Microwave unit for heat treatment of building materials

Irina Vorotyntseva
Moscow State University of Civil Engineering, (National Research University), Yaroslavskoye Shosse, 26, Moscow, 129337, Russia
e-mail: Vorotyntsevall@inbox.ru

Abstract. Building materials microwave processing demonstrates a great number of perspective advantages as compared to traditional heating methods. In order to upgrade the technology of microwave heating there has been developed a mathematical model of the technological process of microwave energy heat treatment of loose building materials. As a result we have won some calculation correlations, developed a numerical model and calculation algorithms for the analysis and synthesis of the microwave dryer of a loose dielectric with losses while it moves along the working camera. The results of the practical calculations have been carried out with the regard for water load and without it, also with the regard for the changes of the electro- and thermal-physic parameters during the heat treatment as well as disregarding them.

1. Introduction
Heat treatment of dielectrics is a widespread technological process. Owing to a volumetric and more even heating the microwave energy of electromagnetic vibrating can be used in order to intensify this process and enhance the quality of the procedure [1,2].

Microwave heat treatment is suitable for different dielectrics with loss, including loose building materials. However, available methodical microwave settings intended for the heat treatment of loose materials are often created based on some design engineering developments and lack sufficient scientific grounds [3,4].

The developers of microwave settings are quite interested in solving such tasks as mathematical modeling of technological processes [5], analysis and synthesis of the camera functioning, as well as the synthesis of an optimal technological process [6].

One of the difficulties of such tasks lies in the fact that it is not always possible to trust the reliability of the given electrophysical parameters that depend on the temperature and humidity because those numbers have been established on low power levels. Given this, there emerges the necessity to develop such methods of calculation of microwave setting cameras that would allow solving the task of synthesis and analysis of both the settings and the technological process as a whole.

The possibility to economize time and material resources spent on designing microwave settings using mathematical and numerical modeling of the technological process determines the topicality of this article. Scientific novelty lies in the development of the methods of microwave camera calculations that are suitable for drying of loose building materials and creating new models of technological process for them.

2. Methods
The heating and drying processes in microwave settings are being described with the help of the system of Maxwell’s equations and heat and mass transfer. Having excluding of the consideration the
heat treatment of a small class of substances whose electrophysical parameters depend on the magnetic $H$ and electric $E$ field strength vectors in relatively weak fields (ferroelectrics and ferromagnets), we can limit the calculations to the linear dependency of the electric displacement vector $D$ of $E$ and magnetic displacement vector $B$ of $H$. The materials that are being warmed up in a microwave setting are characterized by structural heterogeneity. Normally, those heterogeneities are numerous and their size is smaller than the wave length in the environment. Given this, in practical applications the heterogeneous environment can be replaced with the homogeneous one with the equivalent electrophysical parameters.

Some environments have the dependency $\varepsilon_z$ and $\tan\delta$ on the temperature. Therefore while the heating those environments generally $\varepsilon_z$ and $\tan\delta$ are considers as functions of coordinates and time. As for the thermal-physic parameters included in the equation and the boundary conditions of heat and mass transfer, we should accept the traditional admissions of the constancy of those parameters in a narrow interval of temperatures (or time), examining, for instance, their average value in the given interval.

In this case Maxwell’s and heat and mass transfer equations can be figured as following:

$$\text{rot} \mathbf{H} = j + \frac{\partial \mathbf{D}}{\partial t},$$

(1)

$$\text{rot} \mathbf{E} = - \frac{\partial \mathbf{B}}{\partial t},$$

(2)

$$\text{div} \mathbf{D} = 0,$$

(3)

$$\text{div} \mathbf{B} = 0,$$

(4)

$$\frac{\partial \theta}{\partial t} + v \Delta \theta = K_{11} \nabla^2 \theta + K_{12} \nabla^2 U + K_{13} \nabla^2 P + \frac{P}{C},$$

(5)

$$\frac{\partial U}{\partial t} + v \Delta U = K_{21} \nabla^2 \theta + K_{22} \nabla^2 U + K_{23} \nabla^2 P,$$

(6)

$$\frac{\partial P}{\partial t} + v \Delta P = K_{31} \nabla^2 \theta + K_{32} \nabla^2 U + K_{33} \nabla^2 P,$$

(7)

where

$$K_{11} = a_g + a_m \frac{\delta \varepsilon_U^2}{C},$$

$$K_{12} = a_m \frac{\delta \varepsilon_U^2}{C},$$

$$K_{13} = C \rho a_p \frac{\varepsilon_U^2}{C},$$

$$K_{21} = a_m \delta,$$
\[ K_{22} = a_m, \]
\[ K_{23} = C_p a_p, \]
\[ K_{31} = -a_m \frac{\delta e_U}{C_p}, \]
\[ K_{32} = -a_m \frac{e_U}{C_p}, \]
\[ K_{33} = a_p - a_p e_U, \]
\[ p_{sp} = 0.5 \omega e_0 e^t g \delta |E|^2, \]

\( \theta, U, P \) – temperature pressure, specific humidity content, water steam pressure in the heated object; \( v \) – transport speed of the heated object; \( a_g \) – thermal diffusivity of the object; \( a_m \) – moisture diffusion coefficient; \( \delta \) – relative thermodiffusion coefficient; \( e_U \) – phase transformation criterion; \( a_p \) – convection filtration diffusion coefficient; \( C_p \) – capillary-porous object capacity; \( C \) – specific heat; \( \omega \) – angular frequency.

Electromagnetic fields in separate fields of the microwave unit interfit on the surfaces of the division based on the following interfacial conditions:

\[ \begin{bmatrix} n_D - D_1 \end{bmatrix} = 0, \begin{bmatrix} n_E - E_1 \end{bmatrix} = 0, \]
\[ n \left( \begin{bmatrix} D_2 \end{bmatrix} - D_1 \right) = 0, \quad n \left( \begin{bmatrix} E_2 \end{bmatrix} - E_1 \right), \quad \begin{bmatrix} n \end{bmatrix} = 0, \begin{bmatrix} n \end{bmatrix} = 0 \]

where \( n \) is a single vector directed from environment 2 into environment 1. If environment 1 is an ideal conductor, then

\[ [n, E] = 0, nB = 0. \quad (9) \]

The interaction of the heated material surface with the environment by the mass exchange is being described by interfacial conditions of four types. The interfacial conditions of the first type correspond to the case when the mass transfer potential on the objects surface is equal to the mass transfer potential in the environment. The interfacial conditions of the second type assign the mass flow as a time function. The interfacial conditions of the third type are most often used in the applied tasks and can be presented as

\[ \begin{align*}
\lambda (\nabla \theta) + [jQ(t)] + [j_m(t)] &= 0, \\
\lambda \left[ \nabla (\theta) \delta_{\theta} + (\nabla U) + (\nabla p) \delta_{\rho} \right] + [j_m(t)] &= 0, \\
p_n &= 0,
\end{align*} \]

where \( \lambda, \lambda_m \) – coefficients of thermal and mass conductivity of an object; \( \delta_{\rho} \) – filtration humidity transfer coefficient; \( C_m \) – specific mass capacity; \( j \) – heat amount which has been given from the object’s surface as a result of convection; \( j_m \) – evaporation intensity; \( r \) – specific steam formation heat.
Finally, the interfacial conditions of the fourth type characterize the molecular exchange between two environments.

When there is no mass transfer in the heating process, equations (5)-(7) are taken down to one – the equation of thermal conductivity.

Set of equations (1)-(10) can be used as a mathematical model of a microwave dryer with a working camera that represents a transmission line of rectangular cross-section short-circuited on both ends and is set angularly to the horizon. Along the camera axis there is a fluorine-bedded pipe at which enter the material under treatment is being supplied. In order to transport the environment to the outcome, the reactor is being turned around its axis.

The material under treatment is being mixed which removes the steam by microwave energy heating. The energy is being generated with the help of two magnetrons. The magnetrons from the working camera are joined with the help of waveguide pieces. The steam in the camera is removed by vacuum draw-down or aeration.

A characteristic feature of electromagnetic waves distribution in the camera is their multiple passing with damping along the camera because of reflection from its short-circuited ends. On the whole the task is being solved based on the scheme (1)-(10). The discovered electrodynamics task value is used to solve the task of heat-mass-carry

$$\frac{\partial \theta}{\partial t} + v \nabla \theta = a_\theta \nabla^2 \theta + \frac{p_{sp}}{C \rho}.$$  \hspace{1cm} (11)

Thermal processes in the heated environment are being found by solving the regional task of heat-mass-transfer (5)-(7), (10) in the approach of the given electromagnetic field, which has been in its turn found by solving the regional task of thermodynamics (1)-(4), (8), (9). The dependencies of electrophysical and thermophysical parameters of the heated material from the temperature and humidity are being found experimentally. The time of heat treatment is divided into intervals $t$, in which limits those parameters are considered to be independent of the time. Task solving (1)-(4) on this time interval is being determined by the function $p_{sp}$, which helps to solve the regional task (5)-(7). Solving the regional task of heat-mass-transfer enables it to determine the electrophysical and thermophysical parameters of the environment in the next time interval.

The introduced mathematical model helps to solve the following tasks connected to the microwave dryers’ calculations: 1. Numerical modeling of the technological process of heating and drying of loose materials in microwave dryers with the given initial and final process parameters of the camera and generators (analysis of the camera’s working process). 2. Calculations of the optimal camera size under given process and generator parameters (synthesis of the optimal technological process).

While solving those tasks the dependency of electro- and thermophysical parameters on the temperature and humidity are known quantities. While calculating the temperature and humidity distribution along the camera’s axe, the changes of those parameters along $z$ are being carried out with the help of the method of successive approximations. The sharply increasing number of calculation procedures in the method of successive approximations can be essentially reduced if we calculate the constancies $\varepsilon'$ and $t g \delta$, $C$, $\rho$ of the object while calculating the entrance resistance in any section $z$ on the whole camera’s length behind that section. In this case the values $\varepsilon'$ and $t g \delta$, $C$, $\rho$ are considered to be equal to those values that have been last analyzed on an elementary camera’s district. However, in case of project tasks – especially in their very beginning – the dependency of those parameters on the temperature and humidity are unknown that is why it is impossible to take into account their changes along the axe. Thus, it makes sense to consider the average constant values of $\varepsilon'$ and $t g \delta$, $C$, $\rho$.

If we repeat the calculations using new time intervals in order to achieve the given or set heated material temperature, we can ascertain the process dynamics, take into account time variations of the electro- and thermal-physic material parameters, investigate the influence of the setting’s different
parameters on its characteristics, conduct the numerical modeling of the optimal microwave technological units synthesis.

3. Results

Practical calculations of microwave cameras of the dryer have been carried out in several stages. In the stage the task was to synthesize a camera, which meant to calculate the optimal size of the camera considering the given parameters of the technological process and the power of the generators for drying the specific product that has the following characteristics: $\varepsilon_z = 15$, $\tan \delta_2 = 0.015$, $C = 925$ J/kg·K, $\rho = 3700$ kg/m$^3$, initial humidity 15%, final humidity 0.1%, the power of each generator $\approx 25$ kW. The dryer’s productivity varied from 0.15 to 0.25 kg/s, its length – from 2 to 3 meters. Other changes concerned the corner of the generator’s input and the evaporation value by convection $HV$.

The maximum of the positive results – when the object dried out till the given humidity – was achieved under $GV = 0.17$ kg/s, dryer’s length $L = 1.5$ m and $HV = 1000$ Wt/m$^2$ degree. In order to achieve a positive result under a lesser productivity, e.g. 0.15 kg/s, $HV$ should also be lessened, which means reducing the blow-off.

The calculations have shown that in that unit the object can dry out even if only one generator of the same power is being used, but in this case the productivity of the setting should be reduced by two times. Any change in the location of the generator’s input has only little effect on the results as compared to the corner of the input. Thus, the functioning of the camera has been analyzed parallel to the task of the synthesis.

For the setting of the 2.2 meters length and the generators’ powers of $PG_1 = PG_2 = 8$ kW, where the drying of the object with the parameters $\varepsilon_z = 70$, $\tan \delta_2 = 0.15$, $C = 650$ J/kg·K, $\rho = 4260$ kg/m$^3$ has been carried out, by the humidity change of the object from 25% to 5% and the maximum heating temperature 1000 there was set a task to determine the optimal technological parameters.

While solving this task it has been made clear that under given parameters of the object and the setting the object would dry out under the condition that its initial humidity makes up 27% and $HV = 250$ Wt/m$^2$ degree. Minor deviations from the specific given parameter – humidity – prove the accuracy of the tasks to solve with the help of the developed numerical model. The $HV$ increase up to 2000 has shown that it only lightly affects the quantity of the residual humidity in the object.

| $PG_1 = PG_2$ | 0.015 | 0.016 | 0.017 | 0.018 |
|---------------|-------|-------|-------|-------|
| 6000          | 3.812 | 6.384 | 8.535 | 10.396|
| 6500          | 0.563 | 3.282 | 5.672 | 7.698 |
| 7000          | -     | -     | -     | -     |
| 7500          | -     | -     | -     | -     |
| 6000          | 3.558 | 0.079 | 8.287 | 10.259|
| 6500          | 0.298 | 3.009 | 6.412 | 7.527 |
| 7000          | 0.021 | 0.049 | 2.531 | 4.828 |
| 7500          | 1.589 | 0.142 | 0.348 | 2.212 |
| 6000          | 3.209 | 5.733 | 7.938 | 9.912 |
| 6500          | 0.088 | 2.629 | 5.042 | 7.196 |
| 7000          | 0.367 | 0.451 | 2.131 | 4.428 |
| 7500          | 0.291 | 0.519 | 0.789 | 1.689 |

The introduction of the water loading in form of a compact cylinder with regard of the air gap between the load and the object has shown that it has an impact on the temperature and power distribution along the dryer. The calculations have shown that any change in the water load radius
influences the quantity of the residual humidity in the object; however, it does not always affect the general result.

4. Discussion
The article provides an overview of the mathematical model that enables us to carry out numerical modeling of the technological process of drying out loose materials given constant temperature and humidity along the camera $\varepsilon$ and $\tan\delta$, $C$, $\rho$, as well as changing electro- and thermal-physical parameters.

Based on the mathematical model we have examined some questions concerning the analysis of microwave dryers for the heat treatment of loose building materials. It was suggested to amplify the construction of the microwave dryer with a water load in the form of a compact cylinder or cylindrical rings which should be located along fluorine-bedded reactor inside of which the processed environment moves.

We have developed a numerical method for calculating microwave dryers where electro- and thermal-physical parameters of the object under process change during the heat treatment what normally happens in the practical realization of the process.

Thus, the suggested calculation method of microwave settings for the heat treatment of loose building materials can be used for the numerical designing of optimal electrodynamic facilities and technological processes for heat treatment of dielectric environments, including loose building materials, with the help of microwave energy.

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