**Combined solar-fuel drying plant for drying agricultural products**

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**Abstract.** The article presents the development materials of a combined solar-fuel drying unit of a cradle-conveyor type for drying agricultural products with IR radiation, operating in a closed-loop mode. Due to the constant, uniform movement of the drying fluid along a closed circuit, the entire mass of the product being dried is uniformly coated with a flow of drying agent and subjected to intense heat treatment. The superimposed effect of infrared radiation, combined with convective heat exchange, intensifies the heat and mass transfer process and reduces drying time.

**INTRODUCTION**

In the world, the cultivation of environmentally friendly grapes, fruits and vegetables and melons takes a leading place in order to ensure food security. If we take into account that “60-70 million tons of grapes are grown annually in the world and 3.5-4.2 million tons of them are dried”, then one of the most important tasks is considered to be the development of energy-saving technical means and devices with high quality of operation and productivity for the production of dried grapes, i.e. sultanas [1].

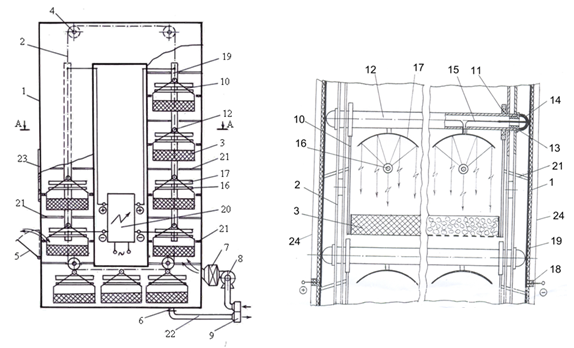
In this direction, certain successes have been achieved in foreign countries, including the USA, France, Spain, Portugal, the Russian Federation, Ukraine, the Republic of Belarus, the Republic of Moldova, Turkey, China, India, Australia and other countries “Special attention is paid to the development of technical and technologically modernized resource-saving technical means for processing and drying grapes” [2].

Research and development work is underway around the world to develop resource-saving methods and new scientific and technical solutions for the technological process of producing dried fruit products. In this regard, in particular, it is important to improve the production of dried fruit products, create innovative technologies and new technical means, as well as substantiate technological work processes. One of the important tasks is the high-quality processing of fruit products during drying, achieving high quality of work and productivity, as well as energy and resource conservation by ensuring the rhythmic operation of drying equipment. In this aspect, the development of combined technical means for new grape drying technology is in demand.

**OBJECT OF STUDY**

The objects of the study are a combined solar-fuel drying unit of the cradle-conveyor type, which we developed, which simultaneously incorporates the principle of the effect of IR radiation and convective heat exchange on dried grapes and other high-moisture agricultural products (Fig. 1-2) [3, 4, 5].

The combined drying plant for fruit and vegetable products comprises a vertically installed closed metal chamber 1 of O-shape, having a rectangular cross-section, load-bearing mesh pallets 3 installed inside the chamber on a traction chain 2, a drive 4, loading and unloading hatch 5 with a door, pipe 6 for exhausting spent drying agent, electric heater 7, fan 8 and ring heat regenerator 9. The pallet 3 is secured by means of a shackle 10 and a bearing support 11 on a hollow shaft 12, the ends of which in turn are secured on mirror-opposite branches of the traction chain 2. At both ends of the shaft 12, a hemispherical contactor of the electric circuit 14 is mounted through an insulator 13, the output of which is connected through an electric cable 15 to infrared emitters 16 installed in rows. Above the emitters 16, reflectors 17 with a parabolic cross-section are installed. The latter is secured to the shaft 12 at a calculated distance from the surface of the tray 3. On the opposite side vertical walls of chamber 1, on the inside, on insulators 18, a conductive busbar 19 is fixed, connected to a power supply unit 20. Flexible cuffs 21 are fixed at a calculated pitch on the vertical sections of chamber 1 from the inside. The exhaust pipe for the spent drying agent communicates through a collector 22 with the exhaust pipe of the annular regenerator 9 of the “Yugstream” type. For visual inspection of the drying process, a glass viewing window 23 is provided on the side wall of chamber 1. The temperature and humidity conditions of the drying process are controlled by known instrumentation and automation equipment (not shown in Fig. 1).



**FIGURE 1.** Combined solar-fuel drying plant of cradle-conveyor type with infrared radiation

The drying plant operates as follows. With discrete-intermittent movement of the traction chain 2 along the closed circuit of the chamber 1, when the mesh trays 3 approach the loading/unloading hatch 5, the product to be dried is alternately loaded/unloaded into them: for example, grapes, apricots, apples cut into pieces, carrots, etc. After loading all pallets 3 and closing hatch door 5, turn on drive 4 of traction chain 2 for continuous operation. Simultaneously, turn on fan 8, electric heater 7, and regenerator 9, as well as power supply 20 for IR emitters 16. The supplied hot air with a temperature of t=60 – 90 0C blows onto the product lying in the cradles, which is simultaneously exposed to IR radiation. If, on average, the temperature of the drying agent at the inlet to the recirculation circuit was t=36 – 46 0C, then due to the radiation absorption capacity of the chamber surface (during the daytime with intense solar insolation), its temperature at the outlet pipe reaches about t=56 –58 0C. The heated air enters the regenerator, where it releases heat as it is sucked in by a fan into a new batch of air. Once the drying process is complete, the product is removed and a new batch is loaded.

**EXPERIMENTAL RESEARCH**

In the heat engineering calculation of the STLC-700 cradle-conveyor type, the engineering approach to determining the energy output limits for the application of energy-saving technology is of practical interest [6-11].

Let us consider the operation of the STLC-700 during the daytime, when the effect of solar insolation reaches its maximum value.

In general, the amount of useful energy regenerated in a ventilated air gap is determined by:

(1)

where *Lb* - is the consumption of drying agent (air), kg/s;

*Cb*– specific heat capacity of air, J/(kg K);

*tbix, tbx*– respectively, the temperature of the drying agent at the outlet and inlet of the ventilated layer, 0C.

As follows *tbix, tbx*, a positive effect is obtained, i.e.*Qpogl > Q.*

On the other hand, the heat received from solar radiation by the surface of the chamber is equal to

(2)

where *Fk* – light-absorbing surface area of the chamber, m2;

*ƞk* – coefficient of efficiency of the heat receiver;

*qcp* – specific density of solar radiation, W/m2;

*kf* – heat transfer coefficient from the main drying agent to the regenerated one;

*kpr*– heat loss coefficient;

*tc, tf* – respectively, the average temperatures of the drying agent at the entrance and exit into the air gap, K;

t0 – ambient temperature, K.

Solving equations (1) and (2), taking into account that the temperature of the main drying agent at the outlet of the chamber *tf.vix* equal to the temperature of the regenerated coolant at the entrance to the air gap *tf*, we obtain:

(3)

If the condition *tbix > tbx* is met, taking into account solution (3), it turns out that a positive energy-saving effect is achieved at temperatures of the spent drying agent before entering the air gap of the chamber t*bx* less than:

(4)

or mathematically transforming, we get

(5)

As can be seen, expression (5) is a linear equation with an angular coefficient

**RESEARCH RESULTS**

Using the example of calculating the STLC-700 cradle-conveyor type for drying grapes with a capacity of 720-800 kg per one loading cycle (τ=36 h), the approximate dimensions of the drying chamber were determined. For design reasons, the following is accepted: cross-section (A×B) = 1000×750 mm; height H = 6000 mm; width of the opening between the ascending and descending sections B = 1000 mm; depth of the gap of the ventilated layer h = 50 mm.

In this case, the consumption of the main drying agent (air) varied within the range of Gb=250-300 m3/hour, and its temperature at the entrance to the chamber was set at the beginning of drying *tср.их*=100 0С.

With a total calculated light-absorbing surface of the chamber *Fk*=44 m2, taking into account the optimal mode of recirculation of the spent coolant through the air gap and the average integral temperature at the outlet *tf*=62 0C, the following were determined:

Substituting these values into the inequality, we obtain:

(6)

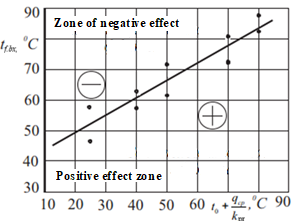
Graphical dependency from in the optimal mode of suction of spent drying agent from the air gap of the chamber according to the results of experimental studies is shown in Fig. 2.

As can be seen from Fig. 2, at temperatures higher than tf in determined by formula (6), the energy-saving effect is negative, i.e. the experimental point is located above the straight line. It should be noted that the minimum value of *tf b*x when the dryer is operating at night, when qcp= 0 and tо ≈ 20 0С is *tf bx* ≈ 47-49 0С.

It is known that the expression for the flow of useful energy in an air collector has the form

(7)

from which it follows that the savings of traditional energy sources depend on the thermal efficiency of the solar air heater η, i.e. on the beam of the absorbing panel and the ventilated air gap. All other things being equal, the energy saving effect in the considered STLC-700 depends on the amount of energy absorbed by the blackened surface of the drying chamber wall *qcp*.



**FIGURE 2.** Graphical dependency

The latter, in turn, depends on the optimal orientation and location of the drying chamber in relation to the cardinal points, with the maximum outer ray-absorbing surface facing the sun's rays.

The calculations performed showed that with an effective useful beam of the absorbing surface Fk=44 m2, the share of the solar radiation component in the meridional location of the installation for August is 33.5% of the total, and in the latitudinal direction - 43.2%.

During daylight hours of operation with solar radiation intensity q=412-444 W/m2 and insolation time from 8.0-17.0 h, the share of energy absorbed by the outer surface of the STLC is 6.5% of the total energy balance *Q*= 19.6 kW. The calculations performed confirm the advisability of locating the STLC with its maximum surface in the latitudinal direction.

The developed drying system has a high level of technological flexibility, since it can be used for drying various heat-sensitive and heat-labile products while maintaining their high quality and physical and chemical composition. Also, due to the constant uniform movement along a closed circuit, the entire mass of the product being dried is uniformly coated with a flow of drying agent and subjected to intensive heat treatment. The superimposed effect of IR radiation in combination with convective heat exchange intensifies the process of heat and mass transfer and reduces drying time.

It's also worth noting that the proposed dryer operates in a combined mode: IR radiation and resting. In the vertical sections of the chamber, the product is exposed to IR radiation, while in the horizontal sections—at the top and bottom—it is rested, similar to the oscillation mode. In this case, the gradient of temperature change and the direction of moisture movement from the deeper parts of the material to its outer surface coincide, which is an intensifying factor during drying. For example, when drying carrots to 12% moisture using combined IR, radiation, and convective drying with 60-second irradiation and 30-second rest periods, the drying time was  minutes, compared to  minutes without IR. For the Kara-Kishmish grape variety, the drying time was reduced from 36 hours to 30 hours.

**CONCLUSIONS**

Thus, it can be stated that the developed new combined solar-fuel drying plant of the cradle-conveyor type is distinguished by wide functional and technological capabilities, high technical and economic indicators, which allows its use in any combination:

- at the initial stage of drying, emphasis is placed on the combination of IR radiation and convective heat and mass transfer;

- during the daytime, when there is active solar radiation, the dryer can operate in air flow recirculation mode;

- at night or in bad weather conditions, the dryer operates only on the heat of the electric heater or without it in the active ventilation mode.

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