EVALUATION OF A HYBRID DRYER FOR THE PRODUCTION OF APPLE CHIPS

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ABSTRACT

The paper highlights the design, development and evaluation of a hybrid convective-far-infrared (FIR) dehydrator for the purpose of drying fruit. The methodology followed is based on an experimental and practical approach. The application of the dryer for this study is aimed at the production of apple chips as well as other types of fruit chips and the more common dried fruit. The fruit dryer proposed uses both infrared energy and convective heating to effectively and efficiently dehydrate apple slices to produce dried apple chips. The apple chips are produced in very short time frames and accomplished by using relatively low heater power. These types of apple chip snacks also contribute to the more healthy variety of snacks available on the market.

Keywords: Hybrid dryer, infrared-convective dryer, fruit drying, apple chips

1. INTRODUCTION

The global trend in recent years is increasingly towards a healthier lifestyle. One of the more important aspects of this way of life is nutrition and diet. The main emphasis is generally on eating foods with a high nutritional value that has undergone minimal processing (McCallough *et al.*, 2003). Studies on the various effects that diet has on the physiological well-being of individuals abound in the literature (Kloranidou *et al.*, 2006; Conway *et al.*, 2002: Popkin *et al.*, 2001). Many food manufacturers in the snack market have begun investing in healthier alternative offerings (Thompson, 2006).

Commercially available snack products most often undergo a process of dehydration to make them suitable for storage and consumption. The dehydration of foodstuff is one of the oldest methods of food preservation and by the removal of the majority of water contained in the food, there is an increase in its shelf-life as well as a reduction of some undesirable reactions (Ibarz & Barbosa-Canovas, 2000). This is because the micro-organisms which cause food spoilage and decay are unable to grow and multiply in the absence of sufficient water and many of the enzymes which promote undesired changes in the chemical composition of the food cannot function without water. Water activity is a measure of free moisture in a food and is also a measure of the availability of water to participate in undesirable chemical reactions. For the production of apple chips it is necessary to effect the removal of the enclosed water to a level below that of its water activity.

One of the most common methods for the drying of agricultural products in developing countries is through the use of solar energy. Solar or sun drying is viable on a large scale in tropical areas but has limitations; such as being weather dependant, contamination of the product by insects and dust and is also not an easily controllable process. In the developed world however, drying by means of electrical methods is more common, such as hot-air or forced convective drying (Vega *et al.*, 2007; Kingsley *et al.,*2007; Baini & Langrish, 2007), microwave radiation (Varith *et al.*, 2007) and infrared radiation (Sharma *et al.*, 2005).

Nomenclature

M	final moisture content (g water/g solid)
M_O	initial moisture content (g water/g solid)
MR	moisture ratio
$m.c.(w.b.)$	moisture content, % wet matter
$m.c.(d.b.)$	moisture content, % dry matter
L	loading density (kg/m³)
A_d	total drying area (m²)
λ	latent heat of vaporisation (kJ/kg)
F	utilized capacity of heat source (kW)
t	drying time (h)

Much research has been done in various aspects of fruit drying by means of either infrared radiation, convective or a combination of convection and infrared drying. The most common method of drying agricultural products is by means of convective drying. Hot air is passed over the product at varying temperatures and air velocities. The modeling of the drying of many different types of fruit and vegetables by means of infrared heating is well documented in the literature. When infrared energy is used to heat or dry a moist substance, the radiation impinges upon the exposed substance, penetrates it and the energy of radiation converts into heat (Hebbar & Rostagi, 2001). In the thin-layer drying of agricultural substances the dehydration is achieved through the drying of the substance in a single monotonic layer in a dryer.

Infrared drying has been investigated as a potential method for obtaining high quality dried foodstuffs, including fruits, vegetables and grains (Abe & Afzal, 1997; Afzal & Abe, 1999; Zhu *et al.*, 2002). The drying of apple slices by infrared heating was evaluated and models developed which best describe the physical process (Togrul, 2005). The theoretical drying models reviewed include the Newton, Page, Modified Page, Wang and Singh, Henderson and Pabis and the Midilli drying equations amongst others. These theoretical drying models predict the drying kinetics of the material undergoing drying and can be of use to industry professionals designing drying equipment for foodstuff. Infrared drying of apples was compared with convective drying alone and the results conclude that with the inclusion of infrared energy, the drying time is shortened by half (Nowak & Lewicki, 2004).

In the drying of onion slices with an infrared radiation dryer the drying rate increased with an increase in infrared power at a given air temperature and air velocity and consequently reduced the drying time (Sharma *et al.,* 2005). The drying rate was doubled when subjecting carrot to infrared drying, as the drying temperature was increased from 50˚C to 80˚C (Togrul, 2006). With the application of far-infrared radiation (FIR) drying to the paddy drying process it was shown that FIR radiation was very effective in moisture reduction of wet paddy and the temperature inside a paddy grain also increased with FIR intensity level (Meeso *et al.*, 2007).

The combined mode of heat transfer incorporating infrared radiation and forced convection drying has been reported. In the drying of apple pomace with the incorporation of forced convection as a method of pre-drying, the drying time was reduced giving a time saving of 20% for a process without convective pre-drying (Sun *et al.*, 2007). For the drying of carrot and potato the performance evaluation studies revealed that the combination drying reduced the drying time by 48%, consumed less energy in the process requiring only 63% and the energy utilisation efficiency of the dryer was estimated to be 38% (Umesh Hebbar *et al.,* 2004). In the study on the numerical modeling of the hygrothermal behaviour of a rectangular-shaped porous material during combined drying, it was shown that when compared with convective drying alone there is a rapid superficial drying with some materials drying in less than 30 minutes (Salagnac *et al.*, 2004). The drying time also decreased in the thin layer drying of onion slices under infrared and convective drying (Jain & Pathare, 2004).

The purpose of this paper is to highlight the development of a hybrid convective-far-infrared batch-type dryer for fruit. An overview of the theory of fruit drying is explored, as well as a brief overview of the theory of drying, and the drying kinetics curves including the results of drying tests performed in order to evaluate the dryer are presented. The dryer developed, although only tested using apple slices, is designed to be adaptable for a range of agricultural products requiring drying to various final moisture contents.

2. DRYING THEORY OVERVIEW

2.1 Types of water found in food

The absorption of water by an organic, chemically inert material is a complex process which is not entirely understood. This complexity becomes much greater when biological materials are involved. This complexity is due principally to the fact that water may be present in several different forms (Earle & Earle, 1983).

2.1.1 Water of hydration

This moisture is chemically bound to the constituents of the material and in most cases would not be considered in moisture content determinations. It is considered to be an integral part of the material.

2.1.2 Bound water

Water which is in some way bound to the food so that it exerts a vapour pressure less than that of pure water. Can be bound by dissolved substances (osmotic pressure, suction), chemical bonding (this is not very important in food systems), by the action of capillaries and hydrogen bridges, van der Waals forces and ionic and polar bonds. It can often be thought of as the first layer of water molecules attached to a surface.

2.1.3 Free water

Free water is water which is bound by such minute forces that its vapourpressure is equal to the vapour pressure of pure water. It can be found as free water in cavities and wide capillaries. This can often be thought of as the second and subsequent layers of moisture attached to a surface. The heat of adsorption of this moisture is equal to the normal heat of vaporisation of water at the same temperature.

2.1.4 Absorbed moisture

This is moisture that has passed through cell walls and entered the cytoplasm of the cell. It is this form of water that is believed to account for the hysteresis between the sorption and desorption equilibrium moisture content isotherms.

2.2 MECHANISM OF DRYING

During drying it is necessary to remove free moisture from the surface and also moisture from the interior of the material. During drying, heat is transferred to the surface, and the latent heat of vaporisation causes water to evaporate. Water vapour diffuses through a boundary film of air and is carried away by the moving air. This creates a region of lower water vapour pressure at the surface of the food, and a water vapour pressure gradient is established from the moist interior of the food to the dry air. This gradient provides the driving force for the removal of water from the food. Water moves to the surface by the following mechanisms:

- liquid movement by capillary forces;
- diffusion of liquids, caused by differences in the concentration of solutes indifferent regions of the foods;
- diffusion of liquids which are adsorbed in layers at the surfaces of solid

components of the food; and

- water vapour diffusion in air spaces within the food caused by vapour pressure gradients.

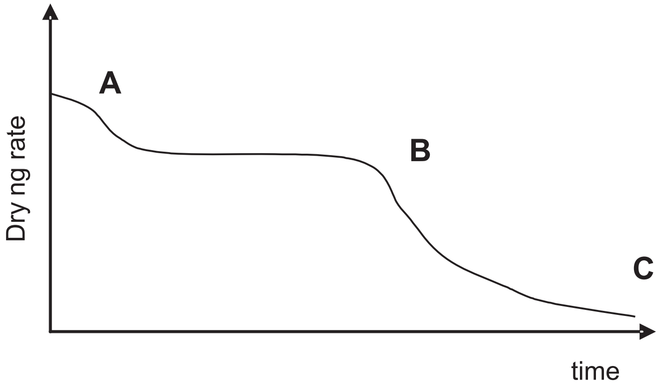

Figure 1: Typical drying curve

The drying rates for different foods will have a wide range of variation, but atypical curve is shown in Figure 1. When the food is placed inside the drier, there is a short settling down period as the surface heats up to the wet bulb temperature (region A). Drying then commences along AB, and provided that water moves from the interior of the food material at the same rate as it evaporates from the surface, the surface remains wet. This period is known as the constant rate period, as can be seen from the drying curve: this is because drying occurs over a constant rate over the period A to B. The constant rate period continues until the critical moisture content is reached. At this point drying enters what is known as the falling rate period (region B to C).

Food systems however, present many challenges, as in practice different areas of the surface of the food will dry out at different rates and overall the rate of drying declines gradually during the 'constant rate period'. In some cases it is accepted that the constant rate period does not exist. Thus the critical point is not fixed for a given food and depends on the amount of food in the drier and the rate of drying. The three characteristics of air that are necessary for successful drying in the constant rate period are: a moderately high dry bulb temperature; a low relative humidity; and a high air velocity.

The boundary film of air surrounding the food acts as a barrier to the transfer of both heat and water vapour during drying. The thickness of the film is determined primarily by air velocity. If this is too low, water vapour leaves the surface of the food and increases the humidity of the surrounding air, to cause a reduction in the water vapour pressure gradient and the rate of drying.

3. MATERIAL AND METHODS

3.1 The experimental dryer

The dryer designed and developed for this study is based on a hybrid design that incorporates the use of infrared radiation and forced convection heating. The design is based on a batch-type dryer with a removable tray. The types of infrared heaters used are the far-infrared ceramic type and are arranged in a heater bank inside the dryer cavity directly above the tray. The distance from the FIR heater bank to the tray is fixed at 24cm. Figure 2 illustrates the constructed experimental hybrid FIR-convective dryer developed. The convective heater is a separate metal-sheath type in conjunction with a fan, positioned at the rear of the unit. The installed electrical power capacity of the infrared heaters is 16 x 400 watt heaters and 1 x 2500 watt convective heater. The total installed electrical power capacity of the hybrid dryer is approximately 9 kilowatts. The dryer cavity is not heat insulated and is not enclosed by an access door.

Figure 2: Experimental hybrid IR-convective dryer

3.2 The experiments

Apples (Golden Delicious) were purchased from a local fresh produce market and allowed to acclimatise in a refrigerator to 4°C for approximately two hours. Apples of similar size and mass were sliced into widths of between 4 mm and 6 mm and the widths were measured and verified using vernier callipers. The slices of similar size were arranged on the tray, completely filling it, and placed inside the dryer. The experiments were conducted in triplicate and in order to obtain the drying kinetics data, periodic sampling or weighing of a sample in each experiment was adopted. The complete batch of apple slices per experiment was approximately 280 grams. Individual samples were intermittently removed from the dryer at fixed time intervals and weighed on an electronic mass balance with a resolution of 0.01g. In order to prevent enzymatic browning and prolong shelf life it is common practice for the commercialisation of dried fruit to treat it with either a solution of lemon juice or citric acid; however the apple slices used in these experiments were untreated.

The dryer was preheated to the specifications as indicated in Table 1 below.

Table 1: Dryer specifications

Experiment	Air velocity, average (m/s)	Air temperature, average (°C)	FIR Heater input voltage (V)	FIR Heater percentage total power (%)
1	0.4	60	80	12
2	0.4	60	100	19
3	0.4	60	120	27

The air velocity and air temperature were kept constant throughout and only the infrared heater parameters were modified. The initial relative humidity was measured at between 40 and 45% throughout each of the experiments. The final relative humidity was not determined.

The initial moisture content of the apples was not determined intrinsically. Instead the value was estimated based on available data. Percentage moisture content (wet basis) is derived from the following relation:

$$m.c.(w.b) = \left(M_O - M \big/ M_O \right) * 100 \qquad (1)$$

According to Earle and Earle (1983), the moisture content of apple was measured as 84% w.b. and in another study, Sacilik and Elicin (2006) determined the value to be approximately 82% w.b. For the purposes of the present study the moisture content of the apple slices used was estimated to be approximately 80% w.b.

However, the moisture content based on the dry weight basis is used in the calculations and the drying kinetics curves plotted from the experimental data obtained. Percentage moisture content (dry basis) is given by the formula:

$$m.c.(d.b) = \left(M_O - M \big/ M \right) * 100 \qquad (2)$$

A further quantity of interest in drying is the moisture ratio (MR), a dimensionless quantity, described as a ratio that compares the mass or volume of air to the mass or volume of moisture contained in that air and is expressed as the following:

$$MR = \left(M \big/ M_O \right) \qquad (3)$$

In infrared drying the sample may be dried as much as dried matter content (Togrul, 2005). The material dried in the hybrid dryer was subjected to infrared radiation intensities as indicated in Table 2 below.

Table 2: Hybrid dryer radiation intensities

Infrared heater voltage (V)	Radiation intensity (kW/m²)
80 100 120	2.47 3.87 5.57

4. RESULTS AND DISCUSSION

The results of the drying experiments performed with the hybrid dryer indicate that the drying of the apple slices occurred exclusively in the falling-rate period. There was no part of the drying happening in the constant-rate period. An indication of the mass variation of each of the samples over time in the drying experiments performed is shown in Figure 3.

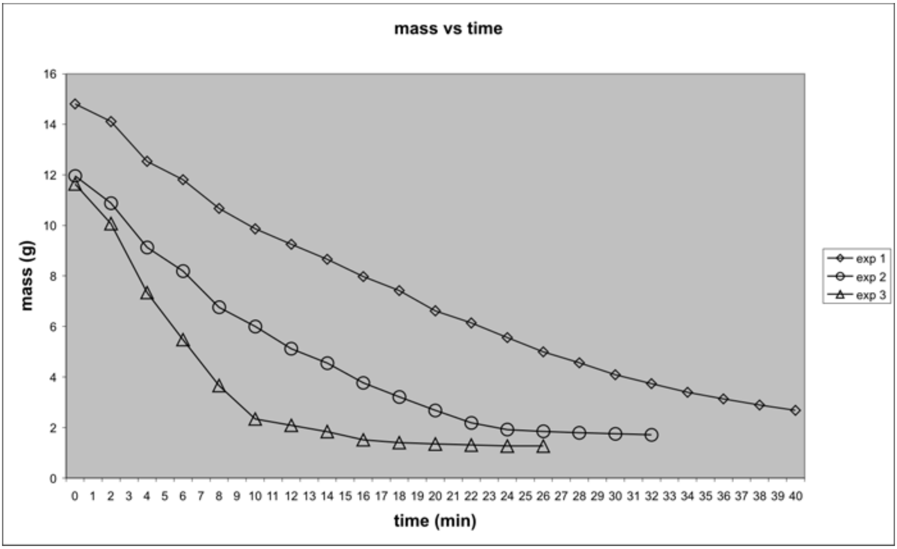

Figure 3: Mass of samples vs. time

Each of the samples tended towards a constant mass the end of the experiments. This steady mass is an indication that the final moisture content was reached and that most of the moisture present in the samples was removed. Further drying is possible but the samples are in jeopardy of being burnt and damaged. The variation of the moisture content (d.w.b) of each of the samples is given in Figure 4. Analysis of the curves indicates that the higher the infrared heater power (experiment 3) the quicker the drying occurs even with a sample having of higher initial moisture content. The gradient of the drying curve is initially very steep. Consequently drying at lower infrared heater temperature shows a longer drying time and has a gradual decreasing slope. Of interest here is whether such steep temperature gradients have an adverse effect on the agricultural product being dried, to such an extent that this results in undesirable effects on the quality of the product, taste, texture, colour and nutritional content. These studies are the subject of further research that incorporate the hybrid dryer.

Figure 4 provides evidence of the drying of the apple slices occurring only in the falling-rate period. The drying time takes place in a range from approximately 26 minutes (27% infrared power) to 40 minutes (12% infrared power). The drying experiments were performed until a moisture content (w.b.) of approximately 15% was reached. Although the drying was allowed to continue until a final moisture content of less than 10% was reached, many of the samples had turned brown and showed signs of damage and spoilage at this point. Therefore, although apple slices can be dried to lower and lower final moisture contents, the agricultural product is not always able to withstand the strong temperature gradients and vapour pressures exerted on it and consequently the samples can be completely denatured and ruined as a commercially viable product.

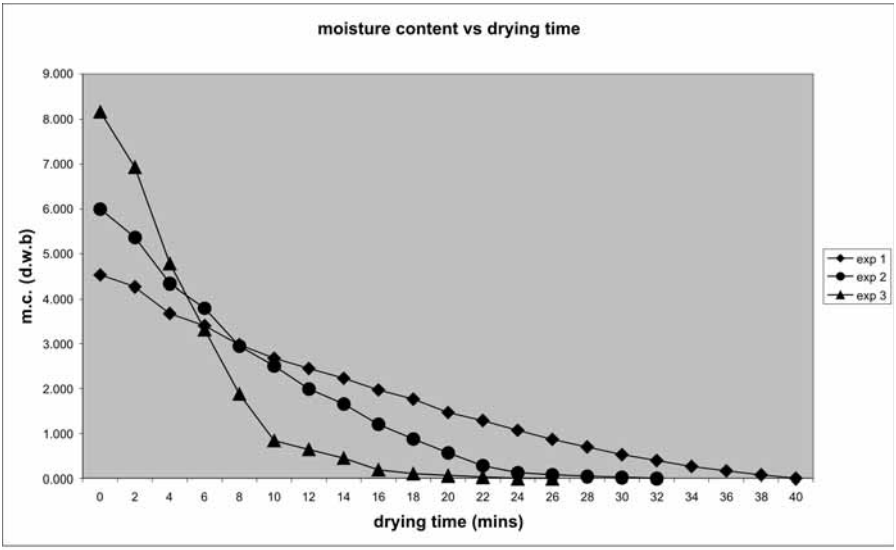

Figure 4: Moisture content vs. time

An important quantity in the evaluation of the effectiveness of a dryer design is the variation of moisture ratio, which is derived from the experimental moisture content data, versus drying time. The deviation of moisture ratio with drying time for the samples is indicated in Figure 5. The variation of the drying rate with drying time is shown in Figure 6. These curves reveal the faster drying achieved with the higher infrared heater power. However, the risk at a higher infrared power is the possible damage to the fruit that could result.

Careful control mechanisms need to be implemented in order to prevent this from occurring. This could be in the form of a control action, which varies the infrared heater power in comparison to measurements of either moisture contents, colour recognition of the fruit surface or a time factor.

An evaluation of the combined infrared and convective hybrid dryer efficiency is derived and expressed as the heat utilisation efficiency (η) and given by the formula:

$$\eta = {LA_d \lambda (M_O - M)} \Big/ {Ft(100 - M_O)} \qquad (4)$$

Nominal values derived from the drying process are indicated in Table 3. The high values indicated in Table 3 are possible because relatively small batches of apple slice samples were loaded into the dryer. Previous values for heat utilisation efficiencies were found to be of the order of 36% and 39% for the combined infrared and hot air drying of vegetables (Umesh Hebbar et al., 2004).

The dryer is capable of being modified to incorporate air recirculation to possibly further increase the drying efficiency. Figure 7 provides a thermal image of the drying temperatures (deg C) present on an apple slice and near the dryer interior during a drying cycle. An indication of the quality of the dried apple slices achieved with the use of the hybrid dryer is shown in Figure 8. Figure 9 further indicates the result of drying apple samples to lower and lower moisture contents with the consequence of browning and spoiling the final dried product.

Table 3: Values of heat utilisation efficiency per drying experiment

Experiment	Heat utilisation efficiency (%)
1	62
2	55
3	48

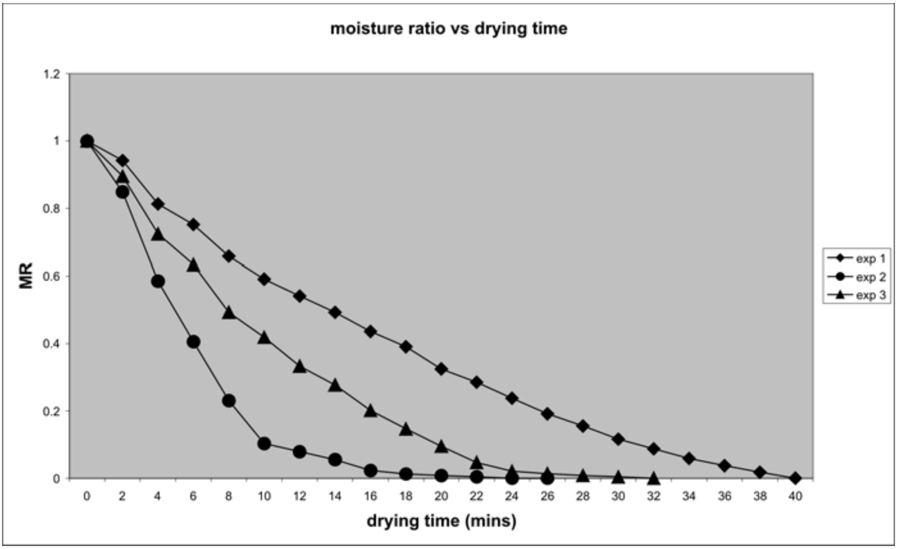

Figure 5: Moisture ratio vs. time

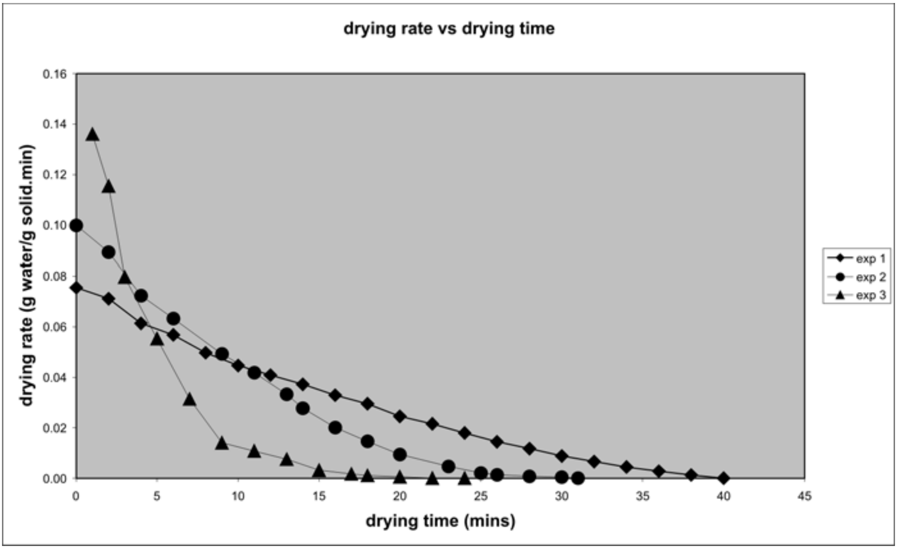

Figure 6: Drying rate vs. drying time

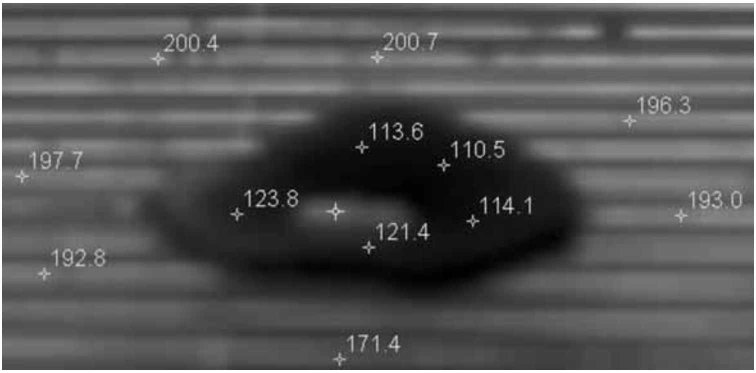

Figure 7: Thermal image of apple slice being dried

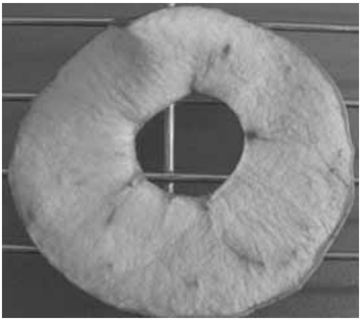

Figure 8. Sample of dried apple slice

Figure 9: The result of drying samples to lower moisture contents

5. CONCLUSION

The hybrid infrared convective dryer presented is able to dehydrate apple slice samples from an initial moisture content of 80% to final moisture content of 15% and lower. Small batches of untreated apple slices were dried in relatively short drying times and at moderately high dryer efficiencies. The results obtained from the experiments using the dryer show some promise and further refinement of the techniques involved should produce a fully commercially viable artifact. Modifications of the device for a range of agricultural products would extend the usefulness of this apparatus in the dehydration of fruits and vegetables and such a device could be of value to producers in the snack market.

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