Research of optimum calculation of vibrating infrared dryers

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Abstract. The purpose of this study is to develop and improve the technological process and experimental and technical means of drying mulberry silkworm cocoons in an infrared (IR) drying unit, which can significantly speed up the processing and obtain a quality end product, as well as reduce energy costs for drying. The scientific novelty consists of the application of vibration in the process of drying silkworm cocoons by infrared radiation and the development of generalized calculation of such drying units. Our proposed calculation of infrared drying units is the most optimal calculation for silkworm cocoon morphing and drying.

1 Introduction

Recently, attempts have been made to restore the technology of high-temperature drying of mulberry silkworm cocoons to produce high-quality silk at cocoon-processing plants. Implementing improved high-efficiency plant designs solves several scientific and technical problems in this field. In such developed countries as China, Japan, Italy, India, Brazil, Korea, and Russia, silkworm breeding for primary processing of mulberry silkworm cocoons getting quality products by improving technical means and technologies plays the most important role. In this regard, technical support of technological processes is of great importance. From this point of view, scientists around the world are working on a variety of dryers equipped with infrared heating. The main advantage of the cocoon drying process with infrared rays is the higher moisture removal rate than other drying methods [1-3].

At the same time, several Tashkent State Technical University scientists have experience in using infrared drying of agricultural products, including mulberry silkworm cocoons, while maintaining the quality of the final product and silk. The temperature in our dryers does not exceed 65...70 degrees, and at the same time, the cocoon worms are destroyed, allowing the quality of the product to be maintained and the shelf life to be extended.

The main advantage of the cocoon mortaring and drying process by infrared rays is the higher moisture removal rate compared to current processing techniques and technologies [4]. This advantage is due to the action of the flux of radiant heat energy, which penetrates to a certain depth in capillary-porous products (about 0.1...2.0 mm) [5].

Due to the high number of reflections from the unit walls, infrared radiation rays can be

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absorbed almost completely. In this case, the heat transfer coefficient is considerably higher. In this way, a considerable amount of heat is transferred per unit of the surface area of the product to be dried per unit of time. This advantage greatly speeds up the process of killing and drying the cocoon.

2 Methods

In contrast to other processing methods, infrared drying produces an end product that retains almost all its valuable properties. The energy consumption for the drying process in an infrared dryer is up to one-fold 10 lower than in other types of devices [6]. Drying of moist raw materials or materials by infrared radiation usually takes place in two periods characterized by different changes in the moisture content of the raw material [7].

- in the first period, the moisture content of the raw material decreases linearly over time;
- in the second period, the process of humidity change over time becomes a non-linear transient process.

The rate at which vapor is removed from the evaporation surface throughout the volume of the drying agent limits the drying speed in the first period and is determined by the input disturbing external influences: the heating rate of the raw material, the temperature and wavelength of the infra-red emitter, and the distance of the emitter from the evaporation surface.

The second drying period is often called the falling drying speed period. This drying period is characterized by an increase in the heating temperature of the raw material; however, the temperature on the surface of the raw material rises faster than on the inside, which results in a temperature gradient in the raw material towards the outside surface, causing the phenomenon of thermal moisture conduction which in this case inhibits the internal mass transfer process [8].

For engineering calculations of drying plants, drying transition curves are used to represent the change in speed and temperature. Drying curves are obtained experimentally because calculating the heating time constant is impossible without knowing the geometric characteristics of the cocoons, the volume, and the outer surface area of the product to be treated, which has a complex geometric structure such as that of a cocoon.

However, evaluating the drying kinetics of a particular raw material allows us to proceed to the next stage of radiation drying plant design, which is the thermal calculation. The thermal calculation of an IR plant is preceded by the task of determining the capacity of the radiant energy generators, their geometrical dimensions, and their location in the drying plant concerning the raw material to be treated [9].

To solve the problem of creating efficient plants for drying plant raw materials, P.D.Lebedev proposed a differential heat balance equation, which is valid for calculating the technological procedure for drying raw materials and bodies of any configuration [10].

The equation of thermal balance for the conditions of uniform heating along the thickness of the irradiated body, when the energy absorbed by the irradiated raw material during the time $d\tau$. The equation of thermal balance under the conditions of uniform heating of the irradiated body thickness, where the energy absorbed by the irradiated body during the time will be spent on its heating, heat transfer by convection and radiation to the surrounding space, and on evaporation of moisture from it [11], is of the following form:

$$0.86AES_0d = HGcd\tau + a_k(t - t_a)Sd\tau + 4.9\varepsilon_{gh}\left[\left(\frac{T}{100}\right)^4 \cdot \left(\frac{T_0}{100}\right)^4\right] \cdot Sd\tau + q'rl^{-xl}d\tau \quad (1)$$

here A is the radiation absorption coefficient of the irradiated raw material; E is radiation density, W/m; S_0 and S are areas of irradiated and total surfaces of the raw material, m; H is the time from the beginning of irradiation, h; G is the weight of the irradiated plant material, kg; t and t_a are raw material and ambient air temperatures, °C; c is the heat capacity of the irradiated raw material, kcal/kg·grad; ε_{gh} is the reduced blackness of the irradiated raw material and the internal envelopes of the drying plant; a_k is the coefficient of heat transfer by convection, kcal/m^2·h·grad; T and T_0 are the temperature of the raw material and its surroundings, °C; q' is the evaporation rate of the raw material (initial intensity), kg/m^2·h; x is the radiation absorption index of the cocoon, 1/m; l is the depth of penetration of raw material by infrared flux from its outer surface, m.

The ratio of total heat transfer (convection and radiation) to convection loss is assumed to be constant due to the minimal heat loss due to the small heating temperature of the irradiated raw material:

$$\frac{dQ_k+dQ_u}{dQ_k} = \xi \tag{2}$$

In this case, the value of the heat loss by heat dissipation over time dn is roughly defined as:

$$dQ_k + dQ_u = \alpha_c \xi (t - t_a) S d\tau \tag{3}$$

here $\alpha_c = \alpha$ is the total heat transfer coefficient, kcal/m^2·h·grad.

In practical conditions, the value of the total coefficient, α varies between 16 and 20 kcal/m^2·h·grad [12].

The thermal balance of the irradiated raw material is also determined with approximation since the rate of moisture evaporation is assumed to be constant and equal to the average intensity of q'. The equation can be represented as:

$$0.86AEd\tau = \frac{\Theta\gamma}{\sigma}\bar{S}d\tau + a\bar{S}(t - t_a)d\tau + q'\bar{S}d\tau \tag{4}$$

here $\bar{S}$ is the ratio of the total surface area to the irradiated part of it; $\Theta = \frac{S}{v}$ is the ratio of the total surface area of the irradiated raw material to its volume m^2/m^3; γ is the specific weight of irradiated raw material, kg/m.

By dividing the variables in the resulting differential equation and substituting

$$B = \frac{(0.86AE - q'r\bar{S})}{\Theta\gamma\bar{S}} \tag{5}$$

$$D = -\frac{\alpha\sigma}{\Theta\gamma} \tag{6}$$

The final form of the heat balance equation of the irradiated raw material takes the form of:

$$d\tau = \frac{dt}{B + D(t - t_a)} \tag{7}$$

Integration of the resulting expressions by η from $\eta = 0$ to $\eta = \eta_i$ and over t from a given initial temperature t_n to the final temperature t_i makes it possible to obtain an expression for the corresponding heating time η_i [13]:

$$\int_0^{\eta_i} d\tau = \int_{t_n}^{t_i} \frac{dt}{B + D(t - t_a)} \tag{8}$$

From the resulting heat balance equation, the equation for the heating kinetics of the irradiated body can also be derived:

$$\tau_i = \frac{1}{D} + ln\frac{B+D(t_i-t_a)}{B+D(t_n-t_a)} \quad (9)$$

Calculation of vibration parameters. The main characteristics (frequency *F* and amplitude of displacement *A* from the equilibrium position) and their derivatives (vibration velocity υ_m and vibration acceleration a_m, where index *m* denotes the amplitude value of the parameter) are distinguished [14].

Frequency F is the number of vibrations per unit of time. The unit of frequency is (*Hz*) hertz, so 1 Hz means one oscillation per second. Frequency is inversely proportional to the period of oscillation. The period of oscillation *T* is determined by the time of one complete oscillation.

$$F = \frac{1}{T}, \text{Hz} \quad (10)$$

Amplitude *A* is the largest deviation from the equilibrium (neutral) position and is measured in micrometers (μm), millimeters (mm), centimeters (cm), or meters (m).

Vibration velocity (vibration velocity) υ_m is defined as the first derivative of displacement over time - frequency and vibration amplitude

$$v_m = 2\pi F\text{A} = \omega\text{A} \quad (11)$$

here ω is the frequency of circular oscillation, rad/s (ω=2πF).

Use formula (11) to determine the vibration amplitude at known values of speed and frequency.

$$A = \frac{v_m}{2\pi F}, \text{m} \quad (12)$$

The vibration acceleration a_m can be defined as the second derivative of the time displacement - frequency and vibration amplitude, according to the following formula

$$a_m = (2\pi F)^2 \cdot A = \omega^2 A, \text{m/s}^2 \quad (13)$$

The vibration acceleration a_m can be expressed in fractions or units of free-fall acceleration

$$a_m = \frac{4\pi^2 F^2 A}{981}, \text{cm}\cdot\text{c}^2 \quad (14)$$

Vibration can also be estimated from the logarithmic level of vibration velocity and acceleration measured in db.

These design calculations serve as an important factor in reducing energy and material consumption, and from these calculations, it was determined that the residence time of the raw material in the dryer is proportional to the vibration. This allowed us to control heat consumption by constructing a material balance equation.

3 Results and discussion

Our studies show that to intensify the drying process of cocoons, it is necessary to heat the air above the final temperature of the drying object, as shown by the dotted line in Fig. 1; otherwise, it will start to play a negative role in the *bc* section, cooling the dried raw material.

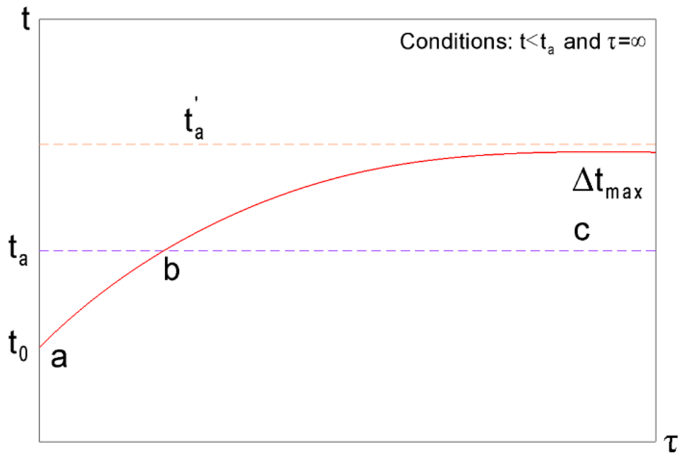

Fig. 1. Temperature curves for heated product and air during infrared drying

Determining the basic characteristics of these dependencies will help in calculating the energy consumption, which depends on the irradiation density and the location of the infra-red generator in the installation:

$$E = \frac{Pua}{l^2} \quad (10)$$

here E is energy illuminance or irradiance, W/m; P is the power of emitters, W; l is the distance between infra-red emitters, m; u is source efficiency coefficient, depending on the degree of filling the irradiated space and the ratio of the chamber length l to h - to the distance from the emitter to the irradiated surface of the raw material. In practical conditions, it varies between 0.7 and 0.85, a - is the multiple reflection coefficient:

$$a = \frac{1}{1 - q_k q_n \psi'} \quad (11)$$

here q_k is the reflection coefficient of the chamber; q_n is the reflection coefficient of the irradiation surface of the products; ψ' is the fraction of the flux reflected by the chamber.

The energy consumption for drying will then be expressed by the equation:

$$J = \frac{ES_0}{\eta ua} \quad (12)$$

here η is the energy efficiency of the transmitter.

Using vibration in an infrared-heated dryer is an alternative to drying with lower specific energy consumption compared to stationary infrared dryers. In the present study, the efficiency of a vibrating IR-heated dryer is investigated by comparing the drying kinetics of raw materials with the specific energy consumption to obtain optimum drying conditions.

To compare the vibration results obtained from the calculations carried out, the operation of the vibrator installed in the infrared dryer was measured (Fig. 2).

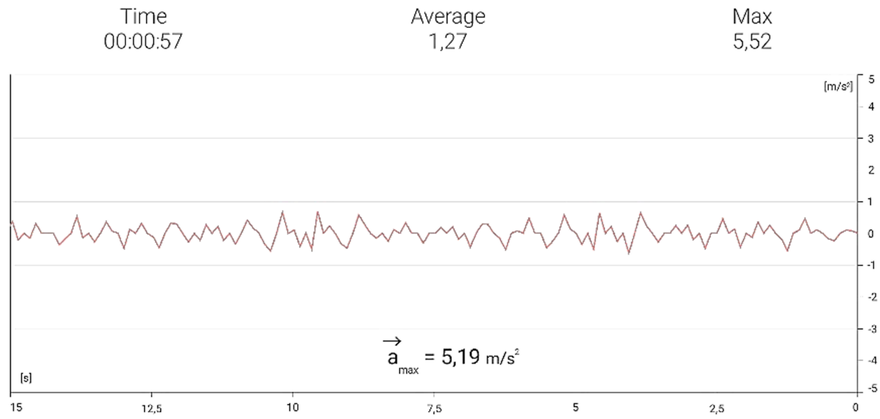

Fig. 2. Vibration diagram in infrared dryer

Higher effective moisture diffusion and lower activation energy have been achieved with vibratory IR dryers. The availability of a mathematical expression for the drying kinetics helps to evaluate the different variables affecting drying and the complex interactions between drying conditions and vibration parameters [15].

4 Conclusions

This calculation makes it possible to evaluate plants for drying agricultural raw materials in the development and design of IR drying plants because a well-designed drying plant must ensure precise maintenance of the drying parameters for uniform drying of raw materials in the entire volume of the chamber. The drying parameters include the most favorable conditions for temperature, radiation wavelength, humidity, speed, and vibration.

In the future, it is advisable to obtain mathematical models of the rate of drying of cocoons depending on the influence of controllable and uncontrollable factors on the drying process. Mathematical models will enable an automatic control system for drying mulberry silkworm cocoons with infrared rays and vibration.

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