Energy Conversion and Management 68 (2013) 227–234

Contents lists available at SciVerse ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

Design, experimental investigation and analysis of a solar drying system ☆

Seyfi Şevik *

Mechanical Education Department, Technical Education Faculty, Gazi University, Teknikokullar, 06503 Ankara, Turkey

ARTICLE INFO

Article history:
Received 11 November 2012
Accepted 20 January 2013
Available online 21 February 2013

Keywords:
Solar air collector
Solar dryer
Heat pump
PID control
Carrot drying

ABSTRACT

In this experimental study, a new type solar dryer has been designed and manufactured by using double-pass solar air collector, heat pump and photovoltaic unit. The performance of solar dryer has been tested for carrot drying. In drying system, double-pass solar air collector (DPSAC) has provided the system heat energy requirement for drying process. Constant drying air temperature has been provided with PID (proportional-integral-derivative) control. Carrot slices were dried from initial moisture content 7.76 g water/g dry matter (dry basis) to final moisture content 0.1 g water/g dry matter (dry basis) at 50 °C drying air temperature and variable air volume. Velocity of air has been changed depending upon air inlet temperature of drying cabinet. During the drying operation, the air velocity was measured 0.4–0.9 m/s. The thermal efficiency of the double-pass collector was calculated from 60% to 78% according to experimental results. Carrot slices were dried at 220 min by using double-pass solar air collector in solar-heat pump dryer. Consequently, system (solar-heat pump dryer) can be comfortably operated without the need to the heat pump under normal ambient air conditions.

1. Introduction

The most important property of the solar energy is a renewable energy resource. Especially, solar energy which is an area to study extremely in drying due to they are easily applicable, simple construction and are getting technologic in recent years. In drying applications, solar air collectors are generally used. Solar air collector is a heat exchanger in the same time. Solar air collector as a heat exchanger transfers solar radiations to air from absorber panel. Thus, hot air is obtained from these collectors and they are used in space heating [1,2], product drying [3,4], greenhouse heating [5] and pre-heating in ventilation systems [6,7], etc.

Solar air collectors are simple device for air heating by utilizing solar energy for many applications which require low to moderate temperature below 60 °C such as drying and space heating. The principal types of these were classified as single pass (with front duct), single pass (rear duct), double duct and double-pass by Forson et al. [8]. Recently, many studies covering different type collectors have been undertaken by several researchers. Hot air generation and drying applications were examined with their designs [9–11]. A single-pass solar air collector [12] and a double-pass solar air collector [13–15] were designed and experimentally analyzed performance of collectors. Sencan and Özdemir [16] thermal performance of single-pass solar air collectors depends on the material, shape, dimension and layout. Wijeysundera et al. [17] concluded that double-pass solar air collector (DPSAC) designs performed better than the single-pass solar air collector (SPSAC) and determined an increase of 10–15% in collector efficiency. The efficiency of the double pass was obtained to be higher than the single pass by 34–45%, maximum efficiencies were found for the SPSAC and the DPSAC as 45.93% and 83.65% respectively by Aldabbagh et al. [18]. In the study of Sopian et al. [19] were reported that typical thermal efficiency of the DPSAC with porous media was about 60–70%. A collector which combines double air passage and porous media is significantly higher than the thermal efficiency of conventional air heaters, exceeding 75% under normal operating conditions. Similarly, Fudholi et al. [20] reported that the DPSAC with finned absorber has efficiency of more than 75% and also finned absorber was 8% more efficient than flat plate absorber.

There are over 500 dryer types for agricultural products in the literature. But, over 100 distinct types of these are commonly used [21]. Potato slices were dried in a continuous band dryer [22], in a convective cyclone dryer [23] and pistachio was dried by using solar energy [24]. Fatouh et al. [25] dried herbs, Ceylan and Aktaş [26] dried hazelnut using a heat pump dryer. Aktaş et al. [27] dried red pepper in a dryer which include heat pipe solar collector and heat pump.

Carrot (*Daucus carota* L.) is the most commonly used vegetable for human nutrition [28]. Carrot can be consumed as fresh, juice and dry. Recently, there have been many studies of the drying method of carrot; (infrared, fluidized bed, solar cabinet, convective air, cyclone type, freeze, vacuum and microwave, etc.) [28–39].

☆ The short form of this paper was presented in The European Workshop on Renewable Energy Systems (EWRES 2012), which took place on 17–28 September 2012, Antalya, Turkey.

* Tel.: +90 3122510678.
E-mail address: seyfisvk@hotmail.com

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http://dx.doi.org/10.1016/j.enconman.2013.01.013

Nomenclatures

c	specific heat (kJ/kg K)
dt	measuring the time interval (min)
F_k	collector surface area (m^2)
I_{DIR}	direct radiation (W/m^2 day)
I_{DIF}	diffuse radiation (W/m^2 day)
I_{TOT}	the energy gained from the total radiation striking the collector surface (W/m^2)
M_i	initial wet weight (g)
M_d	final dry weight (g)
M_t	moisture content at time "t" (g water/g dry matter)
M_{t+dt}	moisture content at "$t + dt$" (g water/g dry matter)
M_e	equilibrium moisture content (g water/g dry matter)
M_0	initial moisture content (g water/g dry matter)
$\dot{m}$	mass flow rate (kg/s)
n	the number of the day, starting from the January 1st
R	conversion coefficient
r_a	the reflection coefficient for the total solar radiation of the inclined plane perimeter ≈ 0.2
$\dot{Q}$	capacity of collector (kW)
T_{in}	outside air temperature (°C)
T_{out}	collector air outlet temperature (°C)
ΔT	temperature difference (°C)
t	time (min)
V	velocity (m/s)
$\dot{V}$	volumetric flow rate of air (m^3/s)
ν	average radiation values before atmosphere for the experiment months (W/m^2 day)
η	efficiency (%)
ρ	density of air (kg/m^3)
ε	opacity factor
θ	pitch angle (°)
φ	the average horizontal surface radiation value for the experiment day (W/m^2 day)
β	the angle of the solar collector and the horizontal plane (°)
δ	declination angle (°)
ϕ	latitude degree (°)
γ	azimuth angle (°)
ω	hour angle (°)
ϖ	specific humidity (g water/g dry air)

Subscripts

DR	drying rate (g water/g dry matter.min)
MC	moisture content (g water/g dry matter)
MR	moisture ratio, M/M_0
PID	proportional-integral-derivative
ia	inlet air
mp	moisture production
oa	outlet air
wi	water inlet
wo	water outlet

The factors that affect drying rate are air temperature, air velocity, product type, thickness of product, moisture content of the product, method of drying, and temperature and moisture diffusivity and drying kiln structure [40]. Effects of drying air temperature and flow rate are very important in drying applications. Karim and Hawlader [3] reported that a v-groove collector is 12% more efficient than a flat plate collector of similar design and efficiency of the collector is very much dependent on air flow rate. However, when above certain values are exceeded air flow rate have not too much effect in the drying applications [40]. Similarly, Mulet et al. [41] studied at 9 different drying air velocities (1000–9000 kg/m^2 h). It was found that for flow rates above 6000 kg/m^2 h indicating that when the air flow rate is high it has no influence on the drying rate.

PID control was created in 1942. It is a simple and powerful tool, especially since it allows obtaining decent regulation results with small investments. PID control represents the majority of the control tools used in the industry [42]. PID is used as a control tool in the drying industry, too. Recently, there have been many studies about automatic control systems in dryers. For example; fan speed control in forced convection solar dryer [43,44], PID controlled dryers; heat pump dryer [45], combine far-infrared radiation (FIR) and vacuum dryer [46], microwave–convective drying system [47], hot-air impingement dryer [48], the freeze dryer [49], nozzle atomizer spray dryer [50], infrared dryer [51], etc. Also, PID controller and four different fuzzy controllers were compared for the control of relative humidity and temperature drying parameters by Boeri et al. [52].

Drying is a process that requires high energy. Thus, drying units need efficient processes and alternative energy resources. The consumed energy amount to vaporize moisture per unit from product is important for energy economy in drying systems. So, in this study, heat pump assisted PID controlled DPSAC dryer was designed and system performance was analyzed experimentally by drying carrot slices.

2. Materials and methods

2.1. System design

The purpose of this paper is to carry out a quality product output with the design of an energy efficient system. For this objective; a system that used with together of heat pump was designed and manufactured. Also, PID control was added to DPSAC dryer. System consists of five parts in terms of design; there are PV unit, double pass solar air collector, heat pump, measuring equipments and automatic control system.

Double-pass solar air collectors have high efficiencies. Because of this, it was manufactured for this system (Fig. 1). Double pass air solar collector consists of parallel plate for air pass, an area that divides two parts owing to fin and absorber plate, the double glass cover on the top of the solar air collector and insulated parts on the bottom and side of the solar air collector. Because solar air collector has fins, the heat transfer coefficient and output temperature of air from collector increase. Thus, collector efficiency increases too. Heat is transmitted the collector and the heated air on collector is transferred to insulated drying chamber via a fan. Heat pump unit has been added to provide continuity to the system. Economy (energy, heat, cost, etc.), benefit, shape, control, etc., were taken into account while heat pump was designed. If the solar energy is insufficient for the system, the heat pump activates and the system operates non-stop. Thus, solar air collector and condenser of the heat pump can be used as heat energy resources in system.

Air flow of dryer; firstly, ambient air temperature (TRH1) is increased by heating in the double-pass solar air collector. Secondly, the heated air enters to the drying chamber by passing from the condenser (PT100 1-2). Lastly, the relative humidity of air increases and the air is exhausted.

In control system, PID control and similar equipments were added. In this system, fan is controlled with PID control system that the details are quite complex while the basic concept is sim-