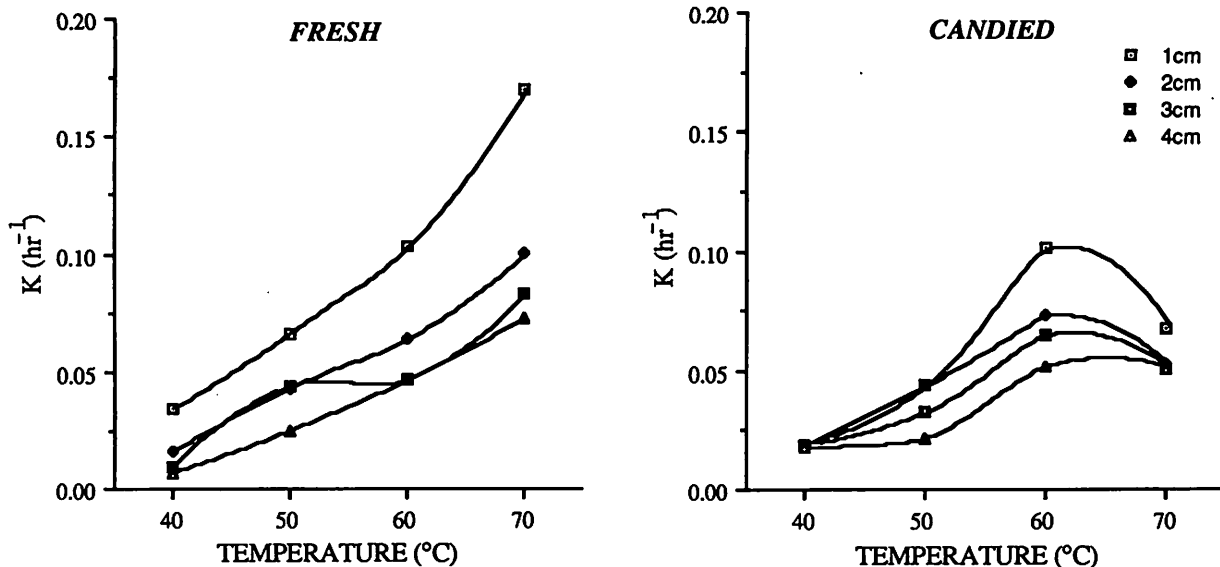


Fig. 6. The relationships between the drying constant K and drying air temperature T for fresh and candied carambola slices.

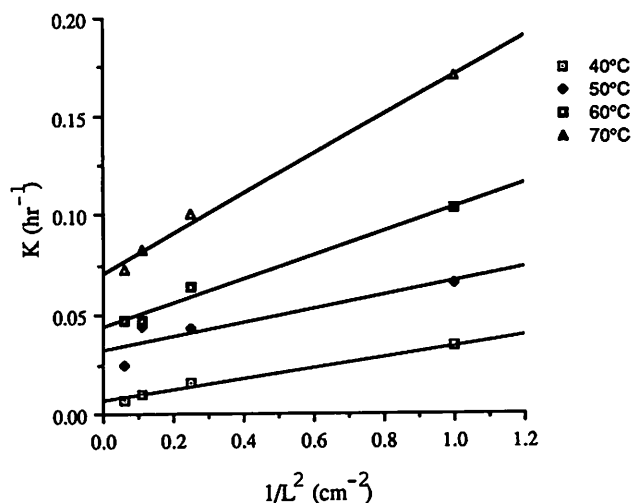


Fig. 7. The relationships between the drying constant K_1 and the thickness of fresh carambola slices.

Drying rates of the fresh fruit slices were clearly influenced by the slice thickness, and the drying constants in the first falling rate period were correspondingly affected. Values of K decreased (Fig. 6) as the slice thickness was increased. Figure 7 shows the variation of K_1 with $1/L^2$ at the four temperatures and as predicted by Eq. 3, a linear relationship is possible:

$$K_1 \propto \left(\frac{1}{L^2}\right) \quad (5)$$

where L = half the initial thickness of the fresh slice. While there was considerable shrinkage (50%) observed during drying, the initial thickness was used in Eq. 5 as this is the usual approach in the drying literature (Vaccarezza and Chirife 1975). It should also be noted that the shrinkage was

not always uniform or even being always greater at the centre than at the periphery of the slabs.

In the second falling rate period, values of K_2 were not consistently influenced by slice thickness, probably due to the considerable shrinkage of the fruit slices as drying progressed. At 70°C, slice thickness did not appear to influence K_2 , and this may again be explained by the case-hardening phenomena which inhibited drying.

Candied fruit slices

For candied carambola slices, the drying rate curves (Fig. 4) show that drying occurs exclusively in the falling rate period. In comparing the drying behaviour of candied and fresh carambola slices, it must be noted that the initial moisture content of the candied fruits was much lower than the fresh fruit slices, 98.8% and 1270%, respectively, on a dry matter basis. Also the initial sugar content, as given by TSS values, was much higher for the candied slices (49.1° Brix) compared to fresh slices (7.5° Brix). As with fresh fruit slices, first and second falling rate periods of drying were also established for the candied fruit, with this "two period" approach providing a better fit to the data than a single drying period. This is also illustrated in Fig. 5 with values of K_1 , K_2 , etc. for candied fruits given in Table III. It is noted, however, that the bulk of the drying and particularly that of commercial interest (m.c. > 10%) occurs in the first falling rate period.

Overall mean K_1 values for fresh and candied fruits were 0.057 h^{-1} and 0.045 h^{-1} , respectively, showing in general a marginally higher drying rate for the fresh fruit slices. Drying constants for candied slices in the first period were again strongly influenced by the air temperature as shown in Fig. 6, but it is noted that at 70°C, values of K_1 were noticeably lower than at 60°C. The exponential relationship of Eq. 4, which was valid for the fresh fruit slices, therefore cannot be applied to the candied slices over the temperature range of 40°C to 70°C. This may again be explained by case-harden-

Table II: The relationship between drying constant K and drying air temperature T ($K = a \exp(bT)$) for fresh carambola slices

Slice thickness (mm)	Constants		Correlation coefficient r
	a	b	
10	-3.854	0.527	1.00
20	-4.557	0.589	0.97
30	-4.922	0.641	0.92
40	-5.498	0.766	0.97

CONCLUSIONS

This study has shown that the drying of both fresh and candied carambola slices under natural convection occurs in the falling rate period. Two distinct drying periods were observed with most of the drying of practical interest occurring during the first falling rate period. During this period, drying of the fresh slices was strongly influenced by air temperature, T , and explained by an exponential relationship between the drying constant K_1 and T . For candied fruits, the values of K at 70°C were lower than at 60°C . This may be attributed to case-hardening of the slices containing high levels of sugar. A temperature of 60°C therefore appears to be the upper limit for candied carambola drying. As the thickness of the fresh fruit slice was reduced, drying rates increased and the 10 mm thick slices showed the highest

Table III: The effects of slice thickness and temperature on the presence of two drying rate constants (K) for candied carambola slices dried under natural convection

Slice Thickness (mm)	Drying constant, K (h^{-1})															
	First falling rate K_1							Second falling rate K_2								
	40		50		60		70		40		50		60		70	
	r^*	r	r	r	r	r	r	r	r	r	r	r	r	r	r	
10	0.019	0.95	0.044	0.97	0.101	0.98	0.068	0.95	0.004	0.98	0.010	0.98	0.024	0.99	0.010	1.00
20	0.019	0.96	0.044	0.99	0.073	0.98	0.052	0.95	0.006	0.96	0.009	0.99	0.020	1.00	0.010	1.00
30	0.019	0.97	0.033	0.99	0.065	1.00	0.051	0.96	0.004	1.00	0.010	1.00	0.022	1.00	0.009	0.99
40	0.018	0.98	0.022	0.98	0.052	1.00	0.051	0.96	0.005	0.99	0.012	0.98	0.023	0.99	0.009	0.99

* r is the correlation coefficient

ing of the candied fruit slices at 70°C . K_1 values for candied fruits at 70°C were therefore much lower than for similarly dried fresh fruit slices. Candied fruit slices dried at 70°C were dark brown in appearance and hard in texture. While there was a trend to higher K_1 values with reducing slice thickness, this trend was not as distinct as for fresh fruit slices. This may have been due to the considerable changes in the conformation of the slices in the candying (osmotic) process, i.e. physical changes of an uneven nature due to loss of moisture from the slices and the infusion of sugar into the slices resulting in net shrinkage and warping.

In the second falling rate period, K_2 values were as expected much lower than those of K_1 , with drying of candied slices occurring at very low moisture contents. Values of K_2 obtained for candied fruits were also noticeably smaller than similar values for fresh fruit slices. Again a hardening and toughening of the slices infused with sugar and as drying progressed to near completion, may account for this behaviour. K_2 values were also positively influenced by the drying air temperature, except again at 70°C , values declined compared to 60°C . As previously observed with fresh fruit slices, K_2 values appeared unaffected by slice thickness.

moisture removal rates. For the fresh slices, the drying constant K_1 was directly proportional to $1/L^2$. This trend was not as strong with candied fruit slices, due to the prior shrinkage of the slices occurring in the osmotic dehydration process. Drying of 10 mm thick fresh and candied fruit slices at 60°C appears desirable. These results are for natural convection and are applicable to solar drying, cabinet drying systems, practices used extensively in developing countries by small farmers or processors. Forced convection drying systems are equally important, particularly for large, commercial drying systems and the drying of carambola slices under such conditions also needs to be investigated. The findings of this study, however, indicate that the drying rate of carambola is internally controlled and air velocity may not have a very strong influence on drying rates.

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