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An experimental study of a heat pipe evacuated tube solar dryer with heat recovery system

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ABSTRACT

The current study designed, constructed and experimentally evaluated a heat-pipe evacuated tube solar dryer with heat a recovery system in which water was used as working and recovery fluid in the solar and dryer loops, respectively, and air was used as intermediate fluid in the dryer section. The heat recovery system was used to enhance the overall efficiency of the system and to make maximum use of solar energy intake of the dryer. The hot water in the storage tank, which is heated by the solar loop, is sent to the dryer, depending on the system requirement, and its heat in the heat exchanger is delivered to the blown air. The heated air enters the main chamber of dryer, where the drying products exist. This system was tested in the weather conditions of Sanandaj city and the obtained results indicated the effectiveness of heat recovery system. In volumetric flow rate of 0.0328 m^3/s, the maximum outlet air temperature of dryer was approximately 44.3 °C. At the end of the day, the exergetic efficiency of the system reaches its maximum rate, approximately 11.7%. Using regression analysis, the most accurate equation for expressing the effectiveness of dryer was obtained.

1. Introduction

Heat pipe is a double-phase instrument with very high thermal conductivity that is used for heat transfer. Heat pipes have lower thermal resistance than other metals and a compact heat pipe system has eliminated many restrictions of conventional collectors. High thermal conductivity, ability to function as a heat flow transmitter and isothermal level are the crucial properties of heat pipes for solar applications [1]. Ismail and Abogderah performed a theoretical and experimental comparison of heat pipe and conventional collectors. Methanol was utilized as the working fluid in heat pipes. Also, the slope of collector was considered to be 15° higher than the usual state for better condensation. The obtained results showed that heat pipe solar collector had a better efficiency than conventional solar collector [2]. Jun Feng et al. compared solar water heaters with all-glass vacuum tube collector and heat pipe solar water heaters with all-glass vacuum tube collector. The water circulation system was mandatorily designed and implemented. To analyze the performance, the instantaneous efficiency of the system was determined. The findings proved that heat pipe solar water heaters had less heat loss and better performance [3].

Drying the crops after harvest is essential for longer preservation. The drying process takes out the humidity of the crops and prevents the growth and reproduction of microorganisms. There exists various methods of drying, the most important of which are open sun drying, direct solar drying, indirect solar drying and mixed solar drying [4].

The first type of drying is open sun drying. In this method, crops are spread in thin layers and exposed to solar radiation [5]. Many agricultural products are dried under direct solar radiation, which can reduce their quality and quantity [6]. Despite inexpensiveness of this method, the final quality and quantity of the dried product is very much distant from the international standards. The first disadvantage of this drying method is the need for extensive manpower [7–9]. In addition, too much physical space occupation [10], dependence on environmental conditions [11], animals' attack, dust, humidity, lack of mass production, etc. are other disadvantages [5]. Jain & Tiwari studied the thermal performance of open sun drying and developed a mathematical model afterwards. Their results indicated that this drying method was very slow and had high loss and low quality [12].

The second method is direct solar drying. In this method, products are placed in a chamber and protected from wind and dust by a glass cover. It is a photovoltaic thermal dryer for green house

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Nomenclature

A	area (m^2)
a	air
C	heat capacity (Kj/Kg.°C)
c	collector
G	radiation (W/m^2)
h	enthalpy (Kj/Kg)
I	solar radiation (W/m^2)
i	inlet
m	mass rate (Kg/s)
o	outlet
q	heat rate (KW)
T	temperature
t	tank
w	water
0	dead state

Abbreviation

$\dot{Ex}$	exergy rate
he	Heat exchanger
Sc	solar collector
Sr	solar radiation

Greek letters

η	efficiency
ε	effectiveness

seedless grapes that was presented by Barnwal and Tiwari. In this system, evaporation of moisture, temperature around grapes, ambient temperature and moisture and greenhouse temperature were determined to analyze the heat transfer and mass. Finally, the results showed a satisfactory performance for the system [13]. In their study, Mühlbauer et al. evaluated the performance of this type of dryer and reported that low volumetric capacity is a limitation for this system [14]. According to [5] "In an indirect solar dryer, the sun's heat is first collected by the solar collectors and is then passed onto the dryer cabinet, where the drying occurs".

Eissen et al. investigated the performance of an indirect solar drying system. This system used a flat plate collector for inlet air heating. The heated air entered the dryer chamber through a duct. The maximum temperature recorded in the dryer was 50 °C. Finally, it was claimed that this system was highly efficient and economical. However, the average time of drying was 7–8 days [15]. Sharma et al. analyzed the performance of an indirect dryer and concluded that this method was able to yield high quality products in even non-ideal environments. The given system consisted of a flat plate collector, a drying chamber and pipes connecting the collector to dryer [16]. Kadam and Samuel developed and tested a solar drying system by using V-groove solar air collector. The major components of this system included galvanized iron plate, glass cover and air duct. The study was intended to determine the thermal efficiency of forced convection solar dryer to gain high quality products. It was found out that solar radiation was the most significant parameter in determining the thermal efficiency of the system [17]. Al-Juamily et al. constructed and tested a forced convection solar dryer in Iraq. The solar dryer consisted of a solar collector, a blower and a solar drying chamber. Two double-pass V-groove solar collectors were considered for this system. Having analyzed various parameters, it was concluded that air temperature was the most effective factor in the drying rate. The effect of air velocity change inside the drying chamber was low and could be ignored [18]. El-Beltagy et al. studied an indirect solar drying system under the weather conditions of Minufiya, Egypt. Their experimental results showed the high quality of final products. The performance of the solar collector in heating the air was reported to be satisfactory. At best, the ambient temperature was increased to 48 °C [19].

The third type of drying is mixed solar drying method, in which air is heated by the collector and enters the drying chamber. Due to transparency of the walls and ceiling of the chamber, solar energy is absorbed by the chamber, too [20]. Zomorodian et al. designed, tested and evaluated a mixed solar dryer to dry rice. They argued that their system was able to have a satisfactory efficiency. The maximum efficiency was reported to be 21.24% [21].

Design, development, and performance evaluation of various types of solar dryers were reviewed by Kumar et al. [22]. Techno-economic study and physical characteristics of different solar dryers were presented in their study. Also, Chauhan et al. [23] reviewed the application of software in solar drying systems. The importance of the application of software in developing and analyzing the mathematical models, used to predict the performance of different kinds of solar drying systems, was stated in the study.

Rittidech et al. [24] investigated the direct application of heat pipes in dryers. Closed-ended oscillating heat-pipes were used as air-preheater for energy thrift in a dryer. An experimental prototype was designed and built and the applicability of heat pipe air-preheater, as a heat recovery device, was studied.

Based on what was mentioned, the previous studies have evaluated the heat transfer of solar dryers in the realm of aerial systems and conventional collectors. To the best of the researchers' knowledge, few studies have evaluated another fluid or newer technologies of collectors used in dryers. Thus, the current study was aimed to design, manufacture and test a heat pipe solar dryer with a heat recovery system in which water is used as working and recovery fluid and air is used as intermediate fluid.

2. System description

As indicated in Fig. 1, the given experimental system consists of 1) a heat pipe collector, 2) a hot water tank, 3) a drying chamber, 4) an outer drying chamber, 5) two pumps, 6) a blower, 7) a heat exchanger, 8) a rotameter, 9) thermocouples, 10) an electric control valve, 11) a central control system and 12) pipes and fittings. As the sun is radiated on the surface of collector, the fluid in heat pipes is evaporated and moves toward the condenser area, located at the top of collector. On the other hand, the working fluid of solar cycle, regarded as a cooling fluid, is pumped to the condenser. This pump is controlled by two temperature sensors that are placed at the collector outlet and lower part of the tank. The pumped fluid condenses the working fluid of heat pipes by absorbing its vapor and concurrently increases its own temperature. The heated fluid enters the copper coil in the tank and transfers its heat to the water. Following the reduction of temperature, this fluid is conducted to the condenser again. The heated water in the tank is pumped to the dryer depending on the needs of the system. In the dryer, the hot water enters a heat exchanger and transfers its heat to the blown air by a fan. The heated air enters the main drying chamber. Then, the outlet hot water from the exchanger is analyzed in terms of