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Note: APETT's logo was designed by Derek Aleong.

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Editorial

I. Notes from the Editor

The APETT Journal aims to provide a broad coverage of subjects relating to engineering. Preference will be given to papers describing original engineering work, or material of specific interest to engineers and those working in related fields, in Trinidad and Tobago and the Caribbean region.

This issue also includes an announcement and a Call for Papers for the Fourth Industrial Engineering and Management Conference 2018 (IEM4-2018) that is to be hosted at the Faculty of Engineering, The University of the West Indies on 7th-8th December 2018. With the theme on "Striving for business/engineering performance excellence with quality management and IEM practices", the Conference IEM4-2018 invites papers for presentation, and suggested topics of interests fall into two groups of 1) Traditional Industrial Engineering areas and 2) with Quality Management focus. For Enquiries and Registration, contact Professor Kit Fai Pun or Dr. Cilla T. Benjamin, c/o Faculty of Engineering, UWI, St Augustine Campus, Trinidad and Tobago, e-mails: KitFai.Pun@sta.uwi.edu; Cilla.Benjamin@sta.uwi.edu

II. About This Issue

This Issue (Volume 46 Number 1) of the Journal includes six (6) articles and a memorial written for the late Emeritus Professor Harry Phelps who was the past President of APETT, 1975-1976. The relevance and usefulness of these articles are summarised below.

O.O.E. Ajibola et al, "Development of Sport Utility Vest that Captures Cardiographic Data and Its Relationship to Arterial Pressure in Real Time", present the development of a sport utility vest that utilises closed circuit system. The system would monitor the cardiovascular activities of an athlete with the capability to report same to a third party device in real time. A continuous monitoring of physiological signals from the heart is the most efficient way of tracking the heart status of athletes who are prone to cardiovascular diseases without prior symptoms. In this paper, the authors demonstrate the possibility of remote acquisition, display, and storage of the heart rate of an athlete in real time using an electrocardiogram system designed on a sport wear. The entire system is comprised of three Lead electrodes, arranged at strategic parts of the sport vest; the electronic circuit which amplifies the data signals and filters to enhance minimum noise to signal ratio; and the transceiver which sends and receives signal through a wireless Radio Frequency linked to a third-party device such as Personal Computer. This system also presents a warning alarm in case the heartbeat goes beyond the pre-set threshold, which allows a great opportunity for rapid intervention by a physician.

Based on their work, "Development, Evaluation and Soot Formation Characteristics of a Low-cost Pressurised Kerosene Stove", **F.O. Anafi, et al.** investigate into the combustion of kerosene fuel in poorly designed cook stoves as a major domestic source of poor indoor air quality in the developing world. They present the design of the pressurised kerosene stove focused on the provision of sizable and adjustable air inlet to ensure availability of sufficient air for complete combustion of the kerosene fuel as well as regulating the flame. Performance test results showed that the pressurised kerosene stove generated more heat and also produced less carbon soot than the conventional kerosene stove (wick stove). The thermal efficiency of the pressurised kerosene stove is higher when compared with the thermal efficiency of the baseline kerosene wick stove. The fuel burns with a blue flame and less smoke with very little soot at the pot base. This was affirmed by the emission test carried out.

A.A. Akinola et al., "Kinetics of the Dehydration of Cucumber Slices with a Refractance Window™ Dryer", investigate into the variation of the rehydration ratio of the cucumber slices with rehydration time using the dryer. It was found that the cucumber slices dried to a moisture content of less than 10% (dry basis) in about 120 minutes. The regression analysis results showed that the Haghi and Ghanadzadeh thin-layer drying model best describes the drying behaviour of the 3 mm thick slices with a coefficient of determination (R^2) value of 0.9994. The rehydration ratio of the cucumber samples varied from 3.47 to 5.25 with rehydration times of 10 to 300 minutes respectively. The effective moisture diffusivity of the 3 mm thick cucumber slices was determined. The implications of the work are that the Refractance Window^{TM} (RW) drying technique will dry cucumber slices at a faster rate than the traditional methods and the drying data obtained can be used in the design of an industrial scale RW dryer.

In their paper, "Temperature Dependence of the Effective Moisture Diffusivity of Yam (*Dioscorea rotundata*) Slices Dried Using a Refractance Window^{TM} Dryer", **A.A. Akinolaa et al.**, further present the dependence of the effective moisture diffusivity of yam slices on temperature using the dryer. The experimental drying data obtained was used to estimate the moisture diffusivities, and the activation energy for the process conditions considered. The effective moisture diffusivities was estimated using Fick's second law for 4.5 mm thick yam slices for the temperatures studied. The activation energy was estimated using the Arrhenius type equation for the given temperature range. Results show that the effective moisture diffusivities values are slightly higher than those reported in the literature because the investigations were performed at higher temperatures than those found in the literature. Higher moisture diffusivities imply that there is higher moisture movement through the interstices of the slices, which in turn indicates a higher rate of drying.

E.I. Ekwue et al., "A Wet Sieving Apparatus for Determining Aggregate Stability of Soils", describe the design, construction and testing of an apparatus that is used to wet sieve soil aggregates and determine their stability to water disruption. Seven soils were used to test this equipment, each at three frequencies of sieving. Aggregate stability measured with this equipment was expressed using percentage water stable aggregates (WSA) and mean weight diameter (MWD). The major advantage of the constructed soil wet sieving apparatus is that two stacks of sieves are incorporated into the design, cutting by almost half, the normal time required for wet sieving using the original design of the equipment which utilised a single sieve stack. The frequency of oscillation of the sieves did not significantly affect the aggregate stability of most of the soils, apart from the sandy loam and one clay soil, where the effect was minimal.

D. Maharaj and K.F. Pun, "Managing Supply Chain Risk in a Petrochemical Firm in Trinidad and Tobago: A Case Study", explore the risk associated with managing the supply chain in the petrochemical firms in Trinidad and Tobago (T&T). Empirical data was acquired and analysed via interviews and surveys conducted in a case company. It was found that one susceptible challenge was operations vulnerability associated with late delivery of material and poor contractor performance. Incorporated the desk research with empirical findings, a structured SCRM (Supply Chain Risk Management) approach comprising of a host of principle, philosophical and procedural elements, was initiated. An implementation agenda was developed along with record of the SCRM adoption at the company. The findings would contribute towards the field of SCRM applications and provide some insights for synthesising emergent issues for future research.

G.S. Shrivastava and C.A.C. Imbert, "Professor Emeritus Harry Orville Phelps (1929-2018): A Memorial", speak about both academic and profession life, and recognise the commitments and contributions of late Professor Emeritus Harry Orville Phelps towards the development of civil engineering disciplines and professional in Trinidad and Tobago and the wider Caribbean region. Professor Emeritus Phelps, being the past President of the APETT (1975-1976) and Head of Department of Civil Engineering (1972-1984) of The University of the West Indies, will live in the memory of his students and colleagues.

III. Acknowledgements

On behalf of the Association, we gratefully acknowledge all authors who have made this issue possible with their research work. We greatly appreciate the voluntary contributions and unfailing support that our reviewers give to the Journal. Our reviewer panel is composed of academia, scientists, and practising engineers and professionals from industry as listed below:

- **Dr. Albert H.C. Tsang**; The Polytechnic University of Hong Kong
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Finally, the views expressed in articles are those of the authors. This does not necessarily reflect the opinions or policy of the Association.

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Kinetics of the Dehydration of Cucumber Slices with a Refractance Window™ Dryer

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Abstract: *Cucumber (Cucumis sativus) slices, 3 mm thick, were dried in a laboratory scale batch* Refractance Window[TM] *dryer. To construct the dryer, a laboratory water bath was modified by covering the bath with a transparent polyethylene terephthalate (PET) plastic film. A water temperature of 60°C was maintained beneath the plastic film. The variation of the moisture content of the cucumber slices was measured during the drying process. Using the experimental data, the drying curve, the drying rate curve, and the Krischer curve, were plotted. The thin-layer mathematical drying model that best describes the drying kinetics of the drying data was determined. The variation of the rehydration ratio of the cucumber slices with rehydration time was determined. The effective moisture diffusivity of the 3 mm thick cucumber slices was also determined. Observations indicate that the cucumber slices dried to a moisture content of less than 10% (dry basis) in about 120 minutes. The regression analysis results showed that from the 17 models studied, the Haghi and Ghanadzadeh thin-layer drying model best describes the drying behaviour of the 3 mm thick slices with a coefficient of determination (R^2) value of 0.9994. The rehydration ratio of the cucumber samples varied from 3.47 to 5.25 with rehydration times of 10 to 300 minutes respectively. The moisture content after 300 minutes of rehydration was about 1150% dry basis (92% wet basis). The effective moisture diffusivity of the 3 mm thick cucumber slices was determined to be 7.30×10^{-10} m²/s. The implications of the work are that the Refractance Window[TM] (RW) drying technique will dry cucumber slices at a faster rate than the traditional methods and the drying data obtained can be used in the design of an industrial scale RW dryer.*

Keywords: *Drying curve; Drying Rate curve; Krischer curve; Rehydration ratio; Thin-layer dying models*

1. Introduction

Cucumber (*Cucumis sativus*), is an edible fruit from the gourd family. In 2013, over 71 million metric tons of cucumbers were produced worldwide; the top five cucumber producers being China, Turkey, Iran, Russia and Ukraine (FAOSTAT, 2014). Cucumbers are rich in vitamins B, C, and K and contain a high level of potassium (Metaljan, 2015). Cucumbers are added to salads, made into soups and often turned into juice. Other common uses of cucumbers are in skin and hair care, in reducing cholesterol and in controlling blood pressure; they aid weight loss and digestion and are believed to relieve bad breath and be an alcohol hangover cure (McCadden and MaCadden, 2003; Laning, 2017). Cucumbers have cooling properties and are useful for bringing relief to the eyes in hot weather (Metaljan, 2006).

However, cucumbers are seasonal fruits, and they need to be preserved if they are to be available all-year round. Drying is a very common fruit preservation method; it reduces storage volume and extends the shelf life of cucumbers beyond the few weeks when the fruits are in season (Kordylas, 1991).

In order to develop a highly efficient drying technique for cucumber, Duan *et al.* (2007), investigated the effects of freeze drying, air drying and vacuum microwave drying methods on the drying procedure and product quality of cucumbers. Freeze drying led to the best quality products, but took the longest time, whilst the quality of the air dried products was the poorest. Vacuum microwave drying combined with freeze drying gave products with acceptable quality and reduced drying time. In order to achieve the optimal drying condition, a series of well-designed experiments was carried out, with a combined method of freeze drying and vacuum microwave drying. Compared with freeze drying, the air drying-vacuum-microwave drying combination could reduce the drying time to half and maintain good product quality. However, the drying methods investigated by Duan, Zhang, and Mujumdar (2007), required a substantial amount of energy. Hence, a simpler technique requiring less energy is desirable.

The Refractance Window[TM] (RW) drying technology patented by Magoon (1986) and developed by MCD Technologies Inc., Tacoma, WA, USA, is a novel technology considered to be suitable for drying foods (Nindo and Tang, 2007). The Refractance Window[TM] drying technique does not require direct extremes of temperature to remove water, rather infra-red energy is used to facilitate the dehydration process (Nindo and Tang, 2007). Also the RW dryer technique is self-limiting in that the drying temperature cannot exceed the boiling point of water (100^{o}C).

Studies have shown that foods dehydrated using the Refractance Window^{TM} drying technology have a higher retention of vitamins, minerals, enzymes and antioxidants when compared to those dried by more commonly practiced methods such as spray or freeze drying.

Nindo and Tang (2007) investigated the Refractance Window^{TM} technique to dry purees and juices prepared from fruits, vegetables, and herbs. Nindo and Tang (2007) observed that purees and juices dried within 3-5 minutes when the water temperature in the flumes was about 95 - 97 ^{0}C.

Nindo (2008) investigated the freeze drying and the Refractance Window^{TM} drying methods for asparagus, squash, berries, aloe-vera, and marine algae. The investigation indicated that freeze drying, a well-established but expensive technology, and the Refractance Window^{TM} drying technique, a simple and relatively inexpensive method, produced similar results.

Akinola and Ezeorah (2016) investigated the use of the Refractance Window^{TM} drying technique to dehydrate yam, cassava and potato slices. Their studies indicated that at a water temperature of 60^{o}C beneath the transparent plastic film, 3 mm thick slices of the root tuber slices could be dehydrated to less than 10% moisture content (wet basis) in less than 180 minutes. This is considerably less than the 3 to 5-day dehydrating times that is experienced in regions where sun drying is used to dry the root tubers (Mlingi, 1995). Akinola *et al.*, (2016) also demonstrated that using the Refractance Window^{TM} drying technique, 3 mm thick carrot slices could be dried to a moisture content of less than 10% (wet basis) within 200 minutes.

The investigation of the dehydration kinetics, rehydration characteristics and effective moisture diffusivity of cucumber slices dried using the Refractance Window^{TM} drying technique is presented in this study. The dehydration kinetics study will provide data to understand the behaviour of sliced cucumbers in a Refractance Window^{TM} dryer, while the rehydration characteristics, and other determined properties will characterize the dried cucumber slices.

2. Materials and Methods

2.1 The Equipment

A schematic diagram of the Refractance Window^{TM} type dryer used in this study is shown in Figure 1. The equipment is similar to that used by Akinola et al. (2016); it consists of a laboratory water-bath, heated with a 2.5kW electric temperature controlled immersion heater which is covered with a 0.15 mm thick transparent polyethylene terephthalate (PET) plastic film. The film was secured in place with metal angle brackets. The brackets were placed so that the transparent PET plastic film was always in contact with the water.

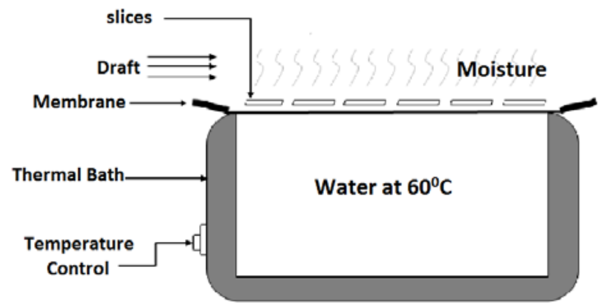

Figure 1. Set up of the apparatus used

2.2 Preparation of the Cucumber Slices

The cucumber fruits were obtained from a local market. The fruits were washed and cut into 3 mm thick slices using a Mandolin type slicer. The moisture content of the fresh cucumber slices was determined using an MB45 OHAUS moisture analyzer (OHAUS, 2011). The average values of the fresh cucumber slices were determined by performing the experiments 3 times.

2.3 The Experimental Procedure

The water in the bath was heated to a temperature of 60^{o}C, and this temperature was maintained throughout the set of experiments. A temperature of 60^{o}C is considered low enough not to adversely degrade the nutritional value of the cucumber sample (Patras et al, 2010). The cucumber slices were put on the plastic film to dry. At 10-minute intervals, as the experiment progressed, some cucumber slices were removed from the dryer and the moisture content determined, using an MB45 OHAUS moisture analyzer. The drying process was stopped when the moisture content of the cucumber samples was about 10% on a wet basis. The drying experiments were repeated three times for each drying period and the average moisture content values for each period determined.

During experimentation, a draft of air was maintained across the Refractance Window^{TM} dryer. This draft of air was used to ensure that a saturated stagnant layer above the surface of the cucumbers did not exist as this would hinder the drying process.

2.4 Measurement of the Moisture Content and Slice Size

The mass and moisture content readings on a wet basis (w.b) of the cucumber slices were determined to an accuracy of 0.01g and 0.01% respectively. An MB45

OHAUS moisture analyzer (OHAUS, 2011) was used to measure the moisture content on a wet basis and the weight of the cucumber slices. The measured moisture content was converted to dry basis. The thickness of the cucumbers slices was measured using an electronic digital Vernier caliper.

2.5 Processing Experimental Kinetic Data

In this study, the moisture content used was on a dry basis (d.b.) although the MB45 OHAUS moisture analyser determines the moisture content on a wet basis. The relationship between moisture content on a dry basis MC_d and moisture content on a wet basis is MC_w that is given by Eqn. 1.

$$MC_d = \left[\frac{MC_w}{100 - MC_w}\right] \text{x } 100 \quad (1)$$

The experimental kinetic data was processed by first calculating the moisture ratio. The moisture ratio was calculated using Eqn. 2.

$$MR = \frac{MC_t - MC_e}{MC_i - MC_e} \quad (2)$$

where,

MC_t is moisture content of the cucumber slices after drying for time t;

MC_e is the equilibrium moisture content of dried cucumbers and

MC_i is the initial moisture content of fresh cucumber all in the units of g of water removed/g of solids.

In this study, because MC_e is small when compared to MC_t and MC_i, Eqn. 2 can be approximated to Eqn. 3.

$$MR = MC_t/MC_i \quad (3)$$

The moisture ratio (MR) was then fitted to the thin-layer drying models listed in Table 1. The parametric coefficients of each model were determined using Datafit 9.1 data regression software developed by Oakdale Engineering, Oakdale, PA USA (2014). The software uses the Levenberg-Marquardt method for nonlinear least square problems in determining its solution (Gavin, 2013). The thin-layer drying model that best fit the drying data was obtained by performing a regression analysis using the drying data and the models listed in Table 1.

The criteria for the model that best fit the experimental data should have a coefficient of determination (R^2) that is closest to 1.0, and in which the chi-square ($\chi 2$) and the Root Square Error (RMSE) values are closest to zero (Akpinar, 2010; Tunde-Akintunde and Afon, 2010; El-Mesery and Mwithiga, 2014; John *et al.*, 2014). Equations used to determining R^2, $\chi 2$ and RMSE are discussed in many statistical textbooks (Ogunnaike, 2011; Barrett,1974), and have been used in a number of thin layer drying modelling articles (Meisami-asl *et al.*, 2009; Togrul and Pehlivan, 2003; Fudholi *et al.*, 2013; Akinola *et al.*, 2014).

Table 1. Thin-layer Models

S/N	Model
1	$MR = \exp(-k.t^n)$ Page Model (Page, 1949)
2	$MR = a.\exp(-k.t)$ Henderson and Pabis Model (Henderson and Pabis, 1961)
3	$MR = 1 + a.t + b.t^2$ Wang and Singh Model (Wang and Singh, 1978)
4	$MR = a.\exp(-k.t) + (1-a)\exp(-k.a.t)$ Two term exponential Model(Sharaf-Elden *et al.*,1980)
5	$MR = a.\exp(-k.t) + (1-a).\exp(-g.t)$ Verma et al. Model(Verma *et al.*, 1985)
6	$MR = a.\exp[-ct/L^2]$ Simplified Fick's diffusion (SFFD) equation (Diamente and Munro, 1991)
7	$MR = \exp[-k(t/L^2)^n]$ Modified Page equation –II (Diamente and Munro, 1993)
8	$MR = a.\exp(-k_0.t) + b\exp(-k_1.t)$ Two term Model (Madamba, 1996)
9	$MR = \exp(-k.t)$ Newton Model (Ayensu, 1997)
10	$MR = \exp(-(k.t)^n)$ Modified Page Model (Ozdemir and Devres,1999)
11	$MR = a.\exp(-k.t) + b.\exp(-g.t) + c.\exp(-h.t)$ Modified Henderson and Pabis Model (Karathanos,1999)
12	$MR = a.\exp(-k.t^n) + b.t$ Midilli et al. Model (Midilli *et al.*, 2002)
13	$MR = a.\exp(-k.t) + c$ Logarithmic Model (Togrul and Pehlivan, 2003)
14	$MR = a.\exp(-b.t^c) + d.t^2 + e.t + f$ Haghi and Ghanadzadeh Model (Haghi and Ghanadzadeh, 2005)
15	$MR = a.\exp(-k.t) + (1-a).\exp(-k.b.t)$ Diffusion Approach Model (Demir *et al*., 2007)
16	$MR = \exp(-(t/a)^b)$ Weibull (Corzo *et al.*, 2008)
17	$MR = \exp(-k_1.t/1+k_2.t)$ Aghbashlo et al. Model (Aghbashlo *et al.*, 2009)

After obtaining the best thin-layer drying model that fit the drying data, the drying curve (moisture content *vs.* time plot), the drying rate curve (drying rate *vs.* time plot), and the Krischer curve (drying rate *vs.* moisture content plot), were obtained.

2.6 Rehydration Ratio Determination

The rehydration ratio (RR) was determined as recommended by Baron Spices and Seasonings (2015). The mass of the dehydrated and rehydrated solid were measured and the rehydration ratio determined using Eqn. 4.

$$RR = M_r / M_d \quad (4)$$

where,

M_r is the mass of the rehydrated solid in grams and

M_d is the mass of the dry sample in grams.

The rehydration ratio values for the 3 mm thick cucumber slices were determined at 10-minute time intervals up to 180 minutes. The experiments were performed in triplicates and the average values obtained.

2.7 Effective Moisture Diffusivity Determination

The effective moisture diffusivity (D_{eff}) was determined using Fick's second equation of diffusion. The moisture ratio, (MR) can be expressed as a sum of infinite terms as presented in Eqn. 5 Crank (1975).

$$MR = \frac{MC_t - MC_e}{MC_i - MC_e} = \frac{8}{\pi^2}\sum_{n=1}^{\infty}\frac{1}{(2n-1)^2}\exp\left(-\frac{(2n-1)^2\pi^2 D_{eff} t}{4L^2}\right) \quad (5)$$

where,

MR is the moisture ratio,
D_{eff} (m^2s^{-1}) is the effective moisture diffusivity,
L (m) is the sample thickness and
t is the drying time (s).

While the slice is assumed to be of constant moisture diffusivity and of a uniform initial moisture distribution (Crank, 1975), the moisture ratio equation for the slices which involves a series of exponents can be simplified to Eqn. 6 (Lopez *et al.,* 2000). Further detailed discussions can be found in Jena and Das (2007) and Taheri-Garavand, Rafiee and Keyhani (2011).

$$MR = \frac{8}{\pi^2}\exp\left(-\frac{\pi^2 D_{eff} t}{4L^2}\right) \quad (6)$$

A plot of -1n(MR) against time gives a slope of k_d from which D_{eff} can be obtained according to the Eqn. 7

$$k_d = \frac{\pi^2 D_{eff}}{4L^2} \quad (7)$$

3. Results and Discussion

3.1 Obtaining the Best Drying Model

Cucumber slices 3 mm thick, with an initial moisture content of 2003% on a dry basis were dried until the moisture content was less than 10%. During the drying process, the change in moisture ratio was determined. The moisture content data obtained were fitted to the seventeen (17) thin-layer drying models presented in Table 1.

Table 2 presents the details of the statistical analysis obtained from fitting the experimental data to all thin-layer drying models. The results indicate that the Haghi and Ghanadzadeh (2005) model and the Midilli *et al.* (2002) model both have the same R^2 value of 0.9994 and chi-square of 0.0001. However, the MBE of Haghi and Ghanadzadeh model is zero while that of the Midilli *et al.* model is close to zero with a value of -0.0002. This implies that the Haghi and Ghanadzadeh model gives a better fit than the Midilli *et al.* model. Also the RSME of the Haghi and Ghanadzadeh model is much closer to zero than the Midilli *et al.* model with a difference of 0.0004. This justifies that the Haghi and Ghanadzadeh model best describes the drying kinetics of the 3 mm thick cucumber slices compared to other models.

Further validation that the Haghi and Ghanadzadeh (2005) thin-layer drying model best fits the drying kinetics was done by plotting the values of experimental and predicted moisture contents (see Figure 2). The line obtained, had a slope of approximately 1.000, with an intercept of zero; the coefficient of determination (R^2) was 0.9994. The implication is that the experimentally determined moisture content of the 3 mm thick cucumber slices does not vary significantly from the predicted data.

Table 3 gives the model parameters for the experimental data fitted to the seventeen (17) thin-layer drying models.

Table 2. Results of Statistical Analysis

No.	Model Name	(R^2)	MBE	$\chi 2$	RMSE
1	Haghi and Ghanadzadeh (2005)	0.9994	0.0000	0.0001	0.0073
2	Midilli *et al.*(2002)	0.9994	-0.0002	0.0001	0.0077
3	Modified Page (Ozdemir and Devres,1999)	0.9991	-0.0038	0.0001	0.0093
4	Modified Page equation –II (Diamente and Munro, 1993)	0.9991	-0.0038	0.0001	0.0093
5	Weibull (Corzo *et al.*, 2008)	0.9991	-0.0038	0.0001	0.0093
6	Page (1949)	0.9991	-0.0038	0.0001	0.0093
7	Diffusion Approach (Demir *et al.*, 2007)	0.9990	-0.0019	0.0001	0.0100
8	Two term exponential (Sharaf-Elden *et al.*,1980)	0.9987	-0.0008	0.0001	0.0111
9	Verma *et al.*(1985)	0.9856	-0.0076	0.0018	0.0371
10	Logarithmic / Yagcioglu *et al.* (1999)	0.9845	0.0000	0.0019	0.0385
11	Modified Henderson and Pabis (Karathanos,1999)	0.9827	0.0084	0.0029	0.0406
12	Henderson and Pabis (1969)	0.9827	0.0084	0.0019	0.0406
13	Two term (Madamba, 1996)	0.9827	0.0084	0.0023	0.0406
14	Simplified Fick's diffusion (SFFD) equation (Diamente and Munro, 1991)	0.9827	0.0084	0.0019	0.0406
15	Newton (Ayensu, 1997)	0.9798	0.0045	0.0021	0.0440
16	Aghbashlo *et al.*(2009)	0.9793	0.0095	0.0023	0.0445
17	Wang and Singh (1978)	0.9251	0.0141	0.0084	0.0846

Table 3. Constants Obtained by Fitting Data to the Various Thin-layer Models

No.	Model Name	Constants	
1	Haghi and Ghanadzadeh (2005)	a= 1.081363 c= 1.451413 e= 0.00183	b= 0.009631 d= -9.07E-06 f= -0.08169
2	Midilli *et al.*(2002)	k= 0.008989 n= 1.485535	a= 0.9994381 b= 7.25E-05
3	Modified Page (Ozdemir and Devres,1999)	k= 0.041729	n= 1.468509
4	Modified Page equation –II (Diamente and Munro, 1993)	k= 0.237374	n= 1.468467
5	Weibull (Corzo *et al.*, 2008)	a= 23.96414	b= 1.468509
6	Page (1949)	k= 0.009432	n= 1.468137
7	Diffusion Approach (Demir *et al.*, 2007)	a= -7.2943 b= 0.882083	k= 0.095887
8	Two term exponential (Sharaf-Elden *et al.*,1980)	a= 2.029017	k= 0.06858
9	Verma *et al.*(1985)	a= 18.24369 g= 0.027906	k= 0.028596
10	Logarithmic / Yagcioglu *et al.* (1999)	a= 1.071511 c= -0.02059	k= 0.043731
11	Henderson and Pabis (1969)	a= 1.056257	k= 0.046254
12	Modified Henderson and Pabis (Karathanos,1999)	a= 0.091163 g= 0.046256 b= 0.481481	c= 0.483614 h= 0.046253 k= 0.046255
13	Two term (Madamba, 1996)	a= 0.91272 b= 0.143537	k0= 0.046254 k_1= 0.046255
14	Simplified Fick's diffusion (SFFD) equation (Diamente and Munro, 1991)	a= 1.056256	c= 0.416287
15	Newton (Ayensu, 1997)	k= 0.044211	
16	Aghbashlo *et al.*(2009)	k_1= 0.042834	k_2= -1.16E-52
17	Wang and Singh (1978)	a= -0.02457	b= 0.000138

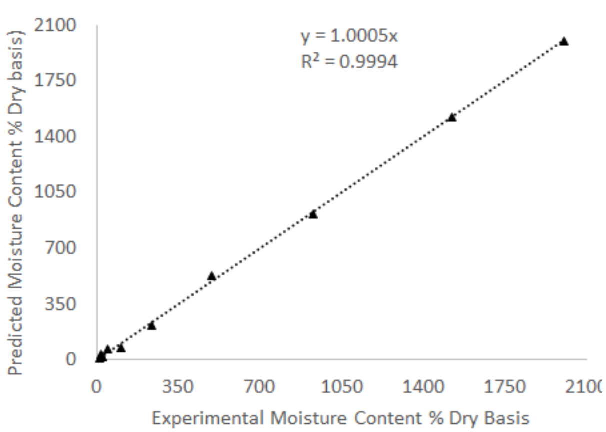

Figure 2 Haghi and Ghanadzadeh model fitness of predicted moisture content values *vs.* experimental moisture content values

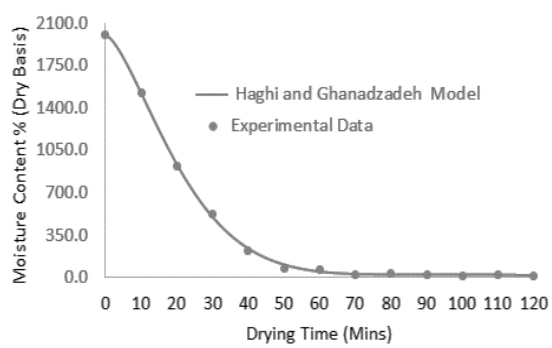

Figure 3. Drying Curve – Moisture Content vs. Drying Time plot for 3 mm thick cucumber slices

3.2 The Drying Curve

Figure 3 shows the drying curve, (i.e. moisture content vs. drying time plot), for the cucumber slices. The figure displays the data points obtained from the experiments and also the line plot obtained from the Haghi and Ghanadzadeh (2005) model. In about 120 minutes, the 3 mm thick cucumber slices dried to a moisture content of less than 10% on a dry basis.

3.3 The Drying Rate Curve

The drying rate curve, (i.e. drying rate *vs.* time plot) for the 3 mm thick cucumber slices is shown in Figure 4. Figure 4 is a line plot that was obtained by differentiating the equation obtained by fitting the Haghi and Ghanadzadeh model (Haghi and Ghanadzadeh, 2005) to the experimental data points. As shown in Figure 4, the drying rate rises as dehydration begins; this is the initial drying rate period. In this period, sensible and latent heat of evaporation is transferred to the moisture. The drying rate then reaches a peak value and then starts to fall. The peak drying rate occurs about 12 minutes after drying commences and the moisture content at this time, known as the critical moisture content value is about 1524% on a dry basis (Kemp *et al.*, 2001). This is the beginning of the constant drying rate period. The period is controlled by external heat and mass transfer.

In this instance the constant rate period is very short and then the drying rate starts to fall in 2 stages. The first falling rate period is the unsaturated drying period, where the surface is drying out; the second drying rate period is the saturated drying period; where moisture has to move through the product structure before being released. This observation is consistent with the different stages of drying presented by Kemp et al. (2001), Fyhr and Kemp (1998) and Traub (2002a, 2002b).

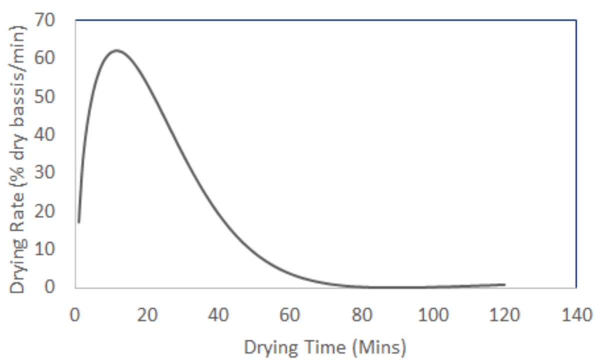

Figure 4. Drying Rate Curve – Drying Rate *vs.* Drying Time plot for 3 mm thick cucumbers slices

3.4 The Krischer Curve

The Krischer curve, (i.e. the drying rate *vs.* moisture content plot) for the cucumber slices is shown in Figure 5. The plot is a combination of the Drying curve and the Drying rate curve. Figure 5 shows that the drying rate (right to left) increases from its initial value at 2003% moisture content (dry basis) when the cucumber slices are fresh, it reaches a peak value and then drops (falling rate period). The peak drying rate reached was observed when the moisture content was about 96% on a dry basis.

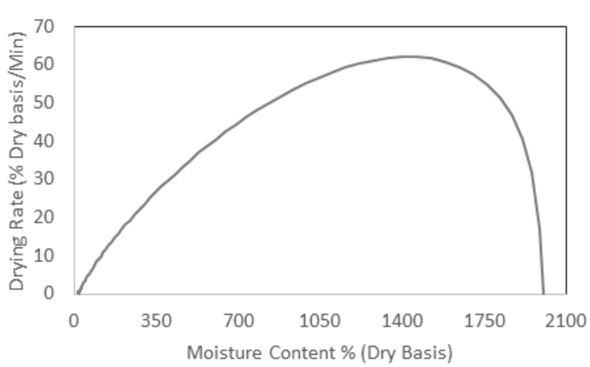

Figure 5. Krischer Curve – Drying Rate vs. Moisture Content for 3 mm thick cucumbers slices

3.5 Rehydration Ratio (RR)

The Rehydration ratio *vs.* Rehydration time plot for the 3 mm thick cucumber slices is shown in Figure 6. The rehydration ratio rises rapidly to 4.46 in the first 60 minutes. Thereafter, the rehydration ratio steadily increases to a value of 5.12 after 260 minutes, 5.23 after 280 minutes and then 5.25 after 300 minutes. This increase was less than a 1% in the rehydration ratio value in the last 20 minutes preceding the entire 300 minutes of rehydration. The moisture content of the cucumber slices after 300 minute of rehydration was 1150% dry basis (92% wet basis).

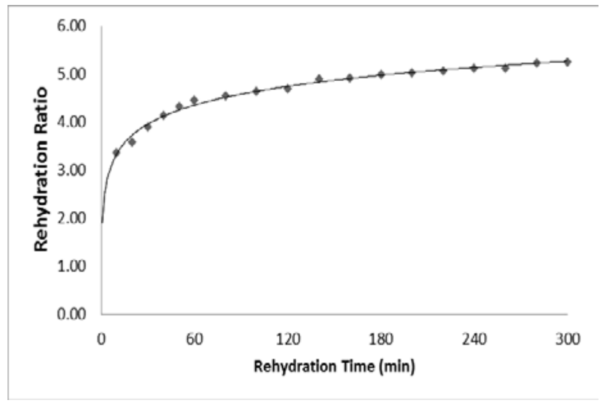

Figure 6. Plot of Rehydration Ratio vs. Rehydration Time

3.6 Effective Moisture Diffusivity

Figure 7 displays a plot – ln(MR) against drying time. The line and the linear relationship that best fit the data are also shown on the figure. From the slope, k_d, of the line, the effective moisture diffusivity is obtained, according to Eqn. 10. For 3 mm thick cucumber slices, a value of 7.30 $\times 10^{-10}$ m^2s^{-1} is obtained as the effective moisture diffusivity.

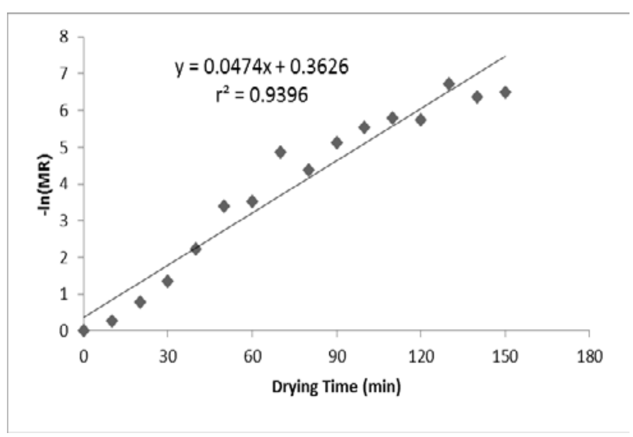

Figure 7. Plot of –ln(MR) *vs.* Drying Time

4. Conclusions

Using a Refractance Window^{TM} dryer, cucumber slices 3 mm thick, with an initial moisture content of 2003% (dry basis) were dried until the moisture content was less than 10% (dry basis).–The following conclusions were made:

1) The Haghi and Ghanadzadeh (2005) thin-layer drying model was determined to be the best fit for the drying kinetics of the 3 mm thick cucumber slices. The model had a R^2 value of 0.9994, MBE value of 0.000, $\chi 2$ value of -0.0001 and an RMSE value of 0.0073.
2) With a water bath temperature of 60^oC in the laboratory scale Refractance Window^{TM} dryer, the 3 mm thick cucumber slices dried to a moisture content of less than 10% dry basis within 120 minutes. This is a considerably shorter time than 4-8 hours experienced using the Excalibur Dehydrator designed (Discount Juicer, 1998).
3) The drying rate curve has an initial rising/ increasing rate period. It attains a peak value and then starts to drop in a 2-stage falling rate period. This is typical of a drying curve (Kemp *et al.*, 2001). The peak drying rate is at the constant rate drying period, though this period was short (see Figure 4).
4) The effective moisture diffusivity was estimated using the diffusion model based on the Fick's second law (Crank, 1975), and it was found to be 7.30×10^{-10} m/s at 60^{0}C for the 3 mm thick cucumber slices.
5) As the rehydration time increased, the rehydration ratio for the cucumber slices increased to a value of 5.25 after 300 minutes of rehydration. The moisture content of the cucumber slices at this time was 1150% dry basis (92% wet basis).

The implications of the work are that the Refractance Window^{TM} drying technique would dehydrate cucumber slices in a shorter time than the methods found in the literature. Also the thin-layer drying model selected to best fit the drying data could be used in the design of an industrial scale Refractance Window^{TM} dryer.

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