Performance characteristics of solar drying system for agricultural products

Xu Ji[*], Ming Li, Yunfeng Wang, Deli Ling, Xi Luo

Key Laboratory of Advanced Technique and Preparation for Renewable Energy Materials, Ministry of Education, School of Energy and Environmental Science, Yunnan Normal University, Kunming 650500, China

Drying has important influences on agricultural products' quality and storage. Drying characteristics of different agricultural products vary. Temperature and velocity of drying airflow affect greatly drying quality and drying efficiency of agricultural products. Two types of solar drying systems for different drying temperature requirement were designed and characterized in this paper: solar air drying system with plate air collector and solar parabolic trough concentrating drying system. In solar air drying system with plate air collector, the drying oven has two ventilation modes. With top inlet and bottom outlet ventilation mode, the overall temperature in drying oven is relatively high, however large vertical temperature difference exists in drying oven. With bottom inlet and top outlet ventilation mode, the temperature in drying oven is uniformity, however relatively low. In notoginseng drying experiment, the drying time is shortened to half of that in nature drying. The average thermal efficiency is 66.5%. The solar trough concentrating drying system utilizes a low cost and reliable V-type metal cavity to collect solar irradiation. In the system, the heat conducting oil can be heated to 230℃, and the air flow from heat exchanger reaches above 200℃. The tobacco shred drying experiments verifies that the drying temperature of the system meets the tobacco shred drying requirement. Solar trough concentrating drying system matchts the drying temperature scope of 80℃~200℃.

Keywords: solar drying, drying system for agricultural products, parabolic trough concentrating, drying temperature

INTRODUCTION

Drying is an essential processing technology for agricultural products, and affects directly their quality, appearance, taste and production cost [1,2]. Solar drying saves traditional energy, and improves the dried products' quality [3-5].

In 2001, Liu [6] employed solar collectors to dry corn. In 2005, Fadhel [7] performed solar grape drying by three different processes. In 2006, Turhan Koyuncu [8] designed six types of solar air collectors, and test their performances for crop drying. Md Azharul Karim [9] conducted performance evaluation on a V-groove solar air collector for drying applications. In 2008, Smitabhindu [10] conducted numerical simulation and experimental researches on economy and efficiency of a drying system with collector area of 26m² for bananas drying. Augustus Leon and Kumar [11] designed a solar-assisted biomass drying system with thermal storage. Utilizing the system, the moisture content of red hot chili peppers was decreased from 76.7% to 8.4% within 32.5 hours. In 2009, Sethi [12] improved solar greenhouse drying technology by using inclined northwall reflection. Zhao [13] investigated sewage sludge drying characteristics in solar greenhouse. In 2011, Romdhane [14] studied the orange peels dryings kinetics and developed a solar dryer by

forced convection. Afriyie [15] simulated and optimised the ventilation in a chimney-dependent solar crop dryer. Peng [16] discussed the energy saving ways of heat pump and solar energy bulk curing barn. With solar-assisted heat pump drying system, the energy cost was USD 0.15 for 1kg tobacco shred drying, and was cut by 32.86% comparing with heat pump alone. In 2012, Shobhana [17] studied test method for thermal performance based rating of various solar dryer. In 2013, Esakkimuthu [18] conducted experimental investigation on phase change material based thermal storage system for solar air heating applications. In 2014, Ahmad Fudholi [19] studied performance of a solar drying system for red chilli. The red chili was dried to final moisture content of 10% w.b from 80% w.b in 33 hours. Some drying applications for agriculture products require higher temperature. Solar trough concentrator can provide heat source to meet such temperature requirements. Tan [20] employed solar trough concentration system to produce electricity and thermal energy with higher temperature.

Generally, solar drying should meet the following conditions: There is abundant solar resource, and the drying system matches with the local climate.

SOLAR DRYING SYSTEM WITH PLATE AIR COLLECTOR

The solar drying system with plate air collector mainly consists of solar plate air collector, drying

* To whom all correspondence should be sent:
  jixu@ynnu.edu.cn

oven, vent-pipe, and draught fan, as shown in Fig.1. Two 2m² double-channel plate air collectors are connected in parallel in the system. The diameter of the vent-pipe is 15cm. The air flow direction in drying oven can be adjusted by regulating valve 1-4. The size of the drying oven is 1350mm×1070mm×960mm. In our experiments, the material to be dried is 8kg fresh notoginseng.
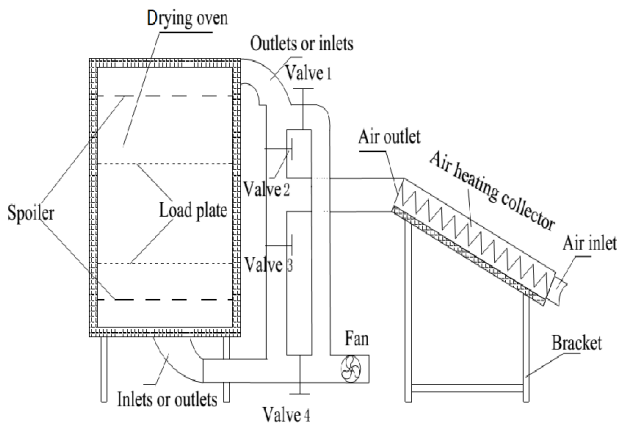

Fig.1. Schematic diagram of solar drying system with plate air collector

Three temperature sensors are separately fixed at the top, middle and bottom of the drying oven to record the temperature distribution in the drying oven. Three humidity sensors HD100S (KIMO instruments, France, measuring range 0~99%, accuracy ±1.8%RH) are respectively fixed at the inlet of the air heating collector, inside the oven and at the air outlet of the drying oven to measure relative humidity. The hot air flow rate in the vent-pipes is measured by the anemometer AR816 (Smarsensor, Hongkong, measuring range 0.3～30m/s, accuracy ±5%). The total radiation is measured by a pyranometer of TBQ-2 (Jinzhou sunshine technology Co. Ltd, China) with an accuracy of ±0.2%. Ambient temperature is also measured by a temperature sensor. All climatic data and temperature readings are recorded by a

computerized data logger (TRM-2) every 5 minutes during experiment.

Fig.2 shows the efficiency and the outlet temperature of solar air collector under different solar irradiation. In figure, the thermal efficiency is always beyond 50%. With sunny weather, the daily average thermal efficiency is above 60%. The outlet temperature of the air collector stays above 54℃.
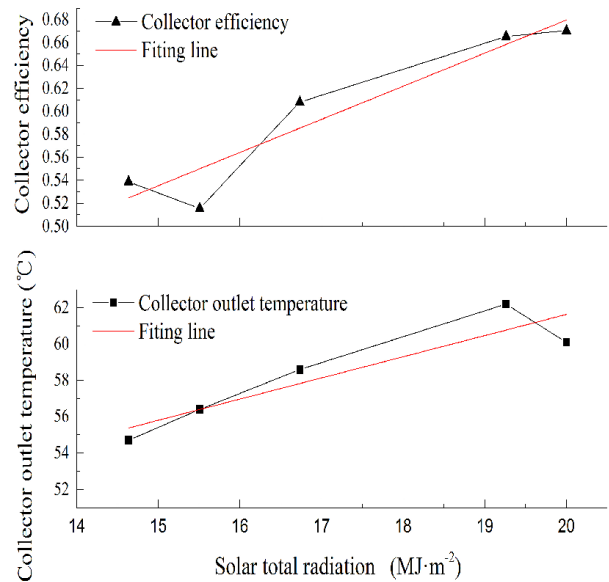

Fig.2. Efficiency and outlet temperature of solar air collector with different solar irradiation
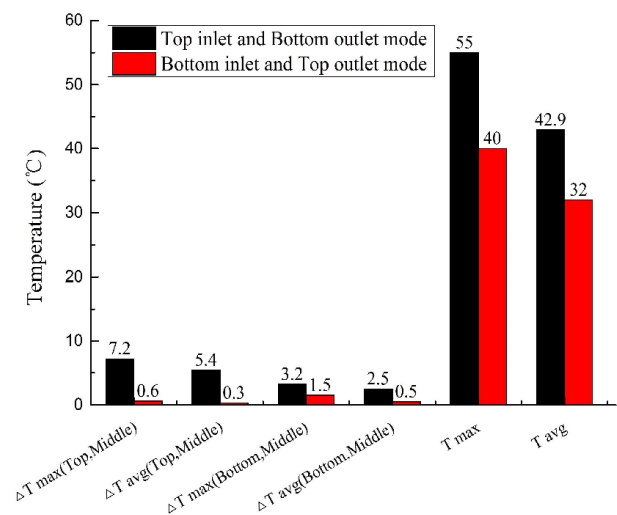

Fig.3. Temperature difference in drying oven with different ventilation modes

For the solar plate air-collector drying system, there are two ventilation modes for drying oven: the bottom outlet top inlet and the top inlet bottom outlet. Fig.3 shows the vertical temperature

differences in drying oven under two modes with the same inlet air flow rate.

With the top inlet and bottom outlet mode, there is large temperature difference between the top, middle and bottom sections of the drying oven. The highest temperature is at the top, and the lowest is at the bottom. The temperature difference between the bottom section and the air flow at the exit is also large. The maximum is up to 17℃, and the average is above 10 ℃. However, the overall temperature in drying oven increases quickly with the ventilation mode. After the system operates for 1 hour, the temperature at the top of the drying oven reaches 40℃, and the overall temperature in the drying oven exceeds 40 ℃ after 2 hours. Afterwards, with the increase of solar irradiance, the temperature in drying oven increases slowly and become gradually stable. The maximum temperature at the top section is 55℃. After 14:00 pm, with the decrease of solar irradiance, the temperature difference in drying oven gradually decreases due to the decrease of the inlet air flow temperature. At 16:00 pm, the temperature of each section in the drying oven approaches to 42℃, with a solar irradiation of 401W/m^2.

With the bottom inlet and top outlet mode, due to the relative high temperature and the relative low density of the air flow at the inlet, the hot air rises from the bottom of the drying oven. The air convection in the drying oven is strong, thus the temperature in the drying oven is relatively uniformity. The temperature difference in drying oven is approximately 1℃. The temperature at the bottom is a little higher and a little lower at the top. The temperature at the top and the temperature of the air flow at the exit is almost the same, and their maximum temperature difference is 2.3 ℃. However, the overall temperature in drying oven is relatively low. At 14:00 pm, with a solar irradiation of 990W·m^{-2}, the maximum temperature 40℃ is reached. It results from that the air flow temperature at the outlet is high, which causes a large heat loss. At the later period of drying process, the drying decelerates, and the required drying temperature need be guaranteed. The bottom inlet and top outlet ventilation mode adverse to energy saving and drying temperature guarantee.

Fig.4 compares notoginseng moisture content changes in solar drying process with the system and in nature drying process. After 450 minutes from drying initiating, the notoginseng moisture content decrease from the initial moisture content of 66.53% to the final moisture content of 17.15% by

utilizing the solar drying system，however, decreases to only 34.11% in nature drying process. With a more 450-minitues drying, the notoginseng moisture content reaches finally 18.36% in nature drying process. In figure, the notoginseng moisture content change rates have little difference within 100 minutes from drying initiating between solar drying process and nature drying process. It results from that the stripped moisture is the unbound moisture and the adhesive moisture in notoginseng in the stage. The bounding strength of these type of moisture is relatively weak, thus easy to dehydrate，and the dehydrating speeds depend mainly on the ambient temperature and the airflow velocity. Thereafter, the notoginseng moisture content change speeds with nature drying are lower than that with solar drying. In this stage, the moisture loss is mainly the bound moisture. This type of moisture is relatively hard to dehydrate，and the dehydrating speeds are mainly dependent on the relative humidity of the ambient air. The temperature in solar drying oven is higher than that in the ambient, thus the relative humidity is low. The moisture partial pressure in notogingseng is higher than that in the ambient air, which will push the moisture to move from the inner to the surface of the notogingseng. It results into the quicker drying with solar drying system.
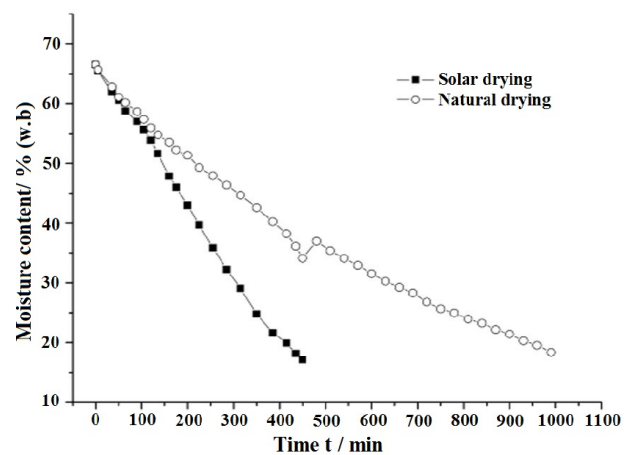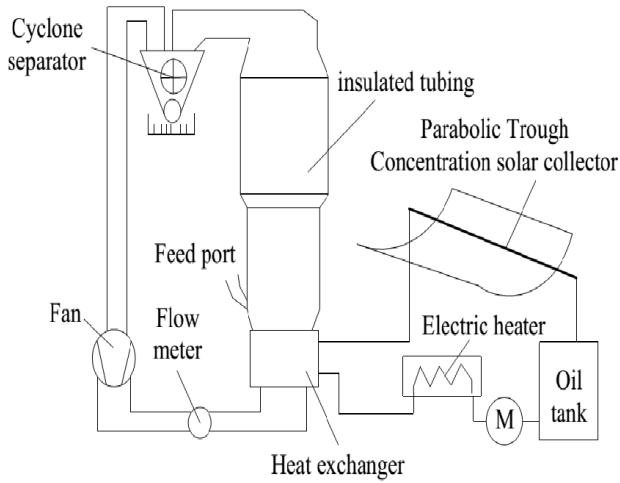

Fig.4. Notoginseng moisture content changes in solar drying process and nature drying process

SOLAR PARABOLIC TROUGH
CONCENTRATING DRYING SYSTEM

The solar parabolic trough concentrating drying system mainly consists of solar parabolic trough concentrator, V-type heat-collecting metal cavity, heat insulated oil tank, liquid-gas heat exchanger, vent-pipe and air drying tube, as shown in Fig.5.

Schematic diagram of solar parabolic trough
concentrating drying system
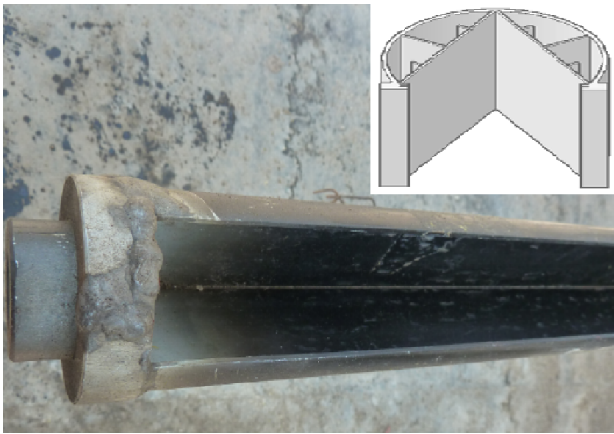
V-type heat-collecting metal cavity

Fig.5. Solar parabolic trough concentrating air drying
system

The solar parabolic trough concentrator collects and concentrates solar irradiation on the V-type heat-collecting metal cavity. A layer of anodic alumina film is electroplated on the heat-collecting surface of the V-type metal cavity to absorb solar irradiation. Some flat fins are arranged in the working medium channel between the heat-collecting surface and the outer surface of the V-type metal cavity to enhance heat transfer. Such V-type heat-collecting metal cavity has high heat collecting efficiency, and is reliable and low cost. The working medium-heat conducting oil flows through the channel and is heated, then is stored in the heat insulated oil tank. In liquid-gas heat exchanger, the heat is exchanged from the heat conducting oil to the air flow.

The material to be dried is tobacco shred, which is dried by hot air from heat exchanger. In order to obtain tobacco shred with high expansion rate and low tar content, a long straight drying tube is usually employed. The height of such straight drying tube reaches 12m, which results in high cost and strict requirement for plants. An adjustable air flow drying tube is designed to decrease the height of the drying tube, and matches with the solar parabolic trough concentrator. The adjustable drying tube consists of two straight tubes with different diameters, which are connected by employing a reducer tube. The length and diameter of the accelerating drying tube are 1.2m and 200mm, respectively. The length and diameter of the constant drying tube are 2m and 300mm, respectively. The taper angle of the reducer is 60°. All climatic data and temperatures are recorded in experiments.

The mass of heat conduction oil in the system is 42.65 kg. In sunny weather, after the system operates for 2 hours, the heat conducting oil temperature in the tank reached 230℃. Fig.6 shows the relationship between solar irradiation and the heat conduction oil temperature. Under solar irradiance around 1000W·m^{-2}, the heat conduction oil is heated from 20℃ to above 220℃ within 2 hours with a heat collection efficiency of 30%.
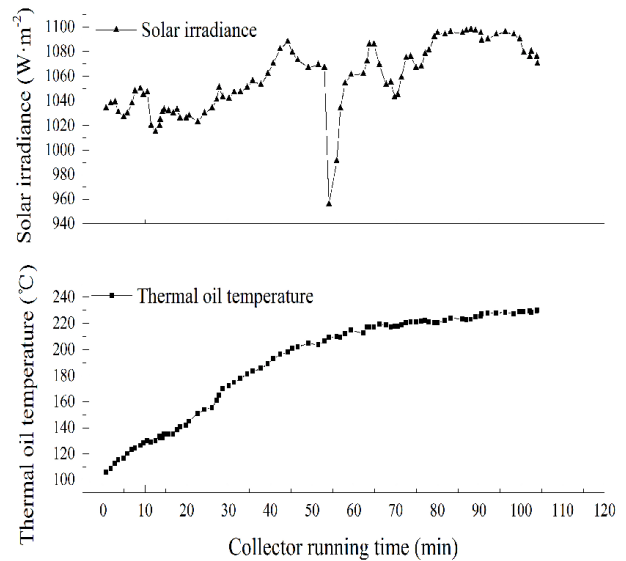

Fig.6. Heating performance of the parabolic trough concentrating system

The heat utilization degree of the drying system is described by heat efficiency η, the ratio of the temperature difference between inlet air temperature of drying tube T_i and outlet air temperature of drying tube T_o and the temperature difference between the inlet air temperature of

drying tube T_i and the inlet air temperature of the heat exchanger T, namely:

$$\eta = (T_i - T_o)/(T_i - T) \qquad (1)$$

Table 1. Drying performances of drying system for different tobacco shred

Type	T_i /℃	T_o /℃	$\Phi_{tobacco}$ /%	η/%
A	190.3	148.5	14.33	52.57
B	199.5	163.4	12.37	47.12
C	199.8	156.9	14.15	52.31
D	200.4	157.7	13.39	51.94

The drying performances of the drying system for four types of tobacco shred are given in Table 1. The initial moisture contents of four types of tobacco shred A, B, C, D are 24% ~ 26%. With the air flow rate of 15m/s, and the heat conduction oil flow rate of 0.4kg/s, the moisture contents are 12.3%~14.3% at the end of drying and meet the drying requirements. When the air temperature in drying tube increases, the outlet temperature of tobacco shred increase. However the moisture content of tobacco shred maintains at about 13%, and there is no obvious change. The drying efficiency maintains at around 50%. It is due to the fact when the tobacco shred moisture content reduce to below 14%, the moisture in tobacco shred mainly exists in the form of bound water, and the moisture content of tobacco shred has few changes.

In the parabolic trough concentrating system, according to the initial moisture content of the dried material, by regulating the air flow temperature and flow rate at the inlet of drying tube, the final moisture content requirement could be reached. The thermal efficiency of the drying system could be improved by better thermal insulation, sealing measures and preheating air and dried materials.

CONCLUSIONS

Two types of drying systems for different drying temperature requirements are designed and characterized. Solar plate air heat-collector drying system is for drying temperature within 80℃ and solar parabolic trough concentrating drying system is for drying temperature within 80℃~240℃.

In solar plate air heat-collector drying system, the air flow direction in drying oven is adjustable by regulating valves. The temperature and humidity uniformity in drying oven are improved by adopting suitable ventilation mode. In notoginseng drying experiment, the drying temperature reaches 62.2 ℃, and the average thermal efficiency is

66.5%. Even with cloudy weather, the heat efficiency of the system maintains over 50%.

By employing solar parabolic trough concentrator drying system, the tobacco shred drying experiments shows that the conductive oil temperature of 230℃ is reached, and the hot air temperature of 200℃ from the heat exchanger is obtained. The drying temperature meets the temperature requirement for tobacco shred drying.

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