Journal of Thermal Engineering
Yildiz Technical University Press, Istanbul, Turkey
Vol. 2, No. 2, pp. 741-747, April, 2016.

http://eds.yildiz.edu.tr/journal-of-thermal-engineering/Articles
Manuscript Received May 28, 2015; Accepted August 5, 2015

This paper was recommended for publication in revised form by Regional Editor Derya Burcu Özkan

EXPERIMENTAL DETERMINATION OF CONVECTIVE HEAT TRANSFER COEFFICIENT DURING OPEN SUN AND GREENHOUSE DRYING OF APPLE SLICES

***Kamil Neyfel ÇERÇİ**
Department of Mechanical Engineering
Osmaniye Korkut Ata University Osmaniye, Turkey

Ebru KAVAK AKPINAR
Department of Mechanical Engineering
Fırat University Elazığ, Turkey

Keywords: Convective heat transfer coefficient, drying, forced convection, natural convection, greenhouse, open sun, apple.

* *Corresponding author:* Phone:+90(328)8271000x3510
E-mail address: kcerci@osmaniye.edu.tr

ABSTRACT

A small scale greenhouse type dryer was designed and tested. Convective heat transfer coefficient of apple slices was identified under open sun at natural convection mode and in greenhouse drying at natural and forced convection mode. The experiments were carried out in May-June, 2014 under the climatic conditions of Elazığ, Turkey (39°14' E 38°41' N). The rate of moisture removal, crop temperature, relative humidity inside and outside the greenhouse and ambient air temperature for complete drying was recorded at 30 min intervals. The values of constants (C and n) in Nusselt number expression were found by using linear regression analysis of the data gathered from apple slices. Finally, convective heat transfer coefficients were determined. The average convective heat transfer coefficient values for apple slices were calculated as 2.863 $W/m^2\ {}^oC$ for open sun drying under natural convection mode, 2.065 $W/m^2\ {}^oC$ for greenhouse drying under natural convection mode, 2.724 $W/m^2\ {}^oC$ for greenhouse drying under forced convection mode, respectively. The convective heat transfer coefficient in open sun drying was slightly higher than forced convection in greenhouse drying. The convective heat transfer coefficient in greenhouse drying under natural mode was found as the lowest one.

INTRODUCTION

Food products can be produced in certain periods of the year and in a short time due to salient features. Generally, few intensive made products can be consumed as fresh in this period. Thus, a substantial portion of the product must be stored safely until they reach the consumer [1].

There are many techniques for a long storage of food products. These techniques are drying, cooling, treating with chemicals. The most common application among them is drying [2]. Drying is defined as removal of the water or liquid in the material. As a result of this removal process, biochemical reactions and the growth of microorganisms which may take place in the products will be stopped down to a level, and then the products can withstand in a long time without impairing [1].

The term of drying, which is a heat and mass transfer process, under open sun drying is known as one of the oldest methods of food storage [2]. But under open sun drying conditions, quality of the product seriously decreases due to dusts, impurities, insects and birds. Thus, marketing chances of low quality products decrease [3]. To overcome this problem, drying process can be carried out by indoor drying systems.

Greenhouse type dryer is one of the indoor drying systems. In general, the greenhouse type dryers are evaluated as integral (direct) type dryers and sometimes they are evaluated as mixed (direct + indirect) mode type dryers [4]. The greenhouse dryers have simple design and are easy to manufacture at low cost. Firstly, the greenhouse was used to cultivate agricultural products [5]. In later years, it was used to heat ambient, soil solarization, poultry raising or aquaculture. After that, researchers discovered that the greenhouse could be used as dryer with low temperature. As a result, the greenhouse can be used both to cultivate agricultural products and to dry agricultural products. These favorable developments increased its economic value [5]. According to the type of heat transfer, greenhouse type dryers are divided into two classes. These are greenhouse drying at natural convection and forced convection mode. Natural convection drying process works on the principle of thermosyphic effect. Humid air which formed in the forced convection of greenhouse dryer gets ventilated through the ventilator -provided at the roof or through the chimney of the dryer [5]. Elkhadraoui et al. [6] performed an experimental analysis to examine the performance of a new mixed type solar greenhouse dryer at forced convection mode to dry red pepper and sultana grape. Experimental drying curves on the results of this study showed only the falling rate period.

One of the most important factors to be considered is the convective heat transfer coefficient. The convective heat transfer coefficient varies due to temperature difference between air and product. Thus, it is an important parameter in determining of drying rate and dryer design. Generally two methods can be used to evaluate convective heat transfer coefficients of products. These are dimensional analysis and direct measurement of heat transfer on a product bed by comparing the temperature curves with Shumann's exact solution. The dimensional analysis is mathematically simple and has a wide range of applications. This method is incomplete without sufficient experimental data, although it facilitates the interpretation and extends the range of application of experimental data by correlating them in terms of dimensional groups [3,7,8].

Although some theoretical and experimental studies were studied about drying, limited studies were carried out to evaluate convective heat transfer coefficient. Anwar and Tiwari [9] studied to find convective heat transfer coefficient in Open Sun Drying. They benefited from experimental data obtained from six various food products. Anwar and Tiwari [10] also worked on forced mode drying for six various food products. Akpinar [7,11] calculated the convective heat transfer coefficient in both natural and forced convection drying using experimental data from eight various products obtained. Kumar and Tiwari [12] studied natural and forced convection drying in greenhouse to investigate effect on convective mass transfer coefficient of mass and volume of the product. In this study, the researchers dried jaggery tray in three different sizes and in two different weights of 0.75 kg and 2.0 kg. Kumar and Tiwari [13] performed open sun and greenhouse drying for onion flakes in three different weights. In this study, the effect of mass on convective mass transfer coefficient during drying was found. Burmester and Eggers [14] studied heat and mass transfer to drying coffee. They were intended to understand heat and mass transfer during the coffee drying process. They also determined optimization of the industrial application transport coefficients and coffee properties. Barati and Esfahani [15] worked on simultaneous heat and mass transfer to investigate a new solution approach during the mango drying process. It was intended in this method to be useful for fast and accurate drying simulation in this method. Tzempelikos et all. [16] developed a numerical model for non-steady heat and mass transfer to drying cylindrical quince slices. It shows that this model is correct against experimental data for different air stream velocities (1 and 2 m/s) and temperatures (40, 50 and 60 °C).

In this study, a small scale greenhouse type dryer was designed and manufactured. Convective heat transfer coefficient of apple slices was determined under open sun at natural convection mode and in greenhouse drying at natural and forced convection mode. These values would be useful in designing a dryer for a given range of products and performance analysis of the drying process.

MATERIALS METHODS

Experimental Setup

The experiments were conducted in the months of May-June 2014 in the climatic conditions of Elazig-Turkey (39°14' E 38°41' N). In this study, apples are used as material. When the raws were selected, it was sure that the materials have same size and also non-crushed and non-decayed structure. The apples were given some treatments such as reduction peeling, size reduction, slicing. Finally they were put on a wire mesh tray and dried there. The measured quantity of product was kept in a wire mesh tray of 0.17 x 0.30 m^2 size directly over the electronic balance of 3500 g capacity having a least count of 0.01 g. For the dried process of the apple, a greenhouse type dryer was designed and manufactured. The frame of the greenhouse made of wood and covered with a plastic sheet. The greenhouse type dryer was established on concrete floors. The product temperatures and the temperature of air leaving the product surface at different locations were measured by iron-constantan thermocouples connected to a twelve channel-automatic digital thermometer (ELIMKO 6400), with a least count 0.1 °C. Precautions were taken so that placement of the thermocouple would not affect the reading being shown by the balance. An EXTECH 444731 model, thermo hygrometer humidity measuring instrument with a least count 0.1 RH was used for relative humidity measurement just above the product surface. The humidity-measuring instrument was kept on the product surface with its sensing ports facing downwards towards the product surface. Every time, it was kept 2 min before recording observations. For all the observations the data for the rate of moisture removal, crop temperature, relative humidity inside and outside the greenhouse and ambient air temperature for complete drying were recorded at 30 min time intervals. In Figure 1. was seen the schematic picture of the prepared set of experiments can be seen and in Figure 2 the photo of this system can be seen.

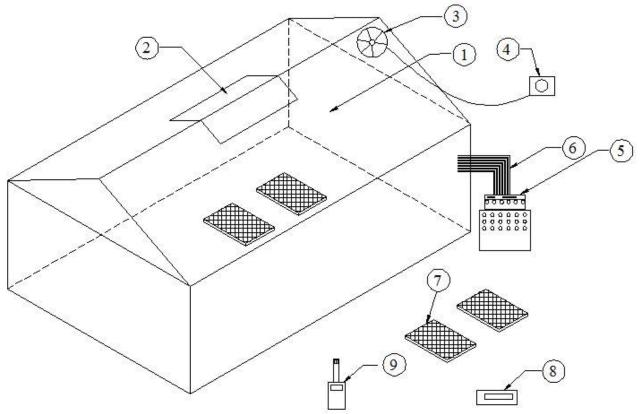

Figure 1. Schematic diagram of greenhouse type dryer: 1- Drying Room, 2- Gap, 3- Fan, 4- Rheostat, 5- Digital thermometer and channel selector, 6- Thermocouples, 7- Tray, 8- Digital balance, 9- Thermo hygrometer

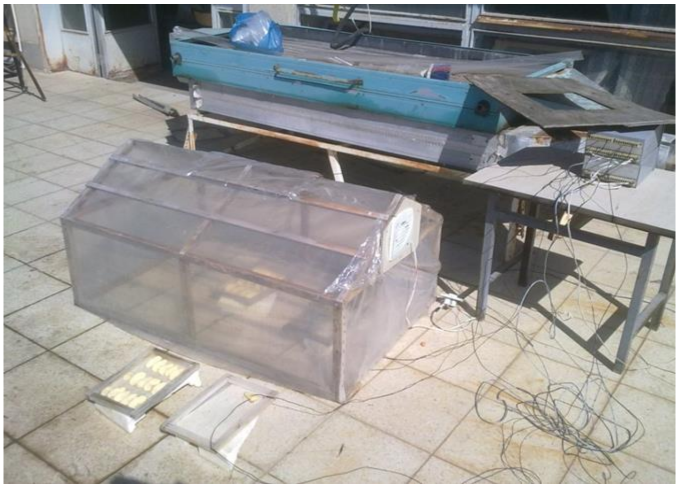

Figure 2. The samples were dried in the greenhouse

Computation Procedure

The values of observations for apple slices are shown in Table 1 under open sun at natural convection mode, in Table 2 in greenhouse drying at natural convection mode and in Table 3 in greenhouse drying at forced convection mode.

The convective heat transfer coefficient (h_c) can be determined using the expression for Nusselt number as [5, 10, 17, 18]:

$$h_c = \frac{Nu\,K_v}{X} \quad (1)$$

or natural convection:

$$h_c = \frac{K_v}{X} C(GrPr)^n \quad (2)$$

forced convection:

$$h_c = \frac{K_v}{X} C(RePr)^n \quad (3)$$

The rate of heat utilized for moisture evaporation is given as [5, 11, 12, 14]

$$\dot{Q}_e = 0.016 h_c [P(T_c) - \gamma P(T_e)] \quad (4)$$

On substituting hc from Eq. (1), Eq. (4) becomes

$$\dot{Q}_e = 0.016 \frac{K_v}{X} C(GrPr)^n [P(T_c) - \gamma P(T_e)] \quad (5)$$

$$\dot{Q}_e = 0.016 \frac{K_v}{X} C(RePr)^n [P(T_c) - \gamma P(T_e)] \quad (6)$$

The moisture evaporated is determined by dividing Eq. (5) and (6) by the latent heat of vaporization (λ) and multiplying with the area of tray (A_t) and time interval (t)

$$\dot{m}_{ev} = \frac{\dot{Q}_e}{\lambda} A_t t = 0.016 \frac{K_v}{X\lambda} C(GrPr)^n [P(T_c) - \gamma P(T_e)] A_t t \quad (7)$$

$$\dot{m}_{ev} = \frac{\dot{Q}_e}{\lambda} A_t t = 0.016 \frac{K_v}{X\lambda} C(RePr)^n [P(T_c) - \gamma P(T_e)] A_t t \quad (8)$$

Putting

$$0.016 \frac{K_v}{X\lambda} [P(T_c) - \gamma P(T_e)] A_t t = Z \quad (9)$$

Eq. (7) and (8) becomes

$$\frac{\dot{m}_{ev}}{Z} = C(GrPr)^n \quad (10)$$

$$\frac{\dot{m}_{ev}}{Z} = C(RePr)^n \quad (11)$$

Taking the logarithm of both sides,

$$\ln[\frac{\dot{m}_{ev}}{Z}] = \ln C + n \ln(GrPr) \quad (12)$$

$$\ln[\frac{\dot{m}_{ev}}{Z}] = \ln C + n \ln(RePr) \quad (13)$$

Eq. (12) and (13) is the analogy of an equation of a straight line,

$$Y = b_1 X + b_0 \quad (14)$$

Where

$$Y = \ln[\frac{\dot{m}_{ev}}{Z}],\ b_1 = n,\ X = \ln(GrPr),\ b_0 = \ln C \quad (15)$$

$$Y = \ln\left[\frac{\dot{m}_{ev}}{Z}\right],\quad b_1 = n,\ X = \ln(RePr),\ b_0 = \ln C \quad (16)$$

The different physical properties of humid air, i.e. density (ρ_v), thermal conductivity (K_v), specific heat (C_v) and viscosity (μ_v), used in the computation of Reynolds number (Re), Grashof number (Gr) and Prandtl number (Pr) have been determined using the following polynomial expressions [5, 12, 13, 18]. For obtaining physical properties of humid air, T_i is taken as average of product temperature (T_c) and exit air temperature (T_e):

$$\rho_v = \frac{353.44}{(T_i+273.15)} \quad (17)$$

$$K_v = 0.0244 + 0.6773 \times 10^{-4} T_i \quad (18)$$

$$C_v = 999.2 + 0.1434 T_i + 1.101 \times 10^{-4} T_i^2 - 6.7581 \times 10^{-8} T_i^3 \quad (19)$$

$$\mu_v = 1.718 \times 10^{-5} + 4.620 \times 10^{-8} T_i \quad (20)$$

$$P(T) = \exp\left[25.317 - \frac{5144}{(T_i+273.15)}\right] \quad (21)$$

The values of the constants C and n have been determined by linear regression analysis by using measured data of the product and exit air temperatures, exit air relative humidity and moisture evaporated during a certain time period.

RESULTS AND DISCUSSION

The average product temperature ($\overline{T}_c$), exit air temperature ($\overline{T}_e$) and exit air relative humidity ($\overline{\gamma}$) have been used for determining the physical properties of humid air which, in turn, used for calculating the values of Reynolds number, Grashof number and Prandtl number. The constants, C and n, were determined by linear regression analysis and considered further for obtaining the values of the convective heat transfer coefficients by Eq.1. Measured and calculated values of the apple slices which were dried in open sun drying, in greenhouse at natural convection and forced convection drying are showed in Table 1, Table 2 and Table 3, respectively. According to the time change, the convective heat transfer coefficient values which were obtained from experiments are showed in Figure 3.

Table 1. The measured and calculated values for apple slicess in open sun drying

Time (min)	T_c (°C)	T_e (°C)	m_{ev} (gr)	γ (%)	Gr ($x10^5$)	Pr	C	n	Nu	h_c ($W/m^2{}^\circ C$)
0	20.4	32.8	-	24.0	2.66	0.70	0.65	0.20	7.45	3.60
30	18.5	23.4	4.95	25.6	1.14	0.70			6.29	2.99
60	19.1	30.5	4.50	22.2	2.51	0.70			7.36	3.54
90	21.0	30.3	6.52	18.4	2.02	0.70			7.05	3.40
120	22.4	30.0	6.54	19.7	1.64	0.70			6.76	3.26
150	23.1	33.7	6.17	16.6	2.21	0.70			7.18	3.48
180	23.7	29.5	6.03	17.4	1.24	0.70			6.39	3.09
210	25.0	28.2	5.07	16.4	0.69	0.70			5.67	2.74
240	27.5	33.3	2.24	15.1	1.18	0.70			6.32	3.08
270	27.2	30.6	3.53	13.7	0.70	0.70			5.70	2.77
300	28.9	30.1	3.84	10.1	0.25	0.70			4.62	2.25
330	29.8	29.0	2.79	9.8	0.16	0.70			4.26	2.07
360	31.1	31.0	2.69	10.6	0.02	0.70			2.79	1.36
390	26.7	28.5	1.62	11.5	0.38	0.70			5.04	2.44

Table 2. The measured and calculated values for apple slicess in greenhouse with natural convection drying

Time (min)	T_c (°C)	T_e (°C)	m_{ev} (gr)	γ (%)	Gr ($x10^5$)	Pr	C	n	Nu	h_c ($W/m^2{}^\circ C$)
0	25.6	41.3	-	30.1	3.04	0.71	0.89	0.13	4.54	2.23
30	26.2	30.0	3.31	27.5	0.80	0.70			3.80	1.84
60	29.7	39.0	4.20	31.5	1.78	0.71			4.23	2.08
90	34.3	47.6	7.37	28.3	2.31	0.71			4.38	2.19
120	35.4	46.7	6.86	20.1	1.96	0.71			4.28	2.15
150	35.8	47.4	7.19	18.1	2.00	0.71			4.29	2.15
180	35.5	44.6	7.01	29.7	1.60	0.71			4.17	2.08
210	31.6	41.7	5.73	19.3	1.87	0.71			4.26	2.11
240	32.5	44.9	2.49	19.4	2.22	0.71			4.36	2.17
270	32.7	41.8	4.15	14.7	1.67	0.71			4.19	2.08
300	33.3	41.0	4.24	13.5	1.41	0.71			4.10	2.03
330	36.7	41.4	2.75	12.9	0.84	0.71			3.83	1.91
360	31.2	42.0	2.22	10.9	2.00	0.71			4.29	2.13
390	31.7	34.2	1.85	12.9	0.49	0.71			3.56	1.75

Table 3. The measured and calculated values for apple slicess in greenhouse with forced convection drying

Time (min)	T_c (°C)	T_e (°C)	m_{ev} (gr)	γ (%)	Re (x10^2)	Pr	C	n	Nu	h_c (W/m²°C)
0	21.0	35.4	-	13.5	8.26	0.70	0.98	0.27	5.57	2.70
30	28.8	36.1	7.73	14.2	8.06	0.71			5.54	2.71
60	30.6	36.1	5.86	15.5	8.02	0.71			5.53	2.72
90	30.3	37.4	9.02	11.8	8.00	0.71			5.52	2.72
120	30.0	38.9	10.12	13.4	7.97	0.71			5.52	2.72
150	31.1	37.2	10.24	12.9	7.98	0.71			5.52	2.72
180	33.3	39.7	10.75	10.6	7.88	0.71			5.50	2.72
210	34.0	40.0	9.28	8.2	7.86	0.71			5.50	2.73
240	33.3	38.9	10.10	16.0	7.90	0.71			5.50	2.72
270	33.3	43.2	10.16	14.1	7.80	0.71			5.49	2.73
300	39.5	43.9	5.81	10.5	7.65	0.71			5.46	2.74
330	41.2	43.2	4.71	15.6	7.63	0.71			5.45	2.74
360	42.0	42.8	6.78	11.1	7.62	0.71			5.45	2.74
390	39.5	38.6	2.76	16.0	7.77	0.71			5.48	2.73

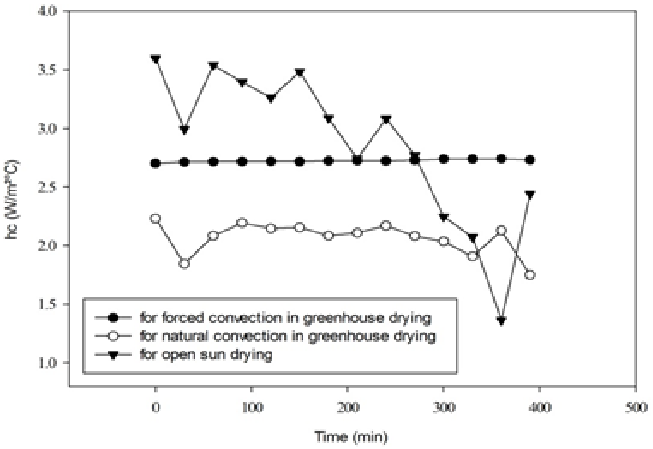

Figure 3. Variation of the convective heat transfer coefficient with time for different drying conditions and modes

The convective heat transfer coefficients were found between 1.36 and 3.60 W/m²°C in open sun drying. The convective heat transfer coefficients were also found between 1.75 and 2.23 W/m²°C in greenhouse drying at natural convection. In addition, the convective heat transfer coefficients were found between 2.70 and 2.74 W/m²°C in greenhouse drying at forced convection. According to Figure 3, especially in the beginning, the convective heat transfer coefficients were found to be at the highest value in open sun drying because of wind effect outdoor and temperature difference. At first, the convective heat transfer coefficient in open sun drying was slightly higher than in greenhouse drying at forced convection. However, towards the end of the drying process, the highest value belongs to the greenhouse drying at forced convection because of external conditions. The convective heat transfer coefficient variation versus time was almost constant in the greenhouse under the forced convection case, since it was not affected by external conditions as musch as the other systems did. Although the temperature difference was more than others, the convective heat transfer coefficient in greenhouse drying under natural mode was found to be the lowest one due to the high moisture content.

The average values of C, n and h_c for apple slices have been showed at Table 4 in open sun drying, in greenhouse drying at natural and forced convection.

Table 4. C, n constants and average convective heat transfer coefficient (h_c) values of apples slices that dried in open sun drying, in greenhouse drying at natural and forced convection.

Methods	Product	C	n	h_c (W/m²°C)
Open sun drying at natural convection	Apple	0.65	0.20	2.86
Greenhouse drying at natural convection		0.89	0.13	2.06
Greenhouse drying at forced convection		0.98	0.27	2.72

The average convective heat transfer coefficient values that were obtained in studies in the literature are showed in Table 5. According to Table 5, the range of the convective heat transfer coefficient (h_c) is partly consistent with experimental studies in the literature. The differences of this study from the ones in literature are that: the climate conditions and the applied drying process.

Dried apple slices are showed in Figure 4. Shrinkage and loose of coloration were not observed in those products.

Table 5. The average convective heat transfer coefficient from the cited references

Literature			
Product	**h_c (W/m²°C)**	**Drying process**	**References**
Apple	11.323	In open sun drying	Akpınar [20]
	2.874	Forced convection drying	Akpınar [6]
	21.43-44.30	The effect of air flow rate	Velic vd. [65]

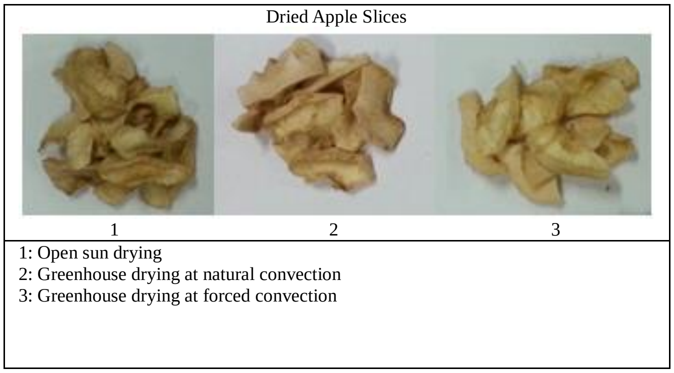

Figure 4. Dried Products

CONCLUSION

In this study, the convective heat transfer coefficient (h_c) values of apple slices have been determined using experimental data for obtaining the values of the constants C and n at different drying conditions and modes. The convective heat transfer coefficient varied between 3.60 and 1.36 $W/m^{2}°C$. Considering the average convective heat transfer coefficient, the highest value was showed in open sun drying. Also the lowest value was found in greenhouse at natural convection drying. Finally, the convective heat transfer coefficient variation was found almost fixed values in greenhouse at forced convection drying. It was identified that the convective heat transfer coefficient varied according to shape and dimensions of the product, porosity, moisture rate, thermophysical properties, experimental conditions and climatic conditions.

NOMENCLATURE

A_t	area of tray, (m^2)
C	constant
C_v	specific heat of humid air, (J/kg°C)
h_c	convective heat transfer coefficient, ($W/m^{2}°C$)
Gr	Grashof number, ($Gr=\beta g X^3 \rho \Delta T/\mu^2$)
K_v	thermal conductivity of humid air, (W/m°C)
m_{ev}	moisture evaporated, (kg)
n	constant
Nu	Nusseltnumber, ($Nu = h_c X/K_v$)
Pr	Prandtlnumber, ($Pr=\rho_v C_v/K_v$)
P(T)	partial vapour pressure at temperature T, (N/m^2)
$\dot{Q}_e$	rate of heat utilized to evaporate moisture, (J/m^2s)
Re	Reynolds number, ($Re=\rho_v v d/ \mu_v$)
t	time, (min)
T_c	product temperature, (°C)
T_e	exit air temperature, (°C)
$\overline{T}_c$	average product temperature, (°C)
$\overline{T}_e$	average exit air temperature, (°C)
T_i	average of product and humid air temperature, (°C)
X	characteristic dimension, (m)

REFERENCES

[1] Darıcı, S., Şen, S., Kivi meyvesinin kurutulmasında kurutma havası hızının kurumaya etkisinin incelenmesi, X. Ulusal Tesisat Mühendisliği Kongresi, 2011;13/16/İzmir.

[2] Akyurt, M., Sevilir, E., Selçuk, K., 1971. Güneş enerjisi ve bazı yakıtlarla meyve ve sebze kurutulması, TÜBİTAK, Tarım ve Ormancılık Araştırma Grubu, Proje No: TOAG-97, Ankara.

[3] Cemeroğlu, B., 1986. Meyve ve Sebze İşleme Teknolojisi, Gıda Teknolojisi Derneği, Yayın no:6, Böl:9, Ankara.

[4] Prakash, O., Kumar, A., 2014. Solar greenhouse drying: A review. Renewable and Sustainable Energy Reviews. 29, 905–910.

[5] Tiwari, G.N., Greenhouse technology for controlled environment, Narosa Publishing house, New Delhi, İndia, 2003.

[6] ELkhadraoui, A., Kooli, S., Hamdi, I., Farhat, A, 2015. Experimental investigation and economic evaluation of a new mixedmode solar greenhouse dryer for drying of red pepper and grape. Renewable Energy. 77: 1-8.

[7] Akpinar, E.K., 2004. Experinemtal determination of convective heat transfer coefficient of some agricultural product in forced convection drying. Int. Comm. Heat and Mass Transfer. 31(4): 585-595.

[8] Thompson, T.L., Peart, R.M., 1968. Foster, G.H., Mathematical simulation of corn drying- A new model, Trans ASAE, 12(4), 582-586.

[9] Anwar, S.I., Tiwari, G.N., 2001. Evaluation of convective heat transfer coefficient in crop drying under open sun drying conditions. Energy Convers. Mgmt. 42(5): 627-637.

[10] Anwar, S.I., Tiwari, G.N., 2001. Convective heat transfer coefficient of crop in forced convection drying – an experimental study. Energy Conversion and Management. 42: 1687-1698.

[11] Akpinar, E.K., 2006. Experimental investigation of convective heat transfer coefficient of various agricultural products under open sun drying. International Journal of Green Energy. 1(4): 429-440.

[12] Kumar, A. and Tiwari, G.N., 2006. Effect of shape and size on convective mass transfer coefficient during greenhouse drying (GHD) of jaggery. Journal of Food Technology. 73: 121-134.

[13] Kumar, A. and Tiwari, G.N., 2007. Effect of mass on convective mass transfer coefficient during open sun and greenhouse drying of onion flakes. Journal of Food Technology. 79: 1337–1350.

[14] Burmester, K. and Eggers, R., 2010. Heat and mass transfer during the coffee drying process. Journal of Food Engineering. 99: 430–436.

[15] Barati, E. and Esfahani, J.A., 2011. A new solution approach for simultaneous heat and mass transfer during convective drying of mango. 102: 302–309.

[16] Tzempelikos, D.A., Mitrakos, D., Vouros, A.P., Bardakas, A.V., Filios, A.E. and Margaris, D.P., 2015. Numerical modeling of heat and mass transfer during convective drying

of cylindrical quince slices. Journal of Food Engineering. 156: 10–21.

[17] Goyal, R.K., Tiwari, G.N., 1998. Heat and mass transfer relations for crop drying. Drying Technol. 16(8): 1741-1754.

[18] Zhang, Z., Yang, S., Liu, D., 1999. Mechanism and mathematical model of heat and mass transfer during convective drying of porous materials. Heat Transfer Asian Research. 28(5): 337-351.