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# GENERAL CHARACTERISTICS OF AN INDIRECT SOLAR DRYING DEVICE WITH NATURAL AIR CONVECTION AND HEAT PIPES

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**Abstract.** This paper analyzes the structural characteristics and operating principle of an indirect solar drying system based on natural air convection and the application of heat pipes. Particular attention is given to the instability of the drying process for agricultural products under variable climatic conditions, especially during cloudy periods when the temperature of the heated air in the solar collector fluctuates significantly. In order to improve the efficiency and stability of the drying process, a solar drying system with integrated heat pipes and a thermal accumulator in the solar collector is proposed. The developed system consists of a solar collector and a drying chamber hermetically connected to each other. Heat transfer is achieved through the evaporation and condensation processes of the working fluid inside the heat pipe, which ensures rapid transfer of latent heat to the heat exchanger located in the drying chamber. As a result, the efficiency of solar energy utilization increases and a more uniform thermal regime in the drying process is ensured. The results indicate that the integration of heat pipes and a thermal accumulator improves temperature stability, enhances the energy efficiency of the system, and contributes to maintaining the quality of dried agricultural products.

**Keywords:** solar dryer, indirect solar drying, heat pipe, natural air convection, solar air collector, thermal accumulator, heat transfer, drying chamber, agricultural product drying, energy efficiency.

**Аннотация.** В данной статье проанализированы конструктивные особенности и принцип работы косвенной солнечной сушильной установки, основанной на естественной конвекции воздуха и применении тепловых труб. Рассмотрены проблемы снижения стабильности процесса сушки сельскохозяйственной продукции при изменении погодных условий, особенно в облачные периоды, когда температура нагретого воздуха в солнечном коллекторе резко изменяется. Для повышения эффективности и устойчивости процесса сушки предложена конструкция солнечной



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сушильной установки, в которой в коллекторе интегрированы тепловые трубы и тепловой аккумулятор. Разработанная система состоит из солнечного коллектора и сушильной камеры, соединённых герметичным образом. Передача тепловой энергии осуществляется посредством испарения и конденсации рабочего тела внутри тепловой трубы, что обеспечивает быстрый перенос скрытой теплоты к теплообменнику, расположенному в сушильной камере. В результате повышается эффективность использования солнечной энергии и обеспечивается равномерность теплового режима в процессе сушки. Установлено, что применение тепловых труб и теплового аккумулятора способствует стабилизации температурного режима, повышению энергоэффективности установки и улучшению качества высушиваемой продукции.

**Ключевые слова:** солнечная сушилка, косвенная солнечная сушка, тепловая труба, естественная конвекция воздуха, солнечный коллектор, тепловой аккумулятор, теплообмен, сушильная камера, сушка сельскохозяйственной продукции, энергетическая эффективность.

**Annotatsiya.** Mazkur maqolada tabiiy havo konveksiyasi asosida ishlovchi va issiqlik quvurlari bilan jihozlangan bilvosita quyosh quritish qurilmasining tuzilishi hamda ishlash prinsipi tahlil qilingan. Tadqiqotda qishloq xo‘jaligi mahsulotlarini quritishda ob-havo sharoitlarining o‘zgarishi, ayniqsa bulutli kunlarda quritish jarayonining barqarorligi pasayishi muammolari ko‘rib chiqilgan. Ushbu muammoni bartaraf etish maqsadida quyosh kollektoriga issiqlik quvurlari va issiqlik akkumulyatori integratsiya qilingan konstruktsiya taklif etilgan. Qurilma kollektor qismi va quritish kamerasidan iborat bo‘lib, unda issiqlik quvuri orqali hosil bo‘lgan bug‘ issiqlik almashtirgichga uzatiladi va quritish kamerasidagi havoni isitadi. Natijada quritish jarayonining samaradorligi oshadi hamda issiqlik energiyasidan samarali foydalanish ta’minlanadi. Tadqiqot natijalari shuni ko‘rsatadiki, issiqlik quvuri va issiqlik akkumulyatori qo‘llanilishi quritish jarayonining uzluksizligini ta’minlab, mahsulot sifatini saqlashga xizmat qiladi.

**Kalit so‘zlar:** quyosh quritgichi, bilvosita quyosh quritish, issiqlik quvuri, tabiiy konveksiya, quyosh kollektori, issiqlik akkumulyatori, quritish kamerasi, issiqlik almashinuvi, qishloq xo‘jaligi mahsulotlarini quritish, energiya samaradorligi.

## INTRODUCTION

It is well known that on cloudy and sunless days the temperature of the air heated in a solar air collector varies significantly. Such fluctuations negatively affect the quality of dried grapes. This can be explained by the fact that the temperature of the grape pulp decreases as the moisture evaporation temperature decreases. When the temperature subsequently rises, before the moisture from the



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inner layers of the grapes has completely evaporated, the surface of the fruit dries out and forms a dense hardened crust.

Under such conditions, it is advisable to use combined solar drying systems equipped with additional thermal storage units that reduce the influence of fluctuations in thermal load. To address this problem, the use of heat pipes is considered highly effective. This is due to the fact that heat pipes possess a number of advantages, including a high heat transfer rate, simple construction that does not require a large amount of material, high operational reliability, good adaptability to various operating conditions, the absence of moving mechanical components, a long service life, and the ability to maintain performance under different phase states of the working fluid (liquid and vapor).

## LITERATURE REVIEW

Theoretical and experimental studies have been carried out on various designs of combined and hybrid solar drying systems intended for drying agricultural products. Italian researchers Sharma et al. [1] developed and investigated a multistage indirect solar drying unit. In this system, two types of solar air collectors operating at low and medium temperatures are installed on two sides of the drying chamber. Air is drawn through the collectors by means of a fan. The rear side of the air collector is covered with a polyurethane plate in order to minimize heat losses.

The drying chamber is divided into three sections, two of which are used directly for the drying process, while the third is intended for maintenance. The two drying chambers are separately connected to the low-temperature and medium-temperature solar air collectors, respectively. The capacity of each drying chamber ranges from 500 to 3500 kg [2]. The air heated in the collectors passes through a thin layer of material placed on trays. During grape drying, a constant air flow rate of 400 $m^3/h$ is maintained. It was established that the low-temperature solar air collector can heat the air up to 55-60 °C, whereas the medium-temperature solar air collector heats the air up to 75-80 °C at midday. According to the obtained results, the drying time for 90 kg of grapes is 5-7 days.

German researchers Lutz et al. [3] developed and investigated a solar tunnel drying system with an integrated collector. This type of solar dryer is used for large-scale drying processes. The drying unit consists of a solar collector and a tunnel dryer. The grapes to be dried are placed inside the tunnel dryer in a thin layer. Part of the solar energy is absorbed by the collector absorber, while the remaining part is absorbed directly by the grapes. To increase the efficiency of the collector and the tunnel dryer, the tunnels are arranged in parallel. The length of the solar drying system is 20 m, and its width is 2 m. The collector length is also 20 m, with a width



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of 1 m. The tunnel dryer is designed for a load of up to 1000 kg of grapes. Both the collector and the drying chamber are covered with a transparent film. A black metal plate is installed between the walls of the collector and the dryer [4]. To reduce heat losses, the rear side of the collector is covered with thermal insulation material. A vertical radial fan mounted directly on the collector frame supplies air through the collector. The drying air passes along the entire length of the collector and is heated by solar radiation.

At the end of the collector, the air flow turns 180° and enters the tunnel dryer. In order to ensure uniform air distribution across the cross-section of the dryer, baffles are installed in the receiver section. Mesh filters are installed at both the air inlet and outlet to protect the grapes from insect damage. During rainy periods, the air inlet and outlet channels are closed. The payback period of this system is 1-3 years. The grape drying period, depending on weather conditions, ranges from 4 to 7 days. Algerian researchers Abene et al. [5] developed an indirect solar drying system with a solar air collector, in which special baffles were used. The system consists of a flat-plate solar air collector, a drying chamber, and a fan. The upper part of the solar collector is covered with a 1 cm thick transparent polycarbonate sheet. The absorber of the collector is made of an aluminum plate painted black. Baffles with a thickness of 0.4 mm and a height of 2 cm are installed on the surface of the absorber plate. The outer part of the collector is insulated with a 5 cm thick polystyrene layer. The collector is installed at an angle of 45° to the horizontal

The presence of baffles in the air channel promotes more efficient heat extraction from the absorber located between the transparent cover and the insulation, which in turn increases the temperature of the air entering the drying chamber through the collector. It was found that at an air flow velocity of 31.3 $m^3/(h \cdot m^2)$, the drying time of grapes using a flat-plate collector is 13 h 20 min, whereas when cross-longitudinal baffles are used in the collector, the drying time is reduced to 5 h 50 min [6]. The introduction of baffles into the air channel increases the productivity of the drying system, which in turn reduces the drying time of grapes.

## RESEARCH METHODOLOGY

When solar drying systems are used, the drying process is significantly influenced by the geographical characteristics of the region and natural climatic conditions. In particular, under sharply continental climatic conditions, the occurrence of cloudy periods during the day leads to considerable fluctuations in process parameters, which negatively affects the quality of the dried products. Such problems have not been sufficiently addressed in the scientific studies of both foreign and domestic researchers [7]. In existing drying systems, one of the most



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challenging technological issues is the control of abrupt variations in the temperature of the drying agent and the surface temperature of the product under cloudy conditions.

To solve this problem, the application of heat pipes in the structural models of solar drying systems has been proposed. According to the proposed design, the heat pipe system is integrated into the solar collector and the drying cabinet of the installation. The solar drying system consists of the following two main parts:

- a solar collector in which a heat pipe and a thermal storage unit are installed;
- a drying cabinet containing a heat exchanger, shelves for placing the material to be dried, and a chimney for removing the vapor–air mixture.

The flat-plate solar collector is designed in the form of a thermally insulated box in which the heat pipe and the thermal accumulator are installed. The collector housing is made of stainless material and hermetically sealed [8]. The solar dryer and the chamber of the drying cabinet include the following structural elements: a chamber thermally insulated from the surrounding environment; openings for the supply of airflow; an air filtration system; a heat exchange device; trays and shelves for placing grapes; a chimney located in the upper part of the chamber and designed to remove the vapor–air mixture from the drying chamber to the environment; and an additional glass cover installed near the chimney of the chamber.

The operating principle of the heat pipe is as follows. A working fluid is contained inside the heat pipe [9]. When heat flux is supplied to the surface of the heat pipe, the liquid inside evaporates. The generated vapor moves at high velocity toward the heat exchanger and condenses on its inner surface. During this process, the latent heat of condensation is transferred to the outer surface of the heat exchanger, after which the condensate returns back to the heat pipe. The heat pipe is located in the collector of the solar drying system, while the heat exchanger is placed in the drying cabinet [10]. Such a heat pipe system has been integrated into the collector of the solar drying installation.

The operating principle of the solar drying system is as follows:

- solar radiation passes through the transparent surface of the collector and falls on the surfaces of the heat pipe and the thermal accumulator, resulting in their heating;
- the working fluid inside the heat pipe evaporates, and the generated vapor moves through the pipe toward the heat exchanger, where it condenses and subsequently returns to the heat pipe;
- since the heat exchanger is located inside the drying cabinet, the latent heat of vapor condensation is transferred to the air surrounding the heat exchanger, causing the air to heat up and move upward toward the upper chimney;



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- the rising heated air transfers heat to the product placed on the shelves of the drying cabinet, which results in the evaporation of moisture from the product and the formation of a vapor–air mixture;

- the formed vapor–air mixture is removed from the drying cabinet through the chimney located in its upper part.

It should be noted that the application of heat pipes in the structural designs of solar drying systems in this manner has not been sufficiently presented or widely discussed in the scientific publications of international researchers.

**ANALYSIS RESULTS OF THE STRUCTURAL ELEMENTS**

Taking the above into account, a schematic diagram of a combined indirect solar drying system with natural air convection and heat pipes was developed (Fig. 1) [11]. The flat-plate solar collector equipped with heat pipes and the drying chamber (cabinet) are installed sequentially and are hermetically connected to each other.

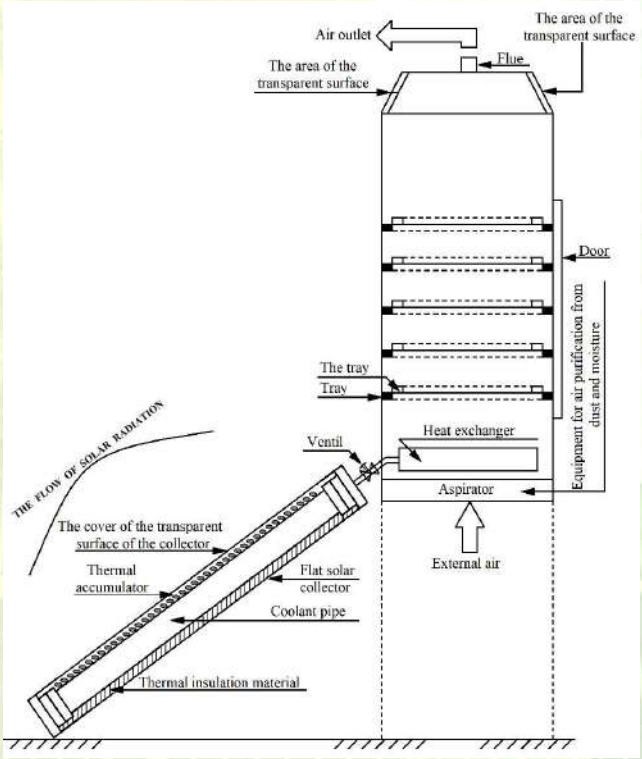



**Fig. 1. Combined indirect solar drying system with heat pipes and a thermal accumulator.**

The overall dimensions of the solar collector are 0.61 × 0.11 × 1.14 m, while the area of its transparent surface is 0.7 m². The flat-plate solar collector is designed in the form of a thermally insulated box (parallelepiped). The frame of the box is made of wooden beams with a cross-sectional area of 0.0016 m² [12]. Both sides of the collector beams are covered with metal plates 0.0012 m thick, with a spacing of 0.04 m between them. The space between the metal plates is filled with thermal insulation material (foam plastic). In the upper part of the parallelepiped, at the



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location where the chimney is installed, a glass cover with a thickness of 0.04 m is provided. Five holes are made in the upper side wall of the collector to allow the pipes connecting the heat pipe of the collector with the heat exchanger to pass through. The efficiency of the developed solar drying system directly depends on the area of the transparent surface of the solar collector, the material and heat capacity of the thermal storage unit, and the stable operation of the heat pipe.

Inside the flat-plate solar collector, five cylindrical heat pipes made of stainless steel are installed (Fig. 2). The total length of each heat pipe is 0.962 m, the outer diameter of the pipe is 0.074 m, and the inner diameter is 0.068 m [13]. Flanges are welded to both ends of the heat pipe, with an outer diameter of 0.108 m, an inner diameter of 0.068 m, and a thickness of 0.01 m. In addition, each flange contains six holes with a diameter of 0.01 m, intended for fastening using hexagonal nuts and M10 bolts.

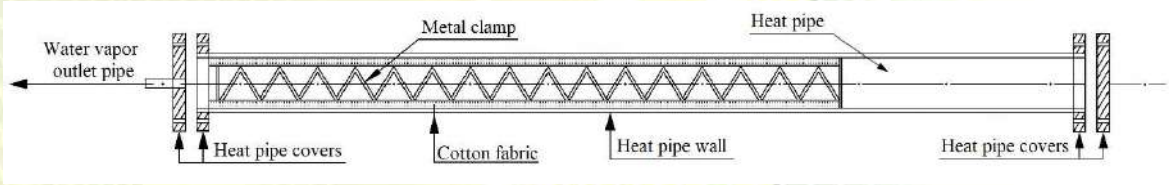



**Fig. 2. Heat pipe manufactured for an indirect solar drying system.**

Distilled water is filled up to half of the volume of the heat pipe. After that, the flange covers mounted on the flanges welded to both ends of the cylindrical pipe are sealed using rubber gaskets and fastened with metal nuts (bolts). Each flange cover is provided with six holes with a diameter of 0.01 m. One of the flange covers is blind, whereas the center of the other contains a hole with a diameter of 0.015 m, to which a pipe with an outer diameter of 0.015 m is welded. The other end of this pipe is welded to the heat exchanger, which is installed in the lower part of the drying cabinet.

Inside the heat pipe, a wick made of natural cotton fabric is installed. The water absorption capacity of the material depends on the density of the fabric, which is determined by the number of cotton threads per centimeter of material. In this study, cotton fabric with an average density of 450-600 g/m was used [14]. In addition, a cylindrical metal mesh frame is installed inside the heat pipe. The diameter of the mesh wire is 0.002 m, and the spacing between the wires is 0.01 m. The main function of this cylindrical mesh structure is to hold the wick in close contact with the inner surface of the heat pipe. The outer diameter of the cylindrical heat pipe is 0.068 m, and its length is 0.95 m. The volume of the wick material is 0.013 $m^3$, the water absorption rate is $17.5 \times 10^{-6}$ $m^3/h$, the density is 1650 $kg/m^3$, the specific heat capacity is 0.88 kJ/(kg·°C), and the thermal conductivity is 0.291 W/(m·°C) [5].



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The housing of the drying chamber is manufactured in the form of a parallelepiped using a four-sided wooden beam with a cross-section of 0.03 × 0.03 m. On both sides, the beam is covered with metal plates with a thickness of 0.001 m and plywood sheets with a thickness of 0.003 m, while the space between the two plywood layers is filled with thermal insulation material [15]. In the lower part of the drying cabinet, a metal plate with a thickness of 0.0012 m and eight holes with a diameter of 0.001 m is installed. Fabric air filters of G1 and G2 grades are placed on the surface of this metal plate. According to the width of the solar collector, the width of the drying chamber is 0.66 m, while its external dimensions are 0.66 × 0.48 × 0.10 m. In the lower part of the cabinet, an aspirator (air filters of classes G1 and G2), a heat exchanger, shelves and trays for placing the product, and an additional transparent cover are installed, while a chimney is mounted in the upper part of the cabinet. The surrounding environment contains a large number of pollutants, including dust, soot, microorganisms, and other harmful impurities. When these contaminants settle on the surface of the dried products, they can degrade product quality, and the consumption of such products may pose a risk to human health. For ventilation of the drying cabinet, coarse air filters (G1, G4) are used, which are capable of retaining particles larger than 10 μm, such as sand, dust, and fibers. The main filter materials are polyester, polyurethane foam, and fiberglass, manufactured using thermal bonding technology. Coarse air filtration materials are used in conditions where strict air cleanliness requirements are not necessary. The G1 filter can remove up to 65% of large dust particles, fine fibrous dust, oil vapors, sand, and welding sparks, whereas the G4 filter can remove up to 90% of aerosols, milk powder particles, zinc oxide vapors, and fine dust.

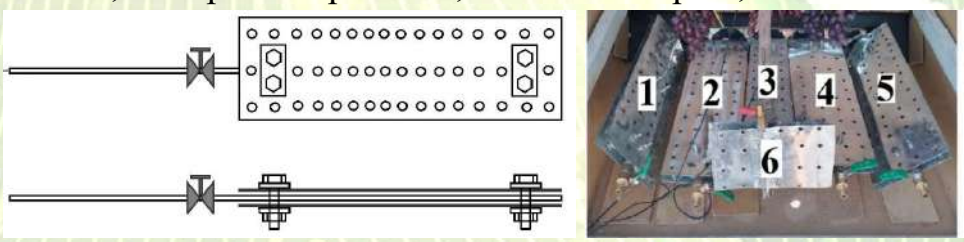



**Fig. 3. Schematic diagram and general view of the heat exchanger of the solar drying system.**

To measure the air purification level and monitor air quality inside the drying chamber, an ABA-1-150-02C aspirator was used. The air purification efficiency inside the chamber reached 80%. The technical characteristics of the aspirator are provided in the appendix of the dissertation. A separate heat exchanger is provided for each heat pipe (Fig. 3). The heat exchanger consists of two parallel flat metal plates with dimensions of 0.22 × 0.47 × 0.001 m, with a spacing of 0.0015 m between them. These plates are attached to the pipe. Each plate contains 48 holes



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with a diameter of 0.005 m. Trays are placed on shelves installed along the inner walls of the drying cabinet. These trays are made of rectangular wooden bars with a cross-section of 0.03 × 0.03 m. The dimensions of each tray are 0.03 × 0.03 m, and they are designed to be easily removable from the shelves. The distance between adjacent trays ranges from 0.15 to 0.18 m.

In the upper part of the drying cabinet, four additional trapezoidal transparent surfaces are installed and oriented toward the north, south, west, and east, respectively. Their dimensions correspond to the external dimensions of the drying chamber. These additional transparent surfaces are installed at an angle of 45° to the horizontal. The total area of the transparent surfaces is 0.091 m². A chimney made of cylindrical metal sheet is installed at the top of the drying cabinet. The height of the chimney is 0.20 m, and its diameter is 0.09 m. A freely rotating blade-type turbodeflector is mounted at the outlet of the chimney. On the northern side of the drying chamber, a door made of thermal insulation material is installed, which serves to protect the chamber from the thermal influence of the surrounding environment.

## CONCLUSIONS AND RECOMMENDATIONS

An analysis of the operating principle and structural features of an indirect solar drying system based on a combination of natural air convection and heat pipes was carried out. The research results show that the heat pipe installed in the collector ensures the high-speed transfer of thermal energy generated in the solar collector to the drying chamber through water vapor acting as the heat carrier. This, in turn, contributes to an increase in the efficiency of the drying process. In addition, the thermal accumulator installed within the collector stores the thermal energy accumulated during the day and enables the continuation of the drying process during evening and nighttime periods. The air filter used in the system protects the dried products from various dust particles and improves the hygienic conditions of the drying process. The inflow of air from the external environment is ensured through openings located in the lower part of the drying chamber, which promotes natural air circulation within the chamber.

The proposed solar drying system differs from existing dryers by the presence of a heat pipe installed inside the solar collector, as well as a heat exchanger hermetically connected to it. Such a structural solution allows efficient organization of heat transfer within the drying chamber. In order to further improve the efficiency of the drying cabinet, the installation of additional trapezoidal transparent covers in its upper part is recommended. These covers should preferably be oriented toward the north, south, west, and east directions. Placing the additional transparent surfaces at an angle of 45° to the horizontal ensures more



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effective absorption of solar radiation. Their dimensions should correspond to the external dimensions of the drying chamber. It is recommended that the total area of the transparent surfaces be approximately 0.091 m². The proposed structural solution enhances heat accumulation in the drying chamber, increases the efficiency of solar energy utilization, and improves the overall energy efficiency of the drying process.

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