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Analysis of drying of melon in a solar-heat recovery assisted infrared dryer

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ABSTRACT

Infrared drying systems are popular in terms of high heat and mass transfer. By using an infrared dryer, it is possible to catch fast heating and short drying time in comparison to the other drying methods. But it consumes a high amount of energy. Therefore, a new type solar air collector (SAC) and air to air heat recovery unit were added to the infrared dryer to reduce specific energy consumption. The general aim of this study is to analyze heat and mass transfer characteristics of the dryer and three-dimensional (3-D) computational fluid dynamic (CFD) simulation and to investigate drying kinetics of melon slices. Experiments were performed at 50 °C and 60 °C melon's surface temperature and 0.5 m/s air velocity. Melon slices were dried from 9 g water/g dry matter to 0.044 g water/g dry matter moisture content. The effective moisture diffusivity (D_e) values varied from 8.25×10^{-10} to 1.24×10^{-9} m^2/s. The average mass transfer coefficient (h_m) values increase from 8.53×10^{-8} m/s at 50 °C to 1.47×10^{-7} m/s at 60 °C. Heat recovery unit has a key role in this system and it provides 23–28% of total input energy. Average solar air collector efficiency was calculated as 50.6%. Obtained theoretical and experimental results are in line with each other. This study shows the successful and efficient combination of solar energy, infrared energy and heat recovery in food processing.

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1. Introduction

Drying is a part of the post-harvest process and it encompasses a sequence of activities and operations that can be divided into two main categories as natural and technical. Solar energy as an energy source is used in both of these methods. In drying systems, energy needed for drying is key point for evaporating the amount of moisture from the product. Infrared drying as one of radiation type methods is preferred since heat and mass transfer rate are high. However, it has high energy consumption. Therefore, researchers are turning to the combined dryer. Many researchers have studied on the performance of single infrared dryer or combined one. They used different techniques such as infrared drying (Nowak and Lewicki, 2004; Toğrul, 2006; Nasıroğlu and Kocabıyık, 2009), infrared and convective drying (Kumar et al., 2006; Jaturonglumlert and Kiatsiriroat, 2010; Supmoon and Noomhorm, 2013; Yinqiang et al., 2014). They reported that infrared dryer has important advantages to maintain product quality and to increase the drying rate. Recent studies show that infrared technology has priority over hot air drying (Raksakantong et al., 2011; Yinqiang et al., 2014). Combining convective and infrared drying enhance the drying rate (Yang et al., 2010; Supmoon and Noomhorm, 2013).

Solar air collector (SAC) can be used in drying applications because it is feasible and economical in drying applications. They can be used directly, indirectly or in a combination mode (Şevik, 2014). Also, some researchers have studied different type of solar collectors (Kavak Akpinar, 2010; Şevik, 2014; Ramani et al., 2010). Dissa et al. (2016) designed a new solar air collector with a composite absorber. Its composite absorber composed of coupling a non-porous absorber made of a corrugated iron sheet and a porous absorber made of a mesh of aluminum. This air collector is appropriate to use in drying applications because it can rise the air temperature between 50 °C and 75 °C. Croitoru et al. (2016) analyzed and redesigned an unglazed transpired solar collector preheat the fresh air. They increased thermal efficiency by using a new geometry with innovative perforation. This collector used as dryer in some countries.

Melon (*Cucumis melo* L.) belongs to the cucurbitaceae family. 100 g of melon contain 8 g carbohydrate with glucose and fructose being the most predominant sugars and also contain 1 g fiber,

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Nomenclature

A	area, m^2
a_w	water activity
B_i	Biot number
c	specific heat capacity, kJ/kg K
C_∞	water concentration of air, kg/m^3
C_w	water concentration near melon, kg/m^3
D	mass diffusivity, m^2/s
Di	Dincer number
D_e	effective diffusivity coefficient, m^2/s
E	energy, kJ
$e(t)$	instantaneous process error at time
$\hbar$	enthalpy, kJ/kg
h	convection heat transfer coefficient, W/m^2 K
h_m	mass transfer coefficient, m/s
h_w	wind convective coefficient, W/m^2 K
h_{fg}	latent heat, kJ/kg
I	instantaneous radiation, W/m^2
K_P	proportional gain
k	thermal conductivity of air, W/m K
k_c	drying constant, 1/min
L	product thickness, m
Ls	tray length, m
Lw	latent heat of vaporization for water, kJ/kg
M_d	final dry weight, g
M_i	initial wet weight, g
Mr	weight after rehydration, g water
m	mass, kg
$\dot{m}$	mass flow rate, kg/s
m_w	vaporized water weight, kg
Nu	Nusselt number
Q_p	energy for the product heating, kJ
Q_w	energy for the moisture evaporation, kJ
P_{IR}	infrared lamp power, W
P_f	fan power, W
P_{out}	output of the proportional controller
$p0$	controller output with zero error
p	vapor pressure of water, kPa
p_0	vapor pressure of pure water, kPa
Pr	Prandtl number
R	function uncertainty
R_a	ideal gas constant, kJ/kg K
Re	Reynolds number
S	shrinkage
Sc	Schmidt number
Sh	Sherwood number
S_φ	the source rate of φ
X	moisture content, g water/g dry matter
W_R	total uncertainty, %
w_1, w_2, w_n	uncertainties in the independent variables
T	temperature, °C
T_0	reference temperature, 0 °C
t	time, min
U	heat loss coefficient, W/m^2 K
u	velocity, m/s
V	reduced volume, m^3
V_0	initial volume, m^3
$\dot{V}$	volumetric flow rate of air, m^3/s
v	kinematic viscosity, m^2/s
ρ	density, kg/m^3
η	efficiency, %
ω	specific humidity, kg water/kg dry air
σ	Stefan–Boltzmann constant, 56.7×10^{-12} kW/m^2 K^4
ϵ	emission coefficient
φ	any conserved property
γ_φ	exchange coefficient of the entity
z	direction of diffusion process, m

Abbreviations

DR	drying rate, g water/g dry matter per minute
MR	moisture ratio, %
PIR	performance increase ratio, %
SEC	specific energy consumption, kW h/kg

Subscripts

a	air
aa	ambient air
abs	absorbed
ac	accumulated
C	chamber
$conv$	convection
db	dry basis
d	dry
de	drying efficiency
dp	drying process
el	electricity
em	emitted
0	reference
ex	exhaust
eva	evaporation
f	fan
HR	heat recovery
IR	infrared
i	initial
ia	inlet air
inp	inputs
mel	melon
mp	moisture production
oa	outlet air
o	outlet
p	product
pl	plate
sac	solar air collector
si	initial surface
su	upside skin
TOT	total
w	water
eq	equilibrium
x	independent variables

12 mg calcium, 17 mg phosphorous and 31 kcal energy (Amiri et al., 2014). The melon has high water content, vitamins A and C, beta-carotene and potassium. However it has a low caloric value (Gil et al., 2006; Solval et al., 2012). World melon production is about 25 million tons in about one million hectares and Turkey is a major melon producer (FAO, 2010).

Melon is a short-lived product and typically is consumed raw. Its supply to supermarkets is limited to harvest season; however, its shelf life is limited to 15 days (Ayhan et al., 1998). Many studies have been done to prolong shelf life. For example; Mahmoud et al. (2008) extended the shelf life of cantaloupe with the treatment 5.0 mg^{-1} ClO_2 by 6 days compared to the untreated storage. But, drying method can be better solution than chemical additives for shelf life prolongation. Dried melon is a healthy snack that is rich in antioxidants, vitamins, and minerals (Berdıyev et al., 2009). Drying of melon has been studied by few researchers (Solval et al., 2012; Rodrigues and Fernandes, 2007; Chayjan et al., 2012; Darvishi et al., 2015). Solval et al. (2012) reported that the juice powder produced

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