Development and justification of parameters of a microwave convective hop dryer

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Abstract. To solve the problem of low energy efficiency and the absence of small-sized hop dryers, a microwave convective continuous-flow hop dryer has been developed with reasonable parameters that allow preserving the consumer properties of hops. The scientific innovative idea of implementing the technology of drying hops in the working chamber of a microwave hop dryer, made in the form of tiered rotors located between stationary non-ferromagnetic bases, forming coaxial resonators in which a traveling wave from microwave generators is excited, is considered. The rotors are made in the form of perforated non-ferromagnetic outer and inner shells, where ceramic perforated partitions are rigidly installed in the annular space, allowing to concentrate radiation energy in raw materials and reduce radiation losses. Having calculated the dimensions of the coaxial resonator, having created its three-dimensional model in the Compass 20 program, we imported it into the CST Microwave Studio program to substantiate the electrodynamic parameters. A hop dryer with a capacity of 5 kW microwave generators with spiral decelerating systems will ensure uniform drying of hops in compliance with electromagnetic safety, with a capacity of 100 kg/h when the rotor is located without microwave energy sources between two coaxial resonators to comply with a process duty cycle of 0.5.

1 Introduction

It is known that with the convective method of drying freshly harvested hop cones, with a humidity of 76-82%, about 40 components of bitter resins and 224 compounds of essential oils and other valuable substances are transformed into less valuable. This means that first-class hops after drying are classified as second grade, besides, energy costs per unit of production remain high [1, 2].

Low energy efficiency of hop dryers with convective heat supply and the absence of small-sized continuous-flow hop dryers for hop farms that ensure the preservation of the

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consumer properties of hops at reduced operating costs is a primary scientific and economic problem that needs to be solved.

Therefore, in order to preserve the consumer properties of dried hops, another intensive drying technology of freshly harvested hops is proposed at reduced operating costs in the conditions of hop farms, implemented in a microwave convective continuous-flow hop dryer with coaxial metal-dielectric resonators.

It is known that newly produced hop dryers must comply with GOST 28150-89 [3]. It sets the maximum permissible indicators of specific consumption of thermal (5 GJ), electrical (0.4 GJ) energy by a continuous hop dryer when drying hops per 1 ton of evaporated moisture. These data can be observed if: the temperature of the supplied air does not exceed 65 ° C with the initial humidity of hops equal to 75-80%; the final humidity of dried and conditioned hops is 11-12%.

At the same time, the preservation of consumer properties of dried hops, such as: golden-green color; aroma; light yellow lupulin; absence of crumpled cones (no more than 5%) is possible with a combined endogenous-convective drying method in working chambers - volumetric resonators of non–standard designs with air-cooled magnetrons, providing a continuous drying mode [4-10]. In this hop dryer, there are difficulties in coordinating technological parameters among themselves, namely, layer thickness, density and speed of movement of raw materials, heating temperature of raw materials and air in each resonator. Therefore, there are difficulties in step-by-step adjustment of the heating and drying speed of freshly harvested hops.

The scientific innovative idea of implementing this drying method is that the working chamber is made in the form of tiered rotors with perforated ceramic compartments located between stationary non-ferromagnetic bases, forming coaxial resonators in which a traveling wave is excited from three microwave generators.

Some nodes of the developed hop dryer are similar to the nodes of the carousel extractor [11].

2 Materials and Methods

Based on the analysis of the developed designs of microwave convective continuous-flow hop dryers with resonators of non-standard structural designs and air-cooled magnetrons for compliance with their basic criteria for hop dryers, shortcomings have been identified. When designing a hop dryer, the following criteria are taken as the basis:

- three-stage continuous-flow mode of uniform drying and disinfection of freshly harvested hops in working chambers that implement the necessary dose of endo-exogenous heat exposure;
- excitation of a traveling wave in a coaxial resonator from air-cooled magnetrons, which ensures uniform distribution of a high-intensity electric field to achieve a bactericidal effect;
- variation of the performance of the hop dryer with a system of control and measuring instruments and automatic control of the technological process of drying freshly harvested hops of different humidity and grade;
- ensuring electromagnetic safety and free dismantling of the main units of the dryer;

The design is based on the developed microwave convective continuous-flow hop dryers with metal-dielectric resonators and air-cooled magnetrons for hop farms (patents: 2774186, 27749612, 272987, 2772987, 2770628). Mathematical modeling of a microwave convective hop dryer was carried out using the technique of B.K. Sivyakov [12].

Three-dimensional modeling of the structural designs of hop dryers was carried out in the Compass 20 program. In the CST Microwave Studio program, the power of the radiation flux, the intensity and structure of the electromagnetic field in the resonator were investigated [13]. Low-power generators operating at a frequency of 2450 MHz are used as sources of microwave energy. The duration of drying hops in each tiered working chamber is proposed to be adjusted by changing the speed of the gearbox motor controlled by the Digital Tachometer DT2234B. Compliance with the sanitary radiation norm of 10 MW/cm^2 is monitored by the energy flux density near the hop dryer using the electromagnetic radiation meter PZ-41.

3 Results and Discussion

The rotary microwave convective hop dryer (Fig. 1) contains screening cylindrical non-ferromagnetic housings 1 arranged in tiers. Inside each housing, electrically driven perforated rotors 4, 8, 12 are arranged coaxially and in tiers between perforated non-ferromagnetic stationary bases 2, 7, 11, 15 with sector cutouts. In each rotor, the outer and inner non-ferromagnetic perforated shells form an annular space. Rotors with fixed non-ferromagnetic bases form coaxial non-ferromagnetic perforated resonators. Each annular space is divided by vertical radial perforated ceramic partitions 6, 10, 14 into several compartments 5, 9, 13. In cross section, these ceramic partitions have a downward-tapering shape to facilitate loading of raw materials to the lower tier or unloading into an unloading container.

The loading of raw materials into the compartments and its unloading from the compartments takes place through the sector cutouts in the bases of each resonator. The individual drive of the rotors is carried out by means of gears with toothed crowns 20, 22, 24 mounted on the outside, along the perimeter of the outer shell of each rotor. Due to the coupling of the drive gear on the shaft of the gear motor with a gear ring the rotor rotates.

To implement the drying process, heat guns should be turned on to supply warm air of a certain temperature and performance through non-ferromagnetic air ducts 10, 21, 23 into perforated rotors of all tiers. The supply of convective heat from individual heat guns is carried out through air ducts directed through the screening cylindrical body of the hop dryer. Turn on gear motors for rotating non-ferromagnetic perforated rotors 4, 8, 12 by coupling the drive gear on the shaft of the gear motor with gear rings 20, 22, 24 on the outer shells of the rotor. Load the freshly harvested hops into a receiving container with a closed valve. Open the valve and turn on the electric drive of the non-ferromagnetic spiral auger 3. After that, the freshly harvested hops are loaded into the ceramic compartments 5 of the coaxial resonator of the first tier using a non-ferromagnetic spiral auger 3, which simultaneously performs the function of a retarding system, which ensures electromagnetic safety and uniformity of loading of compartments 5 formed by radial ceramic partitions 6. Next, turn on generators 26 (magnetrons) after that, an ultra-high frequency electromagnetic field (2450 MHz, 12.24 cm) is excited in the coaxial resonator of the first tier, i.e. a traveling wave is excited, which reduces the risk of breakdown at 80% humidity of raw materials and maximum load of the resonator. The energy spent on the polarization of raw materials is generated in the cones of hops in the form of heat. A valuable property of microwave energy is the concentration in the volume of hops, the mass of which is heated selectively depending on the electrophysical properties of its components [14]. The released surface moisture evaporates and is removed by convective warm air (23) outside the hop dryer through the perforation of the rotor and the air outlet 25. When moving the perforated rotor 4 of the first tier with raw materials in ceramic compartments 5 between stationary non-ferromagnetic bases from the sector cutout 7, partially dehydrated and heated selectively, depending on the electrophysical parameters of the petals and rods, hop cones are discharged into the perforated ceramic compartments 9 of the rotor 8 of the second tier. Having made almost a full circle in the upper tier, hop cones are poured through the sector cutout from the unloading compartment into the corresponding compartment of the coaxial resonator of the second tier. In this perforated rotor 8, the warm air from the heat gun, entering through the non-ferromagnetic air duct 21, ensures the evaporation of surface moisture, and the absence of an ultra-high frequency electromagnetic field in this tier contributes to the equalization of pressure, humidity and temperatures in the petals and rods of hop cones due to thermal conductivity, which reduces the fragility of the rods.

Further, the raw material is poured through the sectorial cutout 11 from the rotor of the second tier into the ceramic compartments 13 of the rotor 12 of the third tier. As soon as partially dried hops appear in compartments 13, it is necessary to turn on the microwave generators 18 (it is not allowed to turn on the microwave generators without raw materials in the resonator) to excite the microwave. Then, in the coaxial resonator of the third tie r, the hops will be exposed to endogenous convective heating and dried to a humidity of 10-12%. This alternation of dielectric heating and pause, in which temperature, pressure, and humidity are equalized throughout the cross section of hop cones, ensures the preservation of consumer properties of raw materials. It is expected to reduce the specific energy costs for drying hops due to the exclusion of microwave generators in the second tier and the supply of convective heat to each tier in efficient modes during three-stage drying. The destruction of the structure of the cones is minimal, due to the use of spiral screws for feeding and unloading raw materials.

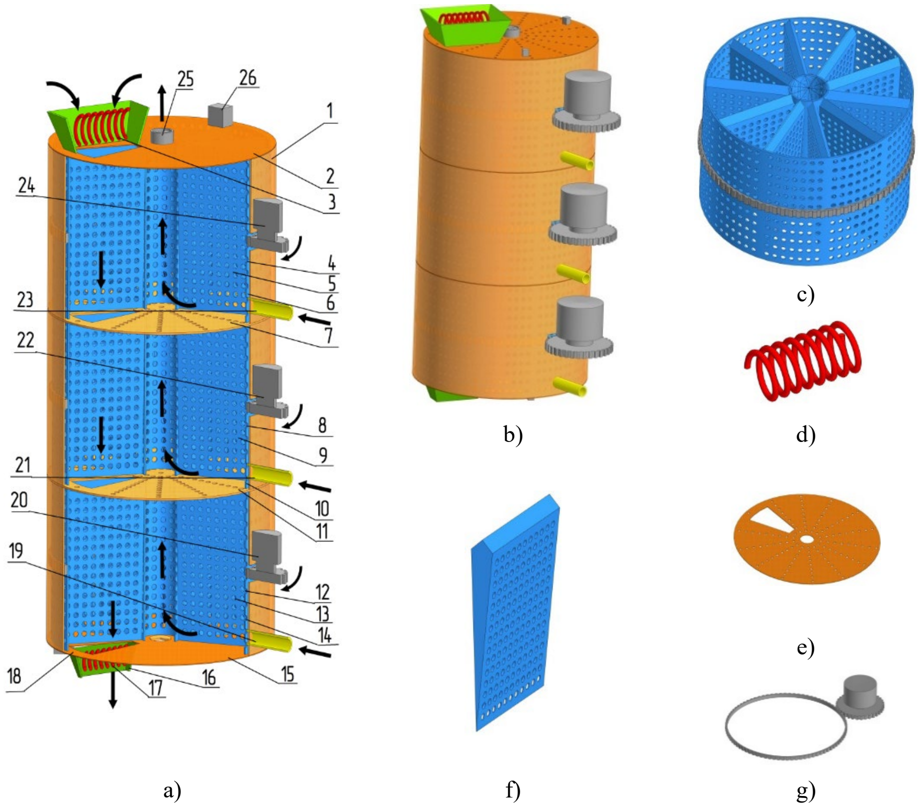

Fig. 1. Rotary microwave convective hop dryer with coaxial resonators: a) general view in section with positions; b) general view; c) perforated rotor with ceramic partitions and with a crown on the shell; d) non-ferromagnetic spiral auger; e) base with a sector cutout; f) ceramic perforated partition; g) crown with electric drive gears; 1 − non-ferromagnetic cylindrical shielding housing; 2, 7, 11, 15 − stationary non-ferromagnetic bases with sector cutouts; 3 − non-ferromagnetic loading tank with a non−ferromagnetic spiral screw; 4, 8, 12 − tiered non-ferromagnetic rotors; 5, 9, 13 - compartments formed by perforated ceramic radial partitions 6, 10, 14; 16 − receiving non-ferromagnetic container; 17 − non-ferromagnetic spiral auger for unloading raw materials; 18, 26 − magnetrons with waveguides and fans; 19, 21, 23 − non-ferromagnetic air ducts with heat guns of the corresponding tiers of the hop dryer; 20, 22, 24 − electric drives of rotors; 25 − air outlet with exhaust fan

The movement of hop cones with the help of rotors 4, 8, 12 on stationary bases 7, 11, 15 is carried out at low speeds of the gear motor, which provides a gentle mode of transportation and preserves the appearance of hop cones. The upper base of the first tier and the lower base of the third tier are not perforated, which reduces the loss of convective heat. Cylindrical non-ferromagnetic housings also reduce the loss of convective heat and ensure the radio-tightness of the hop dryer together with spiral retarding systems 3, 17 (electrically driven spiral augers 3, 17).

If the diameter of a non-ferromagnetic wire is small compared to the diameter of the spiral, then it can be considered as a cylinder whose conductivity is infinite in the direction of the coils of the spiral and is zero in the transverse direction [15]. By the correct selection of the spiral radius and winding step, it is possible to ensure sufficient efficiency of EMF deceleration, i.e. reduction of radiation through the loading window. Calculations show that the power of the radiation flow through the loading tank will decrease by almost 4 times if a spiral decelerating system is applied. In addition, freshly harvested hops have a humidity of up to 80%, which means that the electromagnetic field closes on the raw materials.

Therefore, we should expect compliance with a safe standard of microwave radiation of 10 MW/cm^2 [14].

The management of efficient modes is facilitated by the possibility of regulating the power of generators, the rotation speed of the rotors of each tier, the volume of loading into compartments, the performance and power of heat guns.

Perforated ceramic partitions with a narrowing cross-section, allow you to concentrate the energy of radiation in the raw material. Therefore, it will provide an electric field strength sufficient for disinfection of hops (0.6-1 kV/ cm). Ceramic partitions make it possible to reduce radiation losses through the perforation of the rotor shells [14, 16].

The quality of dried hops depends on the temperature and pressure of the air, the dose of exposure to the electromagnetic field of ultrahigh frequency, the electric field strength at each stage of drying. The uniformity of the hop distribution in the volume of the coaxial resonator and the uniformity of its heating is ensured due to the fact that the distance between the ceramic radial partitions is no more than two depths of wave penetration into the hop cones (4-5 cm). The intrinsic Q-factor of resonators with ceramic perforated partitions is higher than fluoroplastic partitions, i.e. the efficiency of the hop dryer is higher [17]. The absence of thermal inertia of microwave heating on raw materials ensures high accuracy of regulation of the drying process and its reproducibility. With a decrease in the humidity of hops during the drying process, the loss of microwave energy decreases, and heating continues only in those areas of the raw material where increased humidity is still preserved [17]. The intensity and duration of drying of hops depend on the dose of exposure to EMPH, temperature and speed of movement of heated air. The highest air temperature in the lower tier of the rotor is allowed no more than 65° C, and the air velocity should not exceed 0.5 m / s.

Since the diameter of the inner shell is larger than a quarter of the wavelength (3.08 cm), therefore, it is necessary to install an exorbitant waveguide on the upper base of the 2 hop dryer, as a continuation of the inner shell of the rotor. Then the air is sucked out with the help of a fan through the internal perforated shells of the tiered rotors and an exorbitant waveguide.

The transverse dimensions of the coaxial resonator are chosen in accordance with the condition ensuring the absence of resonant higher types of vibrations:

$$R_1 \cdot \left(1 + \frac{R_1}{R_2}\right) \leq p \cdot \frac{\lambda}{\pi};\ \ 12.24 \cdot \left(1 + \frac{6.12}{61.2}\right) \leq 10 \cdot \frac{12.24}{3.14};\ \ 13.46 \leq 39. \qquad (1)$$

where R_1, R_2 – radii of the inner and outer shell.

If the length of the coaxial resonator satisfies condition (2), then the mode is excited E_{011}. $\pi \cdot (R_1 + R_2) \geq L \geq (R_2 - R_1),$ (2)

$$3.14 \cdot (6.12 + 61.2) \geq 85.65 \geq (61.2 - 6.12),\ \ 211.38 \geq 85.65 \geq 55.08. \qquad (3)$$

If $L \leq (R_2 - R_1)$, $85.68 \leq (61.2 - 6.12)$, $85.68 \leq 55.08$, then there is only the lowest type of electrical oscillations (radial oscillations) E_{010}.

The results of the study of the electrodynamic parameters of a system with a coaxial resonator in the CST Microwave Studio program (Fig. 2) show that the electric field strength ranges from 0.6-4 kV/cm, and the intrinsic Q-factor reaches 8000.

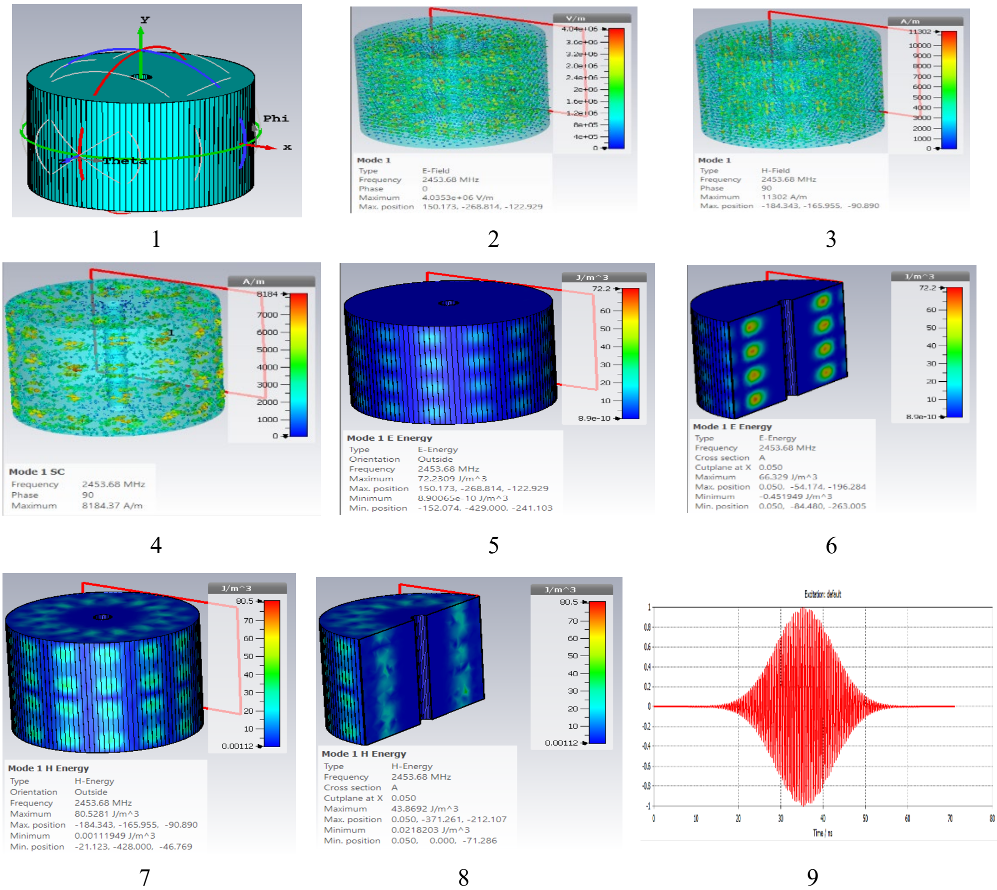

Fig. 2. Electrodynamic parameters of the coaxial resonator: 1 – EMF distribution along the x, y, z axes; 2 – EP intensity, V/m; 3 – magnetic field strength, A/m; 4 – surface current, A/m; 5 – radiation energy of the electrical component, W/m^3 (7 – in the section); 6 – the radiation energy of the magnetic component, W / m^3 (8 – in the section); 9 – oscillations of the excitation signal, ns

The energy that will be accumulated at the permissible electric field strength in a coaxial resonator with dimensions R_2 = 61.2 cm; R_1 = 6.12 cm, l = 85.68 cm on the main type of oscillations is calculated by the method of Baskakov S.I. [15]. The results of the study show that the electric field strength reaches 4 kV/cm (Fig. 2). The electric field of the main wave in the coaxial resonator has only a radial component [15]:

$$E_r = \frac{A}{R_1}\cdot sin\left(\frac{\pi\cdot z}{l}\right), \tag{4}$$

where A – coefficient depending on the permissible electric field strength in the resonator; (distribution of the field along the axis z).

The maximum electric field strength exists on the surface of the inner shell of the coaxial resonator, i.e. at R_1. It equals: $E\frac{A}{R_{1max}}$

Then $$W = \frac{\pi}{2}\cdot\varepsilon_a\cdot\left(E1_{max}()^2\, ln\frac{R_2}{R_1}\right) \tag{5}$$

$$W = \frac{3.14}{2}\cdot 8.85\cdot 10^{-12}\cdot(4\cdot 10^5\cdot 0.1224)^2\cdot 0.8568\cdot ln\frac{1.224}{0.1224} = 0.656\, Dg. \tag{6}$$

To ensure effective hops drying modes, it is necessary to coordinate the performance of the spiral screw and rotors. It is known that surface waves propagate along the decelerating structure, including along the non-ferromagnetic spiral. The spiral auger is a non-ferromagnetic conductor wound with a radius r and with a constant step s. It simultaneously performs the function of a slowing system. For the existence of a surface wave, it is necessary that the diameter of the spiral (D) be less than a quarter of the wavelength, i.e. 3.08 cm [15], and the slope must correspond to the small winding angles of the spiral, i.e. the tangent of the angle of inclination of the spiral turns must be coordinated with the pitch and radius of the spiral according to the formula:

$$tg\alpha = s/2 \cdot \pi \cdot r. \quad (7)$$

$$s = 2 \cdot \pi \cdot r \cdot tg\alpha = 6.28 \cdot 1.54 \cdot tg10 = 6.28 \cdot 3.08 \cdot 0.17 = 1.65\, sm. \quad (8)$$

The performance of all working bodies, namely spiral screws and rotors, should be coordinated taking into account changes in the density of hops during the drying process. Spiral screw capacity, kg/h [11]:

$$Q = 47.1 \cdot D^2 \cdot s \cdot n \cdot p, \quad (9)$$

where D − spiral diameter, m; s – spiral pitch, m; n − spiral rotation frequency, min^{-1}; ρ − bulk density of hops, kg/m^3.

If you set the performance of a spiral screw to 100 kg/h, then the required screw rotation speed is:

$$n = Q/47.1 \cdot D^2 \cdot s \cdot p = 100/47.1 \cdot 0.06^2 \cdot 0.04 \cdot 300 = 50\ \frac{ob}{min} \quad (10)$$

In order for the hop dryer to work in compliance with electromagnetic safety and with a capacity of 100 kg/h, a spiral screw with a diameter of 6 cm, a pitch of 4 cm and a rotation speed of 50 rpm should be installed in the loading and receiving tanks.

4 Conclusion

1. The half-wave coaxial resonators arranged in tiers serve as the working chamber of the hop dryer. They are presented as rotors made in the form of perforated non-ferromagnetic outer and inner shells between stationary non-ferromagnetic annular bases, where ceramic perforated partitions with a distance of less than two wave penetration depths are rigidly installed in the annular space, which will ensure uniform heating of wet hops even with weak resonator loading.

2. With the radii of the shells of the inner 12.24 cm and outer 1224 cm and a height of 83.68 cm of the coaxial resonator, the radial electric field strength is 4 kV / cm, the intrinsic Q factor is 8000.

3. A 5 kW microwave generator dryer with spiral retarding systems will ensure uniform drying of freshly harvested hops in compliance with electromagnetic safety, with a capacity of 100 kg/h at the arrangement of the rotor without microwave energy sources between two coaxial resonators in order to comply with the borehole of the process equal to 0.5.

4. Perforated ceramic partitions with a narrowing cross-section allow to concentrate the radiation energy in the raw material and reduce radiation losses through the perforation of the rotor shells.

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