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Drying of colloidal capillary-porous materials

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ABSTRACT

In the present work we show that in drying of colloidal capillary-porous materials the processes of heat and mass transfer are usually accompanied by the processes of deformation and development of stresses. Application of the Euler approach, which is connected only with the account of small deformations, to description of the occurring processes is erroneous. The stressed–strained state should be described on the basis of the Lagrange approach with account for large displacements and deformations of material. In this connection, we present a physical–mathematical model of the process of drying colloidal capillary-porous materials in curvilinear coordinates in the tensor form. A variational formulation of the problem and its solution by the method of finite elements are presented. The results of calculations and regularities obtained on their bases are given. Special attention is paid to the fact that the developed model and calculation techniques can form a theoretical basis for designing devices of experimental determination of stresses in materials.

1. Introduction

The processes of heat and mass transfer in different disperse materials are rather thoroughly presented in the literature. However, little attention is paid to stresses in deformations in these processes. We mention only some works dealing with the problem mentioned.

Lutsik [1–4] attempted at deriving general equations of heat and mass transfer and deformation of porous bodies on the basis of the thermodynamics of irreversible processes, thermoelasticity theory, and works of A.V. Luikov.

Kang et al. [5,6] developed analytical methods of calculation of stresses in a wood disk in the presence of the gradient of moisture content. The disk is taken to be a cylindrical orthotropic material with radial variation of properties. The authors state that the developed simple analytical methods allow prediction of moisture stresses at early stages of drying. However, in these works the moisture content field in the material is not calculated and the difference of moisture contents necessary for analytical calculations is given arbitrary. Akulich and Militzer [7] considered the problem of heat and moisture transfer and internal stresses in anisotropic pine wood in convective drying. In [8], a procedure of numerical calculation of the equations of heat, mass, and mechanical equilibrium is developed on the basis of the finite volume method for wood.

Itaya et al. [9] presented a three-dimensional mathematical model of interrelated heat and mass transfer and a viscoelastic rheological model for composite food product in the form of a three-layer briquette whose layers consist of starch and sucrose–starch mixture. Using a method of finite elements, Izumi and Hayakawa [10] developed a numerical procedure for calculation of the formation of cracks and their propagation in elastoplastic food products. In [11], calculations by the method of finite elements allowed obtaining of the distribution of stresses in noodle and prediction of formation of cracks in it during drying. Chemkhi et al. [12] studied the processes of heat and mass transfer and stressed–strained state in potatoes in the form of a parallelepiped. In [13] the distribution of viscoelastic stresses in rice grain during drying was obtained. Jia et al. [14] developed software for description of drying a single grain and its thermal and moisture treatment and for analysis of internal stresses.

Murugesan et al. [15] studied the drying-caused shrinkage stresses of a two-dimensional rectangular brick and roof tiles numerically. Kowalski and Rajewska [16] made theoretical analysis of stressed formed in convective drying of kaolin. The authors used elastic and viscoelastic models foe estimating stresses in the material. The equations obtained on the basis of these models were solved analytically for a cylindrical sample. In [17], physical–mathematical modeling of convective drying of a clay plate was made.

An analysis of the above literature showed that in development of mathematical models of the heat and mass transfer processes and the stressed–strained state use is made of the tensor of small

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deformations and Euler variables. This approach does not allow calculation of large deformations of the material. The colloidal capillary-porous systems under consideration have structures with predominant coagulation bonds. On drying of such materials the shrinkage can have a large value. Consequently, derivation of governing differential equations on the basis of the Euler approach is not justified.

2. Physical prerequisites of the developed method (approach)

2.1. Surface forces

Drying of colloidal capillary-porous materials involves both the heat and mass transfer processes and the process of deformation of material structure. Deformability of colloidal capillary-porous bodies is related to the fact that contacts between the particles forming these bodies are executed through the liquid layers. In this case, shrinkage can have a large value because water layers provide substantial mobility of particles relative to one another and the size of pores and wetting films is commensurable with the dimensions of particles. These contacts stipulate the structure and strength of the material as well. A nonuniform reduction of the body dimensions in drying leads to the development of stresses in it. Interaction of particles through water layers is, first of all, caused by long-range molecular surface forces. Dimensions of adsorption and wetting films on the inner surface of the material, its mass content and mass transfer are also determined by the field of surface forces [18,19].

2.2. Interrelation of processes

It is evident that a unique nature of the processes of heat and mass transfer and deformation (determined by surface forces and the presence of water films) leads to their interrelation. The process of heat and mass transfer determines the process of material deformation and, in turn, deformation of the material and transformation of its structure obligatory result in changes in heat and mass transfer. Therefore, consideration of drying as a process of heat and mass transfer without account for shrinkage and stresses is idealization. We should distinguish three ways of interrelation of the processes: motive forces of the processes, dependence of heat and mass transfer characteristics and rheological properties on moisture content, temperature, and structure of the material, and changes in the geometric dimensions of the body.

Moreover, if the stressed–strained state in drying is disregarded, the investigation of heat and mass transfer processes may turn to be pointless. Let us take wood as an example. One of the requirements to drying is the absence of cracks and destruction of the material. Therefore, only that heat and mass transfer in drying is meaningful which satisfies these requirements, whereas it is meaningless to speak of any processes occurring in the material in its destruction.

2.3. Dependence of size on the amount of moisture

The presence of water interlayers and pores results in contraction of all colloidal capillary-porous materials in drying thus leading to the dependence of its dimensions on the water content in it. This dependence is expressed by the formula [20]

$$l = l_0(1 + \beta_{sw}(W - W_0)), \tag{1}$$

where l is the linear size of the material, m^3; l_0 is the linear size of the material corresponding to the initial moisture content W_0, m^3; β_{sw} is the swelling coefficient; W is the moisture content, kg/kg, and W_0 is the initial moisture content, kg/kg.

Here we see a full similarity to the temperature dependence for metals. This makes it possible, by analogy, to write the Hook law with account for moist deformations. A reduction of body dimensions as a result of decrease of moisture content in it is termed shrinkage.

2.4. Large shrinkage and deformations

Shrinkage can be substantial for many bodies. Such material as peat, structural materials, food, leather and others shrink greatly. Relative deformations of linear dimensions amounting less than 1% are considered to be small. Relative linear deformations for colloidal capillary-porous materials are mach larger. In drying that can make 15% for ray, leather, wood, and coal, 30% for clay, 45% for noodles, 120% for peat, and so on [20]. Therefore such deformation are assumed to be large and in studying the processes of drying in colloidal capillary-porous bodies use should be made of the Lagrange approach with mobile curvilinear coordinates rather than of the Euler method.

3. Physico-mathematical model

3.1. Comparison of the Euler and Lagrange approaches

In [21], the authors made a comparative analysis of the calculations of mass transfer and deformation of disperse colloidal capillary-porous materials by the Euler and Lagrange approaches. In particular, the time of the drying process at different initial moisture contents of the material was calculated by the Euler and Lagrange methods. The results of calculations are presented in Fig. 1 from which it follows that these methods give qualitatively different results. We can see that at small initial moisture contents the times of drying termination the results obtained by both methods coincide. It is also seen that as the initial moisture content of the material increases the Euler method leads to an increase in the time of drying. It is quite explainable because the larger the amount of water in the material the more time is required for its removal.

The Lagrange method gives another dependence of the time of the drying process termination on the moisture content. First, the time increases, then it passes through the maximum, and decreases with increase in the moisture content. This behavior is connected with a decrease of the body size in drying. It is known that the smaller material, the quicker it dries. Therefore, there exist two

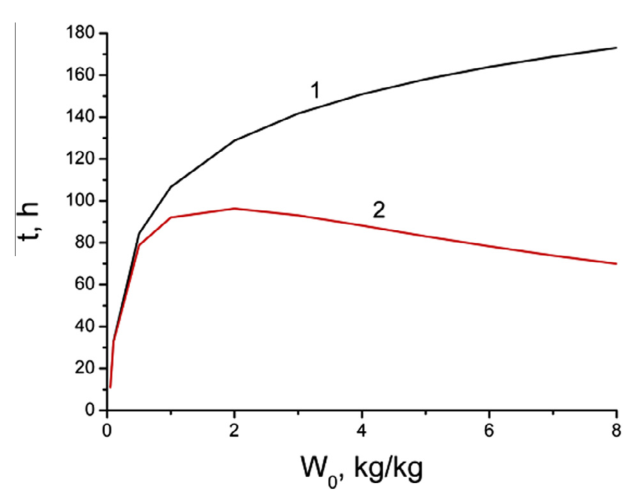

Fig. 1. Time of termination of the drying process at different values of the initial moisture content: (1) Euler method, (2) Lagrange method.