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Performance analysis of heat pump and infrared–heat pump drying of grated carrot using energy-exergy methodology

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ABSTRACT

In this study, a hybrid drying system that combines all of the advantages of different drying methods was developed. This study aims to compare experimental results of a heat pump dryer (HPD) and an infrared assisted heat pump dryer (IRAHPD), to determine the energy and exergy efficiency of dryers and to analyze the drying kinetic of grated carrot for observing the effectiveness of the dryers. Samples were dried at 45 °C and 50 °C set temperatures and 0.5 m/s air velocity. According to dry basis calculation, initial moisture content amount was 7.06 g water/g dry matter and amount of final moisture content of dry matter was obtained as 0.14 g water/g dry matter. Energy efficiency varied between 5.3% and 50%. Minimum and maximum coefficients of performance for the whole system (COP_{ws}) were 2.11 and 2.96 respectively. Maximum exergy efficiency was obtained 66.8% while minimum exergy efficiency was 31.6%. It was concluded that during the time to reach a stable state of system, the exergy efficiency increased in response to exergy loss decreases. This study shows a successful and efficient combination of heat pump and infrared heater in food drying.

1. Introduction

The world population is increasing rapidly that makes difficult to access affordable and healthy perishable foods such as fresh fruits and vegetables throughout the year. The easiest way of continuous supply of perishable products is to dry them. Thus, all-year-round consumption of summer produce can be carried out. Drying of agricultural products has always been in great attention for the preservation of food. This process provides effective and practical preservation in order to reduce the losses after harvest [1]. Moisture removal of agricultural products need vaporizing water content of products that is energy intensive and time consuming process, so economic side of this treatment should be considered in analysis [2,3]. Deceleration of drying rate is caused by falling down the water content. Besides that, low thermal conductivity of food products is a limitation factor during convection heat transfer [4]. High quality production with minimum after treatment processes and energy requirement needs more scientific studies in food drying industries. Researchers had used different drying methods or combination of them to catch an optimum point in terms of drying time, energy consumption and product quality for different agricultural products.

Some researchers studied various dryers for drying vegetables and fruits. Akpinar (2005) evaluated practical convective heat transfer coefficient of various crops (potato, apple and pumpkin) in cyclone type dryer [5]. She indicated that air velocity was more effective variable than air temperature in forced convection phenomena. It was claimed that some parameters such as porosity, moisture content (MC), shape and size of crops, thermophysical properties, experimental working condition and experimental setup properties affect the heat transfer coefficient significantly. Heat pump dryer (HPD) is one of the effective methods in drying of product [6–8]. Closed loop dryers have some advantages due to hygienic conditions, efficient relative humidity control and high efficiency. The high oxygen amount in drying air leads to browning of product during the drying process. It is limited the oxygen amount in drying air due to usage of closed loop air circulation [9]. However, the arrival time to desired drying air temperature prolongs because of the dehumidification of drying air in closed air cycle. Their study shows that working period is shortened by

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Nomenclature

a_w	water activity
Bi	Biot number
$C_{p,air}$	specific heat capacity of air (kJ/kg K)
$\overline{C}_p$	average specific heat capacity (kJ/kg K)
COP_{hp}	coefficient of performance of the heat pump
COP_{ws}	coefficient of performance of whole system
D_e	effective diffusivity coefficient (m^2/s)
Di	Dincer number
DR	drying rate [g water/(g dry matter min)]
e	exergy (kJ/kg)
E	energy consumption (kJ)
E_f	energy consumption of fan (kJ)
E_{IR}	energy consumption of infrared lamp (kJ)
E_m	energy consumption of mixer (kJ)
E_C	energy consumption of compressor (kJ)
E_p	energy consumption of pump (kJ)
E_{xL}	exergy loss (kJ)
E_{xi}	inlet exergy (kJ)
E_{xo}	outlet exergy (kJ)
F	shape factor
h	enthalpy (kJ/kg)
h_{fg}	latent heat (kJ/kg)
h_m	mass transfer coefficient (m/s)
k_c	drying constant (1/min)
L	product thickness (m)
MC	moisture content (g water/g dry matter)
M_i	initial wet weight (g)
M_d	final dry weight (g)
M_e	equilibrium moisture content (g water/g dry matter)
M_o	initial moisture content (g water/g dry matter)
M	moisture content of the product at any level and at any time (g water/g dry matter)
MC_t	moisture content at time "t" (g water/g dry matter)
MC_{t+dt}	moisture content at time"t + dt" (g water/g dry matter)
MR	moisture ratio
m	product weight (kg)
m_w	vaporized water weight (kg)
$\dot{Q}$	mass flow rate (kg/s)
$\dot{Q}_{abs}$	absorbed energy (kW)
$\dot{Q}_{Cd}$	rate of heat delivered in condenser (kW)
Q_w	experimental heat used for moisture evaporation (kJ)
RH	relative humidity (%)
SEC	specific energy consumption (MJ/kg)
s	specific entropy (kJ/kg K)
T	temperature (K)
T_0	dead state temperature (K)
t	drying time (min)
V	velocity (m/s)
$\dot{W}$	rate of energy utilization (kW)
$\dot{w}_C$	power input to compressor (kW)
$\dot{w}_F$	power input to fan (kW)
$\dot{w}_{IR}$	power input to infrared lamp (kW)
$\dot{w}_M$	power input to mixer (kW)
$\dot{w}_P$	power input to pump (kW)
W_R	the total uncertainty (%)
w_1, w_2, w_n	the uncertainties in the independent variables
z	direction of diffusion process (m)
η_{ex}	exergetic efficiency (%)
ω	specific humidity (g/g)
σ	Stephan–Boltzman constant (W/m^2 K^4)
ε	emissivity factor

Subscripts

aai	ambient air inlet
ci	condenser inlet
db	dry bases
DC	drying chamber
emit	emitted
i	inlet
ia	inlet air
M	material
m	mixer
mp	moisture product
o	outlet
oa	outlet air
os	outside
R	the function uncertainty
rad	radiation
ref	reflected
s	surface
trans	transmitted
v	vapor
x	independent variables

using combination of both methods which indicate economical use of energy.

Infrared (IR) drying is also an effective method [10–12]. Apple slices were dried with near-infrared energy and convection drying by Nowak and Lewicki (2004). They found the IR drying as an efficient drying process for apple slices. They reported that the drying time was shortened about 50% with infrared drying process and the energy efficiency of the infrared dryer (IRD) was between 35% and 45% [10]. Wang et al., (2014) studied the effects of infrared wavelength and air velocity on drying characteristics of the shredded squid and qualities of dried squid products by setting the drying medium temperature of 50 °C. According to their findings, the heating and drying at the wavelength of 2.5–3.0 μm were more effective than those at the infrared wavelength of 5.0–6.0 μm. Microstructure observation showed that the infrared-dried rehydrated sample displayed a muscle fiber structure similar to the fresh sample. The infrared-dried squids had less drying shrinkage, brighter color, and better rehydration capacity than dried products with hot air [11]. Above all as a result, infrared drying with wavelength of 2.5–3.0 μm and air velocity of 0.5 m/s was suggested as the best drying conditions for squids in this study. Very low velocities are used in infrared drying. Aktaş et al., (2016) developed a HPD that contains simultaneous control of the relative humidity-temperature-air flow rate and compared an IRD which has proportional control and heat recovery unit [12]. They laid out the detailed advantages and disadvantages of designed dryers.

In literature, infrared dryers are generally used as cabinet type [11]. However, some researchers [2,13] have been used combined continuous conveyor belt with infrared and/or hot air dryer. Also, the pipe-shaped infrared lamps [12] are preferred for food drying as like as lamp-shaped [14,15] or plate-shaped. Studies on the infrared assisted heat pump dryer (IRAHPD) is limited. Some researchers studied on the IRAHPD [13,16,17]. Xiaoyong and Luming (2015) studied on the iron Yam chips drying using a HPD alone or in combination with far infrared (FIR) [17]. Deng et al. (2014) studied the effects of FIRAHPD on the thermal behavior, microstructure and protein quality of squid fillets. Results showed that different drying methods affect the compactness of the tissue