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Modeling of thermal mode of drying special purposes ceramic products in batch action chamber dryers

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Abstract. The article is devoted to the modeling of batch action chamber dryers in the processing line for producing shaped ceramic products. At the drying stage, for various reasons, most of these products are warped and cracked due to the occurrence of irregular shrinkage deformations due to the action of capillary forces. The primary cause is an untruly organized drying mode due to imperfection of chamber dryers design specifically because of the heat-transfer agent supply method and the possibility of creating a uniform temperature field in the whole volume of the chamber.

1. Introduction
At the enterprises of the ceramic industry, in the production of shaped special-purpose ceramic products, special attention should be paid to energy-intensive heat treatment processes, such as drying and burning. If they are not properly organized, various flaws will arise, because of which all batch products are subsequently discarded. Thus, the actual task is to ensure the uniformity of the temperature field in the dryer chamber, which will reduce the percentage of defective products [1].

Drying shaped ceramic products is carried out in batch action chamber dryers whose designs have different overall dimensions and technological parameters that would meet all the requirements for shaped products and take into account their individual design features (sizes, shapes and configurations).

Currently, in the ceramic industry, there is a wide variety of drying plants designed for drying both loose clay, which is the starting material in the production, and molded products, which require further heat treatment to give them the required properties.

2. Analysis of existing designs
In the drying chamber, which has the form of a parallelepiped (Figure 1), the working space is divided into three zones located above one another, using runabouts and special screens, so that the air, as it moves through the chamber, changes its direction twice, being heated in intermediate heaters , which will increase the capacity of the drying chamber. To analyze the thermal mode of the camera, its 3D model was designed in the Flow Simulation module of the SolidWorks software product.

As a result, a model of the temperature field is obtained (Figure 1), where zones with different temperature values (93°C…100°C) can be visually determined. As the heat-transfer agent moves along the chamber, it gives up its heat, heating the products located on the shelves, while increasing its relative moisture. Later, after heating in the heaters and changing the direction of the heat-transfer agent, the temperature increases jointly with increasing moisture content. That is why as it moves

toward the upper shelves the heat-transfer agent reduces the moisture absorbing capacity. The products located immediately after the heaters are washed with a heat-transfer agent with a higher temperature than those at the opposite end of the shelf, just before the next heating stage, so the products are dried under different conditions, which leads to the formation of a spoilage [2].
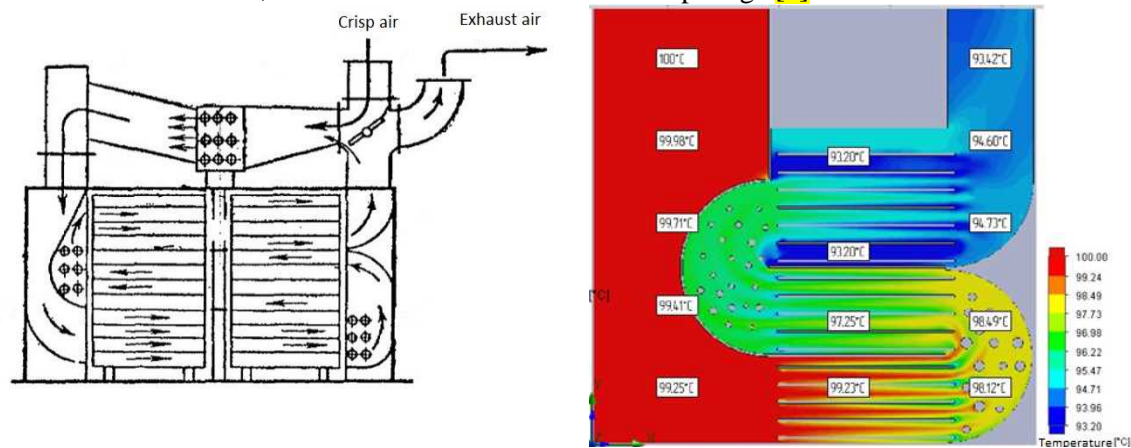
Figure 1. A scheme and a temperature field of a chamber dryer

There are a number of chamber dryers in which the movement of air is carried out without the aid of fans, such as in a V.E. Grum-Grimzhayailo's (Figure 2) dryer [3], which is based air movement due to the difference in its volumetric weight in the hot and cold state. The supplied heat-transfer agent flows into the upper part of the chamber on the side of shelves with products, behind a special partition, which reaches almost the very top of the chamber. After that, the flow of heat-transfer agent rushes down through the perforated shelves with the products, gradually losing temperature and absorbing moisture, becoming heavier, which facilitates its downward movement, where it is removed along the outflow channel. Thus, the temperature difference between the upper and lower part of the chamber is more than 7,5°C.

In dryers that have a forced circulation system, the movement of air occurs more intensively, which makes it possible to intensify the drying processes. For example, a radial fan can be installed for this purpose (Figure 3, shelves for products are not shown) [4]. When it is switched on, air flows into the curved diffusers, which direct the air flow along one of the chamber walls and then circulation occurs on a circular path. This improves the circulation of air through the working volume of the dryer chamber, however, because of its rectangular shape, vortexes and speed differences of the heat-transfer agent flowing around the products placed on the shelves are formed, forming temperature differences of more than 20 ° C, as can be seen in the model of the temperature field in Figure 3.

To improve the movement of the heat-transfer agent, it can be fed into the chamber with the help of manifolds and nozzles, which are distributed along the walls of the chamber. The design of such dryer (Figure 4) provides the presence of a partition in the chamber, with two apertures near the floor and ceiling of the chamber. In the upper aperture, a fan is installed to circulate air from one half of the chamber to the other through the lower opening [5].

Analysis of the most common existing dryers revealed that when drying products of simple shape which does not have stress concentrators in the form of internal or external corners, which changing along the length of cross-sections, temperature difference in the range of 5-7 ° C virtually does not increase the amount of spoilage, as when drying shaped products that have a complex shape. A disadvantage of such dryers is also the low quality of heat treatment of products caused by the formation of stagnant zones in the lower part and at the corners of the chamber due to the uneven distribution of the heat-transfer agent.

Therefore, in order to improve the quality of the heat treatment of the products due to the creation of an even temperature field, a new design of the chamber dryer is proposed (Figure 5), body 1 is arranged vertically and has the shape of a cylinder. Supply device 2 of heat-transfer agent in the form

of vertical pipe, in which holes 3 with reflectors 4 are made, is fixed in the center along the length of body 1. Truncated cone 5 is installed along the internal length of the pipe and coaxially with it, with the base upwards. Heat-transfer agent removal device 6 is made in the form of hollow channels fixed, for example by welding, from the outside along body 1, communicating with its interior space. A package of cylindrical shelves 7 for shaped ceramic products is installed in the body around heat-transfer agent supply device 2.
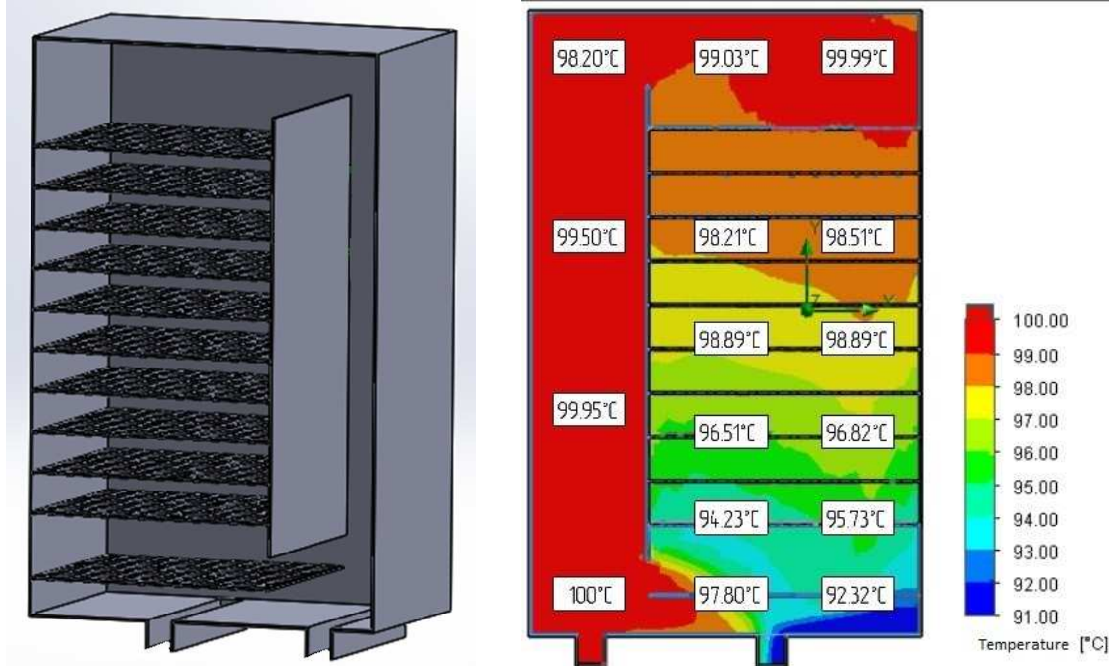

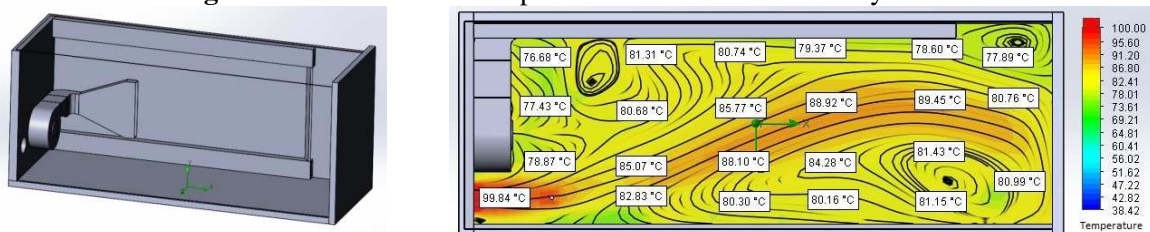**Figure 2.** A model and a temperature field of a chamber dryer

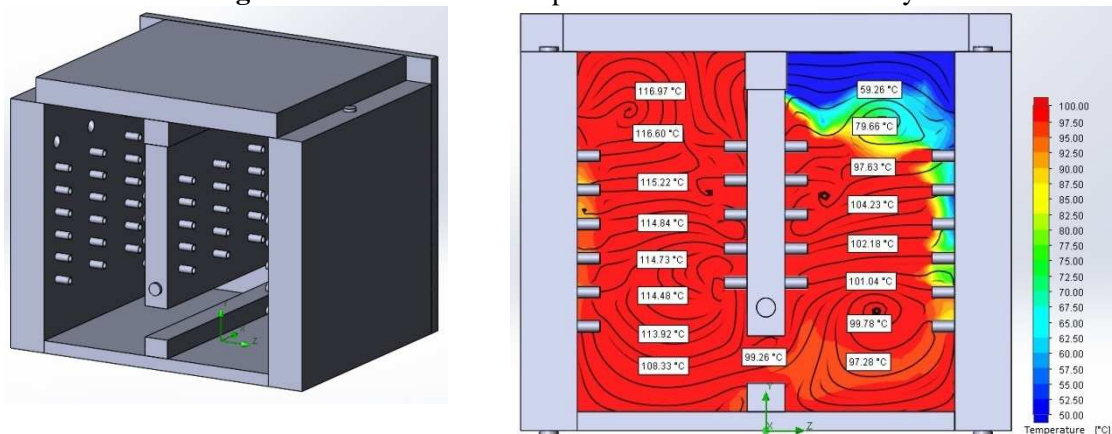**Figure 3.** A model and a temperature field of a chamber dryer

Figure 4. A model and a temperature field of a chamber dryer

To create a uniform temperature field, body 1 is made in the form of a cylinder, which makes it possible to get rid of the lack of existing designs of chamber dryers in the form of formation of

stagnant zones at the corners of the chamber. The vertical arrangement of body 1 with installed supply device 2 at its center and removal device 6 outside allows the supply and removal of the heat-transfer agent from the center to the periphery, improving the movement of the heat-transfer agent both between the shelves and throughout the space of body 1. Reflectors 4 of holes 3 of supply device 2 and located in it truncated cone 5 provide an even distribution of the heat carrier along the height of body 1, such that products at different heights of the package of cylindrical shelves 7 undergo the same temperature mode, which improves the quality of heat treatment and reduces spoilage losses [6].

Modeling of the thermal mode of drying special purposes ceramic products in proposed batch action chamber dryer (Figure 5) showed that the heat-transfer agent supplied from below, passing through the holes along the entire height of the vertical body, is evenly distributed over a package of cylindrical shelves, washing the products.
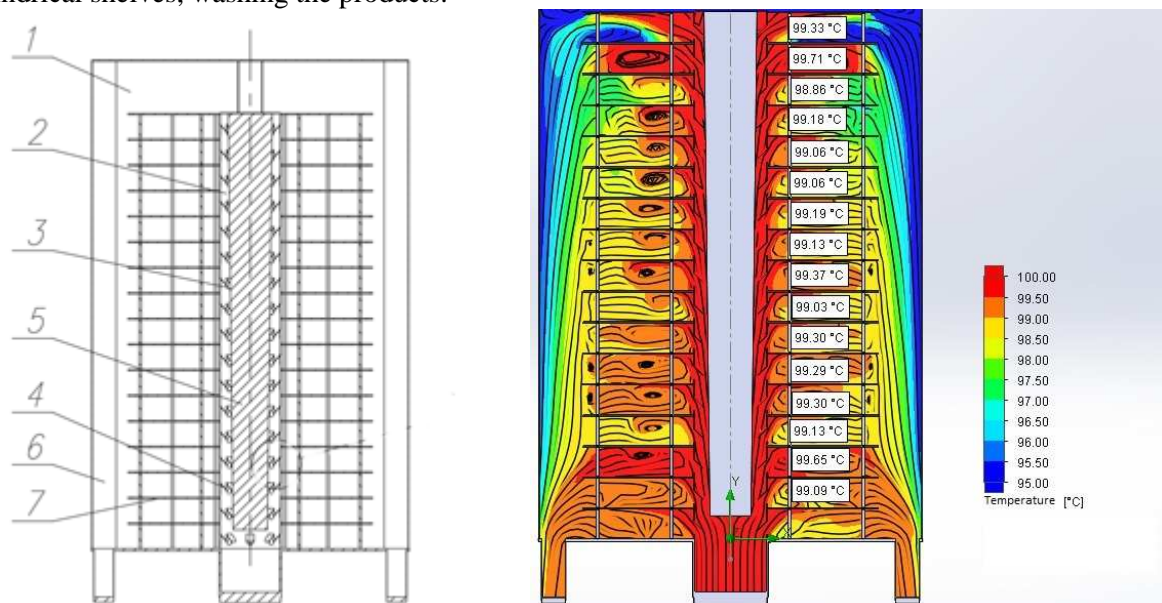
Figure 5. The proposed design of a chamber dryer

The proposed design will improve the movement of the working medium in the space of the chamber of the dryer, create a uniform temperature field, intensify the heating process, improve the quality of heat treatment of the products, and reduce the percentage of spoilage.

To express a generalized mathematical model of the drying process for shaped special-purpose ceramic products, it is necessary to obtain a description of the internal thermophysical processes occurring in chamber dryers in the form of a model that would reflect the qualitative and quantitative characteristics of the heat-transfer agent when moving from the supply to the removal device.

To obtain this model, it is necessary to solve the Navier-Stokes equations. From all approaches to the solution of these equations for different media, let us consider the most suitable for solving the problem posed, taking into account the chemical and thermophysical properties of the agent. Consider some of them, the most suitable for the task.

The solution of the simplified equations does not give us an exact solution for the flow of a viscous fluid and gas, and the complete Navier-Stokes equations are very complicated. Since the authors are considering the motion of gas or air, they can neglect its compressibility.

The Navier-Stokes equation for a non-compressible fluid can be obtained from their analog for a compressible fluid, assuming the fluid is non-compressible. Consequently, in the case of a non-compressible fluid, there is a special case of the Navier-Stokes equations for a compressible fluid.

The Navier-Stokes equation for a non-compressible fluid with constant properties in the absence of mass forces and heat input from the outside, which corresponds to the nature of items involved, is written as follows:

The continuity equation:

$$\nabla \cdot V = 0.$$

The equation of motion:

$$\rho \frac{\partial V}{\partial t} = -\nabla \cdot p + \mu \cdot \nabla^2 \cdot V.$$

The equation of energy:

$$\rho \cdot c_v \cdot \frac{\partial T}{\partial t} = k \cdot \nabla^2 \cdot T + \Phi.$$

where V – velocity vector, m/s; ρ - density of the medium, kg/m³; p - static pressure, Pa; T – temperature, ºC; μ - dynamic viscosity coefficient, mPa * s; Φ – dissipative function.

These equations form a mixed elliptic-parabolic system concerning to the unknowns (V, p, T). The temperature only enters into the energy equation, so that one can consider this equation separately from the others.

Because the chamber dryer is symmetrical in width (Figure 6), it is possible to use the two-dimensional Navier-Stokes equations in the Cartesian coordinate system:

The continuity equation:

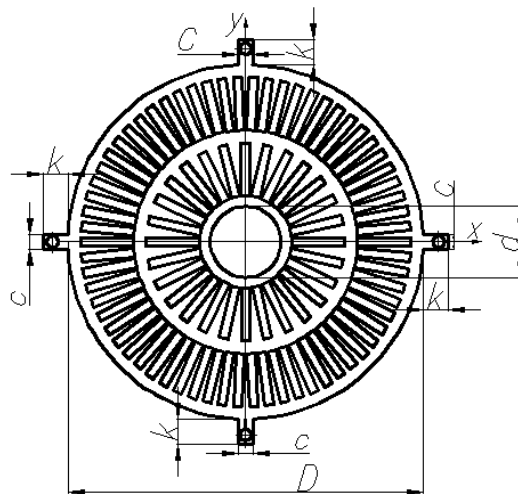$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0.$$

The equation of motion along the x coordinate:

$$\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} = -\frac{1}{\rho} \cdot \frac{\partial p}{\partial x} + \frac{\mu}{\rho} \left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} \right).$$

The equation of motion along the y coordinate:

$$\frac{\partial v}{\partial t} + u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} = -\frac{1}{\rho} \cdot \frac{\partial p}{\partial y} + \frac{\mu}{\rho} \left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} \right),$$

where u, v – velocity vector components.

Figure 6. A scheme of a chamber dryer

The boundary conditions of the velocity and temperature fields must be specified in accordance with the fact that $V_x = V_y = 0$ on the walls of the chamber, and they can be described using the equations:

$$x = \pm \left(\frac{D}{2} + k \right); y \in \left(-\frac{c}{2}; \frac{c}{2} \right);$$

$$y = \pm \frac{c}{2}; x \in \left(-\frac{D}{2} - k; -\frac{D}{2} \right) \cap \left(\frac{D}{2}; \frac{D}{2} + k \right);$$

$$x^2 + y^2 = \frac{D^2}{4}; x \in \left(-\frac{D}{2}; -\frac{c}{2}\right) \cap \left(\frac{c}{2}; \frac{D}{2}\right);$$

$$x = \pm\frac{c}{2}; y \in \left(-\frac{D}{2} - k; -\frac{D}{2}\right) \cap \left(\frac{D}{2}; \frac{D}{2} + k\right);$$

$$y = \pm\left(\frac{D}{2} + k\right); x \in \left(-\frac{c}{2}; \frac{c}{2}\right).$$

Moreover, due to the non-compressibility of the fluid, there should be an equality of incoming and outgoing fluxes per unit time:

$$Q_{in} = Q_{out}; \frac{\pi U_{in} d^2}{4} = \pi U_{out} c^2.$$

3. Conclusion

For further development of the mathematical model of heat-transfer agent distribution in the batch action chamber dryers of the proposed design, it is necessary to solve a system of differential equations and to plot the computational lattice in accordance with the boundary conditions and dimensions of the dryer.

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