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Technological process scheme of the three-stage microwave convection hop drying

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Abstract. At a temperature of 110 ° C, the concentration of alpha-acid reaches 67.5%, beta-acid - 59%, which reduces the consumer properties of hops. The aim of the study is to develop a microwave convective hop dryer, which provides a process flow rate of less than 0.5 to equalize the moisture content of hops in the structure during transportation through a toroidal resonator. We used the programs CST Microwave Studio 2018, Compass 3D V20. The hop dryer contains two truncated conical and toroidal resonators. In the central cylinder of the toroidal resonator there is no EMPSWH, here the moisture in the hop cones is equalized. In the capacitor part of the resonator, the electric field strength is sufficient to reduce the bacterial contamination of hops. A dielectric grid electric drive conveyor and a perforated ceramic trough are laid along all resonators. The technological scheme of the process provides for determining the amount of evaporated moisture from each resonator, air flow, and the required power of heat guns. The electrical circuit provides control of three magnetrons and a conveyor. The expected specific heat consumption is 3.54 MJ/kg. The total air consumption is 300 m3/h, with a hop dryer capacity of 100 kg/h.

1 Introduction

The main sources of increasing the technical and economic efficiency of hop dryers are the reduction of specific energy costs, obtaining a technological effect in the form of an increase in dried hops that meets consumer indicators, as well as increasing the reliability of hop dryers and their rational use in hop farms. Alpha-acid is the most valuable part of bitter substances in brewing. The components of bitter substances are easily oxidized by oxygen in the air, this process especially increases with increasing temperature. Within 1 hour at a temperature of 110°C, alpha-acid concentration reaches 67.5%, beta-acid - 59%, xanthohumols - 56.2% [1]. The most intensive oxidation process occurs in the first hour of heating

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the hop cones. A review of sources shows that under the effect of a number of factors, losses of valuable hop components occur, to preserve them, it is necessary to observe special technological regimes that must be implemented in the design features of the hop dryer with the microwave power supply [2, 3, 4, 5, 6].

2 Materials and Methods

In accordance with the developed methodology, the electrotechnological processes associated with hop drying were considered as a single system of interaction of convective heat sources with a certain temperature and microwave energy, a certain dose of exposure in volumetric resonators with raw materials changing temperature and humidity parameters. In the research, we used three-dimensional modeling of volumetric resonators made using the SolidWorks program, Compass 3D V20 in the CST Microwave Studio 2018 program [7, 8, 9, 10]. Theoretical studies of the process of hop microwave convective drying were carried out according to the method of V.N. Rasstrigin. The control circuit scheme of the microwave hop dryer is compiled according to GOST 2.702-2011 ESKD "Rules for execution of electrical circuits" dated 01.01.2012.

3 Results and Discussion

The microwave convective hop dryer with combined resonators contains (Fig. 1) two truncated conical resonators 1, 3 in the horizontal plane joined together by a common large base and a toroidal resonator 5 (application for invention No. 2023105989). In this case, the central cylinder 8 of the toroidal resonator is perforated and attached to a small base 9 of the second truncated conical resonator 3. Along all resonators 1, 3, 5 on edge of the diameter of the small bases 9 of the truncated conical resonators, a dielectric grid electric drive conveyor 11 is laid, where a perforated ceramic limiter 19 in the form of a chute is permanently installed under its working branch. Waveguides with magnetrons are located with a shift of 120 degrees along the perimeter of the large resonator bases. Individual non-ferromagnetic air ducts 13, 15, 17 from the heat guns and air outlets 2, 4, 6 are located respectively on the side surface of each resonator. The supply of warm air is carried out against the movement of the grid conveyor 11. A non-ferromagnetic loading reservoir 20 is installed above the dielectric grid conveyor in front of the first resonator 1, and a non-ferromagnetic loading reservoir 12 is installed under the grid conveyor, beyond the large base of the toroidal resonator 5.

3.1 The technological process of drying freshly harvested hop occurs as follows

Load the freshly harvested hop into the loading reservoir 20, close the screen. Turn on the electric drive of the dielectric grid conveyor 11. Turn on the fans with the corresponding heat guns 13, 15, 17. Open the screen in the loading reservoir 20, after which the hop cones enter the grid conveyor. As soon as the freshly harvested hop appears in the first resonator in the form of a truncated cone 1, turn on the microwave generators 18. Then, as the raw materials enter the second and third resonators, turn on the corresponding generators 16 and 14. Hop cones along the edges of the dielectric grid conveyor do not crumble, since a ceramic U-shaped chute 19 is located under its working branch.

In the *first* resonator (the first stage of drying), due to polarization currents and convective heat from the heat gun, hop cones are heated to 31-34°C, surface moisture is carried away by air through the air outlet 2.

In the *second* resonator in the form of a truncated cone, the temperature in the raw material increases to 37-46°C, internal moisture due to the temperature and pressure gradient is released on the surface of the cones, and removed through the air outlet 4 (the second stage of drying). The physical and chemical bound water is removed.

In the *third* toroidal resonator, the drying process of hop cones occurs as follows. Due to the fact that the central non-ferromagnetic cylinder 8 is perforated and closed by a non-ferromagnetic base 9 containing a hole for moving a dielectric mesh conveyor with raw materials, and there is no MWEMF in this space, therefore there is no endogenous heating of raw materials, and it is blown through the cylinder 8 perforation with warm air from the heat gun 13. There is an equalization of pressure, humidity, and temperature in the hop cones (65-75°C). Further, the raw materials are moved by means of a conveyor in the condenser part 10 of the toroidal resonator 5, where the electric field strength is high enough (0.6-1.2 kV/cm) to ensure a decrease in bacterial contamination of hop.

The quality of dried hops depends on the temperature and pressure of the air, the dose of exposure to MWEMF, the intensity of the electric field at each stage of drying, thus you should adhere to at least a three-stage drying process. The hop drying rate depends on the specific power of the generators in each resonator and on the coolant parameters: temperature, speed, and relative air humidity. The ceramic chute ensures the concentration of the MWEMF energy in the raw material, reducing radiation losses through the holes between the resonators designed to move the conveyor through a drying chamber consisting of three volumetric resonators. Ceramics have a small value of the dielectric loss angle tangent [11, 12, 13].

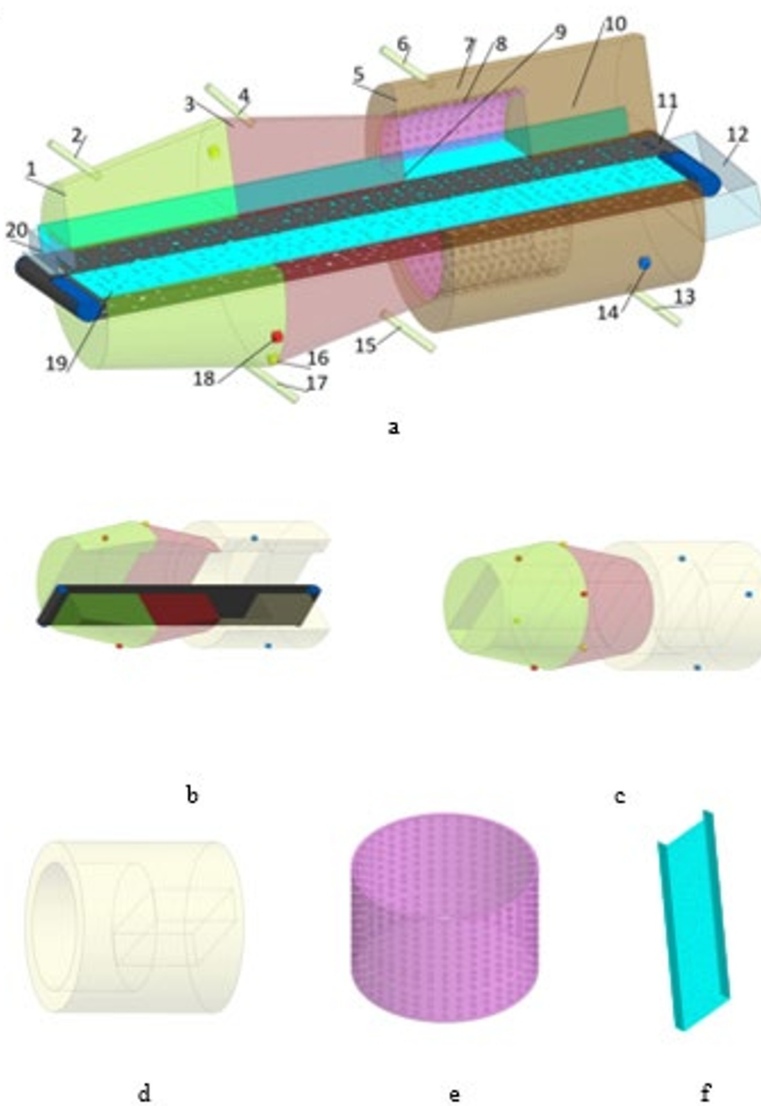


Fig. 1. Microwave convective hop dryer of continuous-flow action with combined resonators: a − general view; b, c − combined resonators; d – toroidal resonator; e – inner cylinder of toroidal resonator; f − ceramic chute; 1, 3 − resonators in the form of truncated cone; 2, 4, 6 − air outlets; 5 − toroidal resonator; 7 − toroidal part; 8 − internal perforated non-ferromagnetic cylinder with a base 9; 10 − condenser part of toroidal resonator; 11 – dielectric grid conveyor; 12 – receiving reservoir; 13, 15, 17 - air ducts with heat guns; 14, 16, 18 − magnetrons with waveguides; 19 − ceramic perforated chute limiter; 20 − non-ferromagnetic loading reservoir.

The duration of the movement of raw materials through the central non-ferromagnetic perforated cylinder 8 is equal to or greater than the duration of the presence of raw materials in the condenser part 10 of the toroidal resonator 5. That is, the technological process cycle in toroidal resonator should be greater than or equal to 0.5 (the ratio of the MWEMF exposure duration to the cycle duration). This contributes to the uniform drying of hop cones by volume. The thickness of the layer of hop cones on the mesh conveyor should not exceed two wave penetration depths (3-5 cm). Warm air is supplied to the drying chamber through the layer of hop cones. The moisture contained in the cones turns into a vaporous state and is removed from the chamber by the air flow. The maximum air temperature in the condenser part of the toroidal resonator is allowed to be no more than 65°C, and the speed of heated air movement should not exceed 0.5 m/s [14, 15].

Hops are dried to a humidity of 8-10% [16]. The hop dryer provides step-by-step removal of moisture from hop cones when moving through resonators using a dielectric mesh conveyor. At the same time, hop cones are subjected to endogenous convective heating, dried and disinfected, i.e., consumer characteristics are preserved and microbiological indicators are improved. In all resonators, the MWEMF exposure dose, temperature, and pressure of the supplied air are controlled and regulated depending on the humidity and volume of the loaded hop by changing the power of the microwave generators and heat guns, as well as the speed of conveyor movement. Organoleptic characteristics of dried hop: hop rustles, cone stem bends, but does not break, and its color turns from green to gray.

3.2 Technological scheme of the process of hop microwave convective drying

Theoretical studies of the process of hop microwave convective drying were carried out according to the method of V.N. Rasstrigin (Fig. 2).

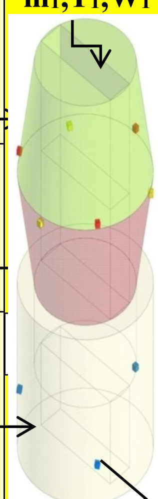
Outer air parameters	Heat guns	Preheated air parameters	Wet hop	Hop parameters	Exhaust air parameters
t_o, φ_o, d_o, I_o	1 resonator	t_1, φ_1, d_1, I_1	m_1, T_1, W_1 	$T_{com\ 1}+\Delta T_{mw\ 1}$	t_1^1, φ_1^1, d_1^1, I_1^1
t_o, φ_o, d_o, I_o	2 resonator	t_2, φ_2, d_2, I_2		$T_{con\ 2}+\Delta T_{mw\ 2}$	t_2^1, φ_2^1, d_2^1, I_2^1
t_o, φ_o, d_o, I_o	3 resonator	t_3, φ_3, d_3, I_3		$T_{con\ 3}+\Delta T_{mw\ 3}$	t_3^1, φ_3^1, d_3^1, 
			Dry hop: m_k, T_k, W_k		

Fig. 2. Technological scheme of three-stage microwave convective drying process for freshly harvested hops.

Atmospheric air having a temperature t_o(°C), relative humidity φ_o (%), moisture content d_o (G/kg), heat content I_o (kJ/ kg) is sucked in by heat guns and fed into the volumetric resonators of the corresponding zone. The heated air acquires the parameters for the corresponding zone: t_1, φ_1, d_1, I_1 (zone 1), t_2, φ_2, d_2, I_2 (zone 2), t_3, φ_3, d_3, I_3 (zone 3) and is fed into the corresponding resonator. In each volume resonator, the heated air passes through a layer of dried hop, takes moisture from it and exits the resonators with the following pa-

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rameters: $t_1{}^1$, $\varphi_1{}^1$, $d_1{}^1$, $I_1{}^1$ (zone 1), $t_2{}^1$, $\varphi_2{}^1$, $d_2{}^1$, $I_2{}^1$ (zone 2), $t_3{}^1$, $\varphi_3{}^1$, $d_3{}^1$, $I_3{}^1$ (zone 3). The incoming hop into the corresponding resonator has the humidity (%) W_1 W_2 W_3, temperature (°C) T_1, T_2, T_3 and weight (kg) m_1, m_2, m_3. The hop coming out of the resonators of the corresponding zones has the humidity W_2, W_3, W_{con}, weight m_2 m_3 m_{con}.

The hop temperature in each resonator, considering the temperature from convective heat and dielectric heating, is:

$$T_2 = (T_{con\ 1} + \Delta T_{mw\ 1}),\ T_3 = (T_{con\ 2} + \Delta T_{mw\ 2}),\ T_{con} = (T_{con\ 3} + \Delta T_{mw\ 3}). \quad (1)$$

The resonator capacities for raw hop should be equal to:

$$Q_1 = Q_2 = Q_3 \text{ (kg/h)}. \quad (2)$$

Initial calculation data are the following: Q_1, W_1, W_2, W_{con}, t_o, φ_o, t_1, t_2, t_3. The exhaust air temperature after each resonator is taken as: $t_1{}^1 = 35$°C, $t_2{}^1 = 50$°C, $t_3{}^1 = 65$°C. The relative humidity at the outlet of the resonators is 80% (from the experience of operating hop dryers). Using the I –d wet air diagram, the values of the air heat content I_o, I_1, I_2, I_3 and moisture content at the inlet to the resonators d_1, d_2, d_3, and at the outlet of the resonators $d_1{}^1$, $d_2{}^1$, $d_3{}^1$ were found. Further, the amount of evaporated moisture from each resonator was determined by the material balance of drying hop:

$$W_{1res} = Q_1 \cdot \frac{W_1 - W_2}{100 - W_2},\ W_{2res} = Q_2 \cdot \frac{W_2 - W_3}{100 - W_3},\ W_{2res} = Q_3 \cdot \frac{W_3 - W_{con}}{100 - W_{con}}. \quad (3)$$

Hourly air consumption required to remove moisture:

$$L_1 = W_1 \cdot 10^3/(d_1^1 - d_1),\quad L_2 = W_2 \cdot 10^3/(d_2^1 - d_2),\quad L_3 = W_3 \cdot 10^3/(d_3^1 - d_3). \quad (4)$$

The differences $(d_1{}^1 - d_1)$, $(d_2{}^1 - d_2)$, $(d_3{}^1 - d_3)$ characterize the specific moisture intake per 1 kg of air passed through the hop layer in each resonator. They increase with an increase in the speed and temperature of the coolant and the initial hop humidity. The power consumption of heat guns is as follows:

$$P_1 = L_1 \cdot (I_1 - I_o)/3600 \cdot \eta,\ P_2 = L_2 \cdot (I_2 - I_o)/3600 \cdot \eta,\ P_3 = L_3 \cdot (I_3 - I_o)/3600 \cdot \eta, \quad (5)$$

where η – heat gun efficiency (0,9-0,95).

Calculations show that the specific heat consumption will be 3.54 MJ/kg. The total air consumption is 250-300 m^3/h, with a hop dryer capacity of 100 kg/h.

Studies of the drying curve characterizing the change in the average hop humidity over time have been carried out (Fig. 3). The hop heating initially depends on the temperature of the convective air from the heat gun. As the dielectric heating increases, the evaporation of moisture from the hop cones increases, and its humidity changes in a straight line. At a certain humidity value (the first critical humidity), the evaporation process begins to slow down [17, 18]. Further, until the drying process end, the hop humidity decreases. At the end of the process, the drying curve approaches the line of the hop equilibrium moisture content.

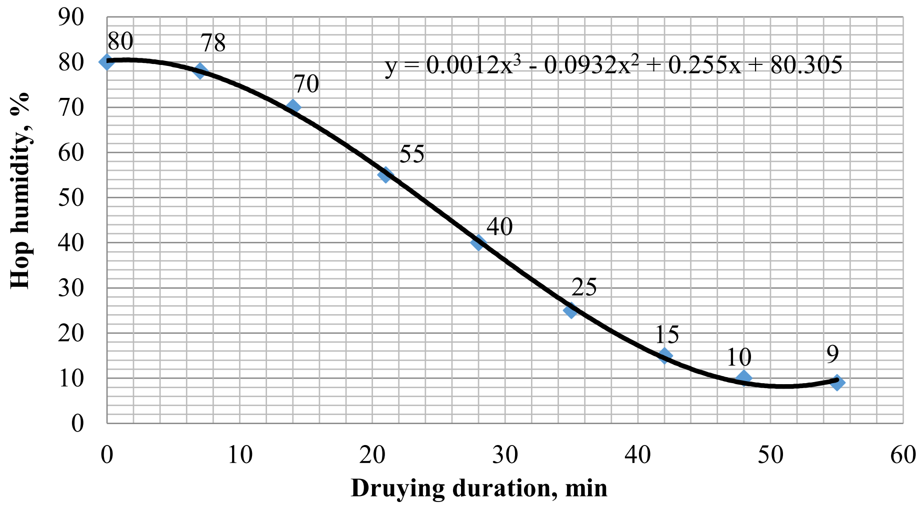

Fig. 3. Dependence of hop moisture on drying duration at an electric field strength of 0.9-1.0 kV/cm.

An empirical expression describing the drying curve $W = f(\tau)$ of freshly harvested hops at an EP intensity of 0,9-1,0 kV/cm: $W = 0{,}0012\cdot \tau^3 - 0{,}093\cdot\tau^2 + 0{,}26\cdot\tau + 80{,}31$.

The control circuit scheme of the hop dryer has been developed (Fig. 4, 5). It provides control of: electric drive (M_o) of grid conveyor; electric motors of nine fans (M1-M9); nine microwave generators (EK1-EK9). The control circuit provides sensors for the input and output temperature of raw materials, a sensor for the hop thickness of hops SQ1. Warning lights are provided. Switching on and off of generator blocks (three blocks of three generators) is carried out through the corresponding magnetic starters KM1, KM2, KM3. Switching on and off of each generator is carried out by the corresponding circuit breakers QF1 – QF9, i.e. the voltage supply to the primary windings of high-voltage transformers is carried out through these circuit breakers.

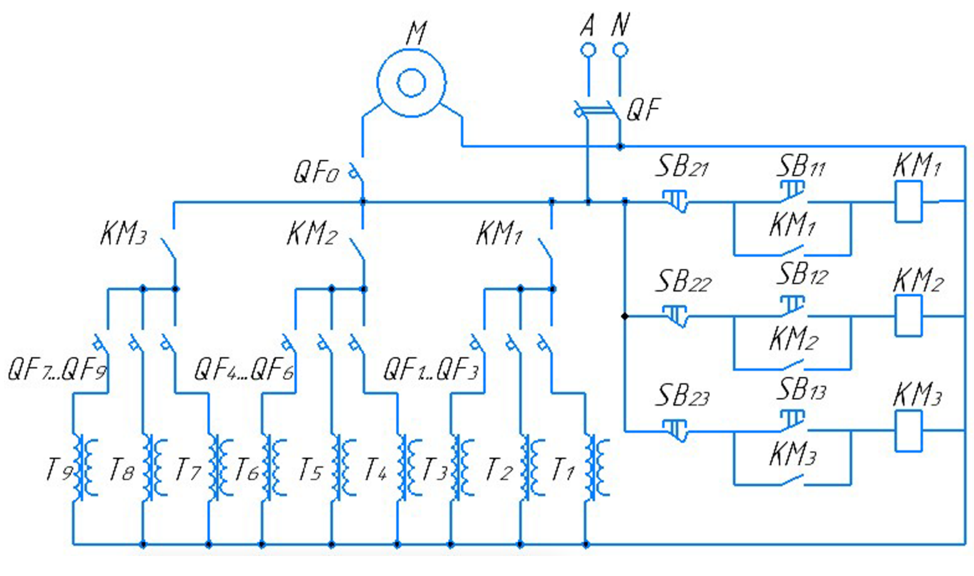

Fig. 4. Control circuit scheme for magnetron blocks in three resonators

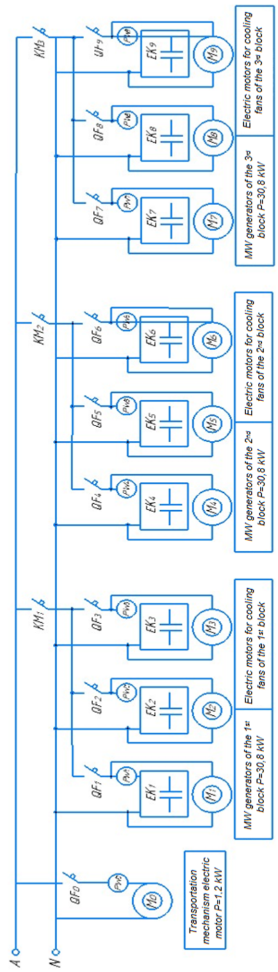

Fig. 5. Control circuit scheme for hop dryer with three resonator blocks.

4 Conclusions

In the central cylinder of the toroidal resonator, there is no MWEMF [19], therefore, pressure, humidity, and temperature in the hop cones are equalized in this space. In the capacitor part of the resonator, the electric field strength is sufficient to reduce the bacterial contamination of hops. The expected specific heat consumption is 3.54 MJ/kg. The total air consumption is 250-300 m^3/h, with a hop dryer capacity of 100 kg/h. The heating of hops initially depends on convective air temperature, and as it heats up in the hops, the evaporation of moisture from the hop cones increases, and its humidity changes in a straight line. At a certain humidity value, the evaporation process begins to slow down. At the end of the process, the drying curve approaches the line of the hop equilibrium moisture content.

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