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MODELLING AND NUMERICAL SIMULATION OF MASS TRANSFER AND MECHANICAL PROCESSES AT CERAMIC WARE IN INDUSTRIAL DRYERS

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Abstract. An algorithm for efficiency improvement of industrial drying processes of ceramic ware with complicated geometries is developed. It is based on mathematical modelling and numerical simulation of the transient moisture content fields and subsequent mechanical processes in three dimensional ceramic bodies. The models allow variations of the drying conditions and time duration of the process in order to choice the most efficient regime at existing or design dryers.

The proposed models are applied for finite element analysis of wet bricks behavior in continuous working drying installation. The shrinkage mode, modulus of elasticity, Poisson ratio, modulus of rupture, effective mass transfer coefficient and critical moisture content are determined by experimental tests of the material. They are used to simulate numerically the moisture, stress and strain fields in the 3D geometry of the ceramic bodies at the existing drying regime. The mathematical models are validated on the base of in situ measurements of parameters of the drying installations.

Ways for estimation of the potential for energy savings on the base of the developed algorithm are discussed.

1 INTRODUCTION

Industrial drying is a key process in the ceramic manufacturing. The right organization of the drying regime is important for the quality of the production and the embodied energy of the ceramic ware [1]. The advanced ceramic industry is continuously evolving in a direction of optimization of geometry and materials of the products in order to increase their functionality. These processes provoke research activities oriented to improving of the energy and technological efficiency of the industrial dryers. Solutions of these actual tasks at operating condition and design stage are possible by in situ experiments or mathematical modelling and numerical simulations of the coupled thermal, moisture and mechanical processes in the dried ceramic bodies. The in situ experiments usually are energy and time consuming. They are successfully displaced the by modelling investigations in the term of rapid development of the software for numerical simulations [2]. Many research efforts are focused to understand, model and predict the complex heat, mass transfer and shrinkage of the ceramic material in order to prevent the possible failure of the articles [3, 4, 5]. Such couple field analysis also can be applied for précising of the initial geometry of the articles - a hard task with multiple solutions that usually is solved experimentally [6].

The aim of the present study is to develop an algorithm for numerical investigation of transport phenomena and subsequent mechanical behavior of the ceramic ware at industrial convective drying in order to improve the efficiency of the process. Such complex investigation, taking into account the real conditions in the dryers has not been reported to now.

2 MATHEMATICAL MODELING – CONCEPTIONS AND APPROACHES

2.1. Convective drying of ceramics

The drying of ceramic materials can be examined in three main periods (Fig. 1): preheating period (0), constant drying rate period (CDRP or I) and falling drying rate period (FDRP or II). In the preheating period the material with initial temperature is heated up/down to the wet bulb temperature of the drying media (K-L) and respectively the drying rate drops/rises (A-B) [7]. The change of the moisture content is insignificant and that period can be examined as part of the next one.

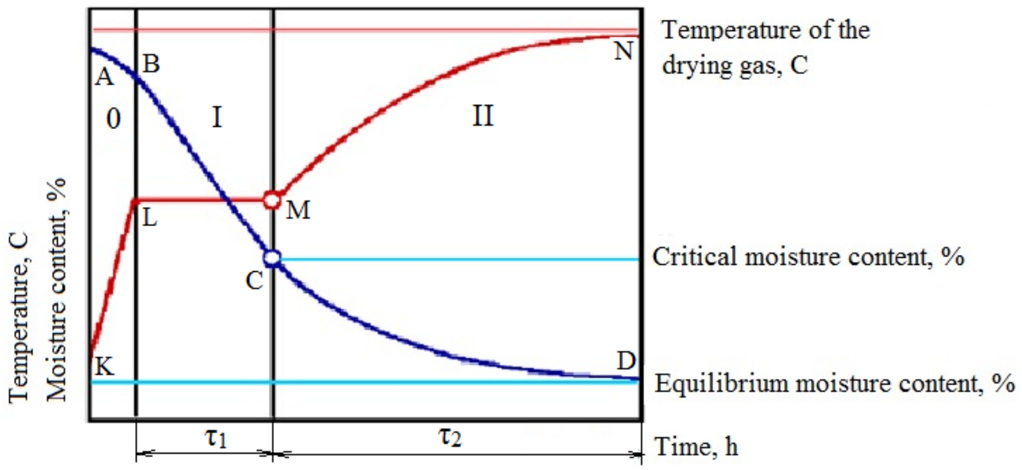


Figure 1: Drying periods

The CDRP begins at temperature of the material, equal to the wet bulb temperature (point B and L in Fig. 1). The surface temperature remains constant during the period (line L-M). The CDRP is governed fully by the rates of external heat and mass transfer since a film of free water is always available at the evaporating surface. The moisture migrates from the inside of the porous material to the surface by diffusion [4]. The drying rate remains constant as long as the moisture transport rate from the interior of the material to the exchange surface is in scale to the evaporation rate from the exchange surface (B-C). The water content at the end of the CDRP is called critical moisture content (point C). The evaporation rate starts to decrease at the end of the CDRP because of the disconnection of the liquid meniscus from the surface. This decreasing trend continues until all the liquid meniscuses are disconnected. Detachment of the last liquid meniscus from the surface marks the onset of FDRP (C and M). The internal moisture transport rate specifies the drying rate of the FDRP. During the transition period and the FDRP the temperature of material surpasses the wet bulb temperature and grows up to the drying gas temperature (M-N). The drying process stops when the equilibrium moisture content is reached.

Several types of strains are expected to exist during the drying of the wet body, formed by porous plastic material. They are provoked by the mass transfer (shrinkage), temperature gradients (thermal stresses) and the gravity [4]. Shrinkage is one of the most important factor effecting on drying behavior of clay-like materials. It occurs during the 0 and I period and stops at the critical moisture content. If drying is performed sufficiently slowly, the shrinkage would be uniform and drying induced stresses are smaller than the strength of the wet material. But for economic reasons the industrial drying processes are usually performed faster and the non-uniform shrinkage usually exists and leads to high tensile stresses. They may lead to cracking and subsequent deterioration in quality of dried products or even make them useless.

It is important to choose suitable drying conditions and time for each specific product to prevent failures of the articles. The time durations of the CDRP τ_1 and FDRP τ_2 are determined by the potential of drying, excepted as the difference between the dry and wet bulb temperatures [7, 8]. As smaller is it as longer is τ_1. To prevent failure of the production due to non-uniform shrinkage the CDRP has to be maintain at a relatively small drying potential provided by high relative humidity and small dry bulb temperature of the drying gas. The models below allow to take into account the fluid flow parameters on the coupled mass transfer and mechanical processes in the dried solid domain.

2.2 Modeling of structural-diffusion processes in the wet ceramic ware at drying.

System of equations

The transient fields of the moisture content and subsequent mechanical behavior of the materials are obtained by coupled numerical solution of mass transfer equation (1) and stress-strain relationship (2) for 3-dimentional finite element mesh, approximating the geometry of the ceramic body.

$$\frac{\partial C}{\partial \tau} = [D_{ef}]\nabla^2 C \tag{1}$$

where C = water concentration, kgm^{-3}; D_{ef} = effective diffusion coefficient, m^{2}s^{-1}; τ=time, s.

$$\{\sigma\} = [D]\{\varepsilon\} \tag{2}$$

where $\{\sigma\}$ = stress vector; $\{\varepsilon\}$= elastic strain vector; $[D]$= elastic stiffness matrix, formed by module of elasticity E and Poisson ratio ν.

In a coupled structural –diffusion analysis the total strain is formed of elastic $\{\varepsilon^{el}\}$ and diffusion $\{\varepsilon^{d}\}$ parts, respectively:

$$\{\varepsilon\} = \{\varepsilon^{el}\} + \{\varepsilon^{d}\} = [D]^{-1}\{\sigma\} + \{\beta\}\Delta C \tag{3}$$

where $\{\beta\}$= vector of coefficient of diffusion expansion, m^3kg^{-1}; ΔC= concentration change according reference value C_{ref}:

$$\Delta C = C - C_{ref} \tag{4}$$

The modulus of elasticity *E*, Poisson ratio, coefficient of diffusion expansion *β* and D_{ef} can be obtained experimentally and used in the models as function of moisture content in the dried material [10, 11].

Boundary conditions

The mass transfer from the boundaries *S* of the ceramic body to the drying gas can be computed by mass flux, depending on the thermodynamically and fluid flow conditions in the dryer [9]:

$$D_{eff} \left. \frac{\partial C}{\partial n} \right|_S = \dot{q}_{mI} \tag{5}$$

The intensity of drying in CDRP is expressed by:

$$\dot{q}_{mI} = \frac{h_{mI}}{R_w T}\left(p_s - p_w\right) \tag{5}$$

where: $\dot{q}_{mI}$ = mass flux of evaporated water by unit surface, $kgm^{-2}s^{-1}$; h_{mI}= mass transfer coefficient in CDRP, ms^{-1}; T = temperature of the drying media, K; R_w = specific gas constant for water vapor: R_w=462 $Jkg^{-1}K^{-1}$; p_w and p_s are respectively partial pressures of unsaturated and saturated water vapor, Pa.

The coefficient h_{mI} depend on the fluid velocity, relative humidity and temperature field in the drier and can be determined by Nusselt number at mass transfer:

$$Nu_{mI} = \frac{h_{mI}.l}{D_{d.m}} \tag{6}$$

where *l* = length of the ceramic body on the drying gas way; $D_{d.g}$ = diffusion coefficient of the dry gas-water vapor mixture, m^2s^{-1}. At isobaric process it can be computed by the temperature of the drying media *t*, °C:

$$D_{d.m} = 22.63.10^{-6}\left(\frac{t+273}{273}\right)^{1.81} \tag{7}$$

The Nusselt number is given in the common form in the literature [7, 8]:

$$Nu_{\partial I} = 2 + A_1.Pr_m^{0.33}.Re^{n1}.Gu^{m1} \tag{8}$$

where A_1, m_1 and n_1 depend on Reynolds number (Re). They are known for large limits of Re and can be calibrated on the base of operating conditions in the dryer.

Re, Prandtl number at mass transfer and Guhman number, used as non-dimensional drying potential, correspondently are:

$$Re = \frac{wl}{\nu}; \; Pr_m = \frac{\nu}{D_{d.m}}; \; Gu = \frac{T - T_w}{T} \tag{9}$$

where w = average velocity, ms^{-1}; ν =kinematic viscosity of the drying media, m^2s^{-1}; T_w=wet bulb temperature, K.

The mass flux, evaporated from ceramic ware at the II period of drying (FDRP) can be obtained according hypothesis for linear decreasing of the drying rate [8]:

$$\dot{q}_{mII} = \frac{\dot{q}_{m1}}{C_c - C_{eq}}\left(C - C_{eq}\right) = h_{mII}\left(C - C_{eq}\right) \tag{10}$$

where C_c = water concentration at the critical moisture content, kgm^{-3}; C_c = equilibrium water concentration, kgm^{-3}; h_{mII}= mass transfer coefficient in FDRP, ms^{-1}.

The boundary conditions for the structural analysis include zero normal displacements at the contact surface between the transport and the dried body and the symmetry surface (if there exists any).

The gravity is taken into account.

Analogy between the heat and mass transfer.

The advanced software for numerical simulation [2] allow structural-diffusion analysis at limited opportunities for definitions of boundary conditions and material properties for solution of equations (1) and (2). The modeling of the mass flux $\dot{q}_{mII}$, mechanical properties and coefficient of mass diffusion as function of the concentration is not directly possible. An alternative approach is to implement the structural-diffusion simulation using the analogies between the mass and heat transfer and between the diffusion and thermal stresses.

The effective diffusion coefficient in eq. (1) can be expressed by:

$$D_{ef} = \frac{K_{art}}{\rho_d c} \tag{10}$$

where K_{art}=artificial thermal conductivity, $Wm^{-1}K^{-1}$; ρ=density of the dry mass, kdm^{-3}; c=specific heat capacity, $Jkg^{-1}K^{-1}$.

The concentration can be referred to the dry mass of the material:

$$C = u\rho_d = \frac{W}{100}\rho_d \tag{10}$$

where u= moisture content of the ceramic mass, kg water/kg dry material; W=moisture content, %.

Then eq. (1) is transformed to:

$$\rho_d c\frac{\partial W}{\partial \tau} = \left[K_{eart}\right]\nabla^2 W \tag{11}$$

and the boundary conditions for its solution is:

$$\frac{K_{art}}{100c}\frac{\partial W}{\partial n}\bigg|_S = \dot{q}_m \quad \text{or} \quad K_{art}\frac{\partial W}{\partial n}\bigg|_S = 100.c.\dot{q}_m \tag{12}$$

If W is replaced by T in equations (11) and (12), they are transformed to Fourier equation for heat transfer and the second kind of boundary conditions for its solution, respectively.

The diffusion strain can be expressed as thermal strain in eq. (2):

$$\varepsilon^{d} = \beta\left(C - C_{ref}\right) \rightarrow \varepsilon^{th} = \alpha\left(T - T_{ref}\right) \tag{13}$$

where α= instantaneous coefficient of thermal expansion, K^{-1}. It is accepted equal to β:

$$\beta = \frac{\Delta l}{l\left(W_{in} - W_{c}\right)} \tag{14}$$

where W_{in} is the initial moisture content, %.

3 MASS TRANSFER AND MECHANICAL PROCESSES IN BUILDING BRICKS IN TUNEL DRYERS

3.1. External mass exchange in the dryer

The proposed approaches are tested to investigate the structural-diffusion behavior of building bricks in industrial continuously working dryer (detail information about the operating conditions in the dryer is not possible due to confidential rules). The drying media is an air-flue gases mixture with predominant air fraction. The drying gas and the wet ceramic articles are moved in counter flow through the drying tunnel. The change of the fluid flow temperature, relative humidity and velocity are obtained by in situ measurements, material and thermal balances. The figures below illustrate the change of the non-dimensions numbers according the dried ceramic ware with the time. The time on the figures is relative (moment time referred to the common time) in order to demonstrate the duration of the CDRP and FDRP durations.

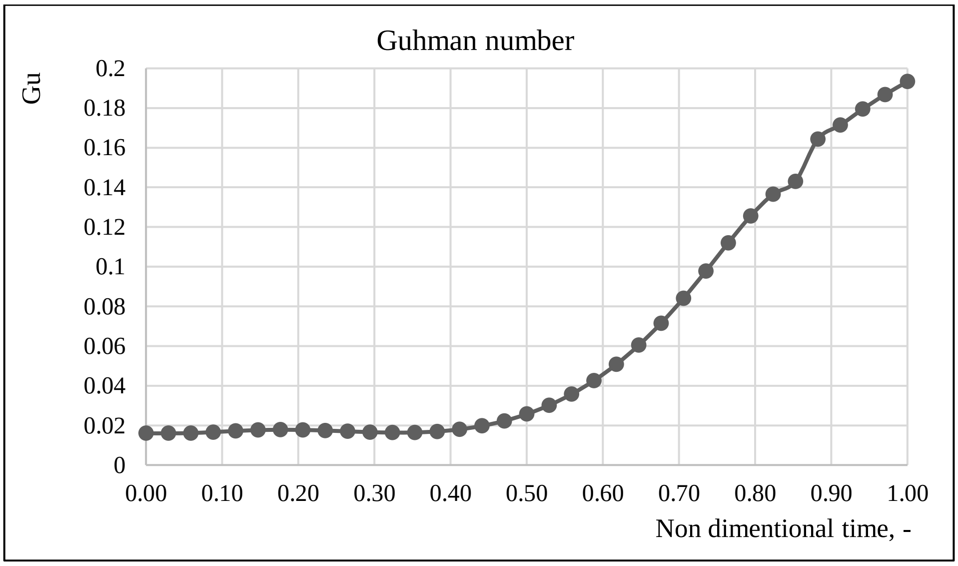


Figure 2: Variation of Gu number according the dried ceramic ware

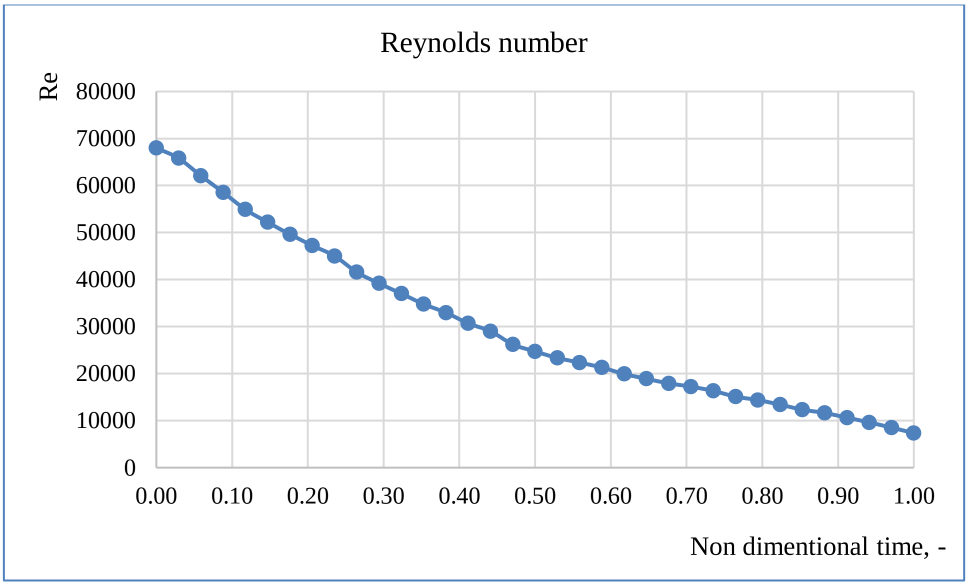


Figure 3: Variation of Re number according the dried ceramic ware

It is obvious from figure 2 that the time duration of the CDRP, corresponding to the smaller Gu number, is a about 60% of the full time process. The coefficients in Nu number are calibrated to obtain the mass transfer coefficient and mass flux according (5), giving the evaporated amount of water per article at drying to the critical moisture after the time integration of the mass flow: A_1=0.49; n_1=0.45 and m_1=0.135. The average value of the mass flux at the CDRP is used to obtain the mass transfer coefficient for the FDRP. So the common form of the mass flux, used as boundary condition to model the mass transfer between the ceramic ware and the dried media is:

$$\dot{q}_m = \begin{cases} \dot{q}_{mI} = const.\ (average\ value)\ for\ \tau_1 \quad at\ W \geq W_c \\ \dot{q}_{mII} = \dfrac{\dot{q}_{m1}}{W_c - W_{eq}}\left(W - W_{eq}\right) \quad at\ W < W_c \end{cases} \tag{15}$$

It is applied on all boundaries, excepting the symmetry ones and the contact surfaces between the ceramic ware to be dried and the floor of the transport or drier.

3.2. Material properties of the wet mass

The wet ceramic material is a mixture of clay and combustible supplements. Standard geometry samples made by a wet material after the extruder are tested after consecutive drying in a laboratory dryer. The critical moisture, shrinkage of the wet mass, modulus of elasticity, Poisson ratio and effective diffusion coefficient are obtained as function of the water content at series of experiments (Fig.4). Additionally the compressive and flexure strength (modulus of rupture) of the material as function of the humidity are obtained. After corrections with safety coefficients they are used as allowable upper limits to compare the stresses, computed by the numerical analyses. The graphics on figure 4 are obtained at averaged values of the investigated parameters for the samples.

The effective diffusion coefficient is obtained at plates, insolated at the smaller sides (to imitate infinite plates) and the relations [7]:
CDRP:

$$D = \frac{R}{\Gamma} . \frac{R_v . \overline{N}_I \left(u_{in} - u_k\right)}{u_{in} - \overline{u}}, \quad \frac{m^2}{s} \tag{16}$$

FDRP:

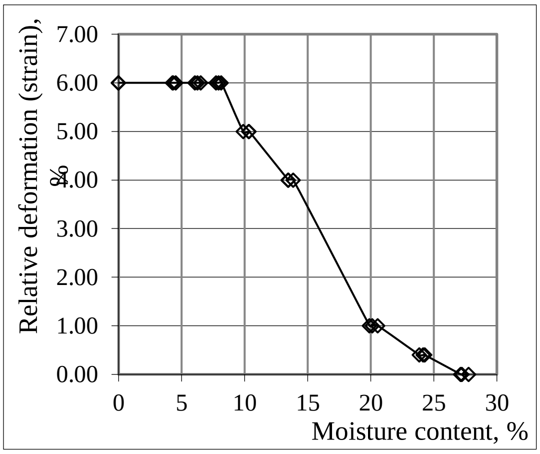
$$D = \frac{R.Rv.\overline{N}_I}{2.\Gamma.u_{in}.B.\left(1.5.B\frac{u_{in}}{\overline{u}} + B\frac{u_{in}}{\overline{u}}\left(\frac{1-1.5.B}{1-B}\right).\ln\left(\frac{\overline{u}}{Bu_{in}}\right) - 1\right)}, \quad \frac{m^2}{s} \tag{17}$$

where

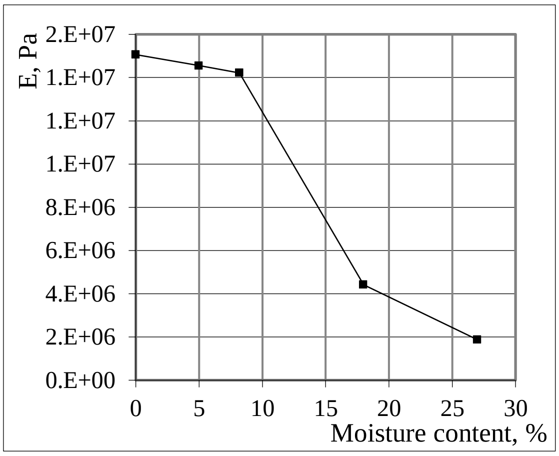
$$B = \frac{u_k - u_e}{u_1} \tag{18}$$

u_{in} = initial moisture content, kg water/kg dry material, u_c =critical moisture content, $\overline{u}$ = average moisture content, kg water /kg dry material; $\overline{N}_I$ = average drying rate, referred to the dry mass, $kgkg^{-1}s^{-1}$ at CDRP. Γ=3 for infinite plate with thickness $2R$. R_v is:

$$R_v = \frac{V}{F} = \frac{2R.F}{2F} = R, \quad m \tag{19}$$



a)



b)

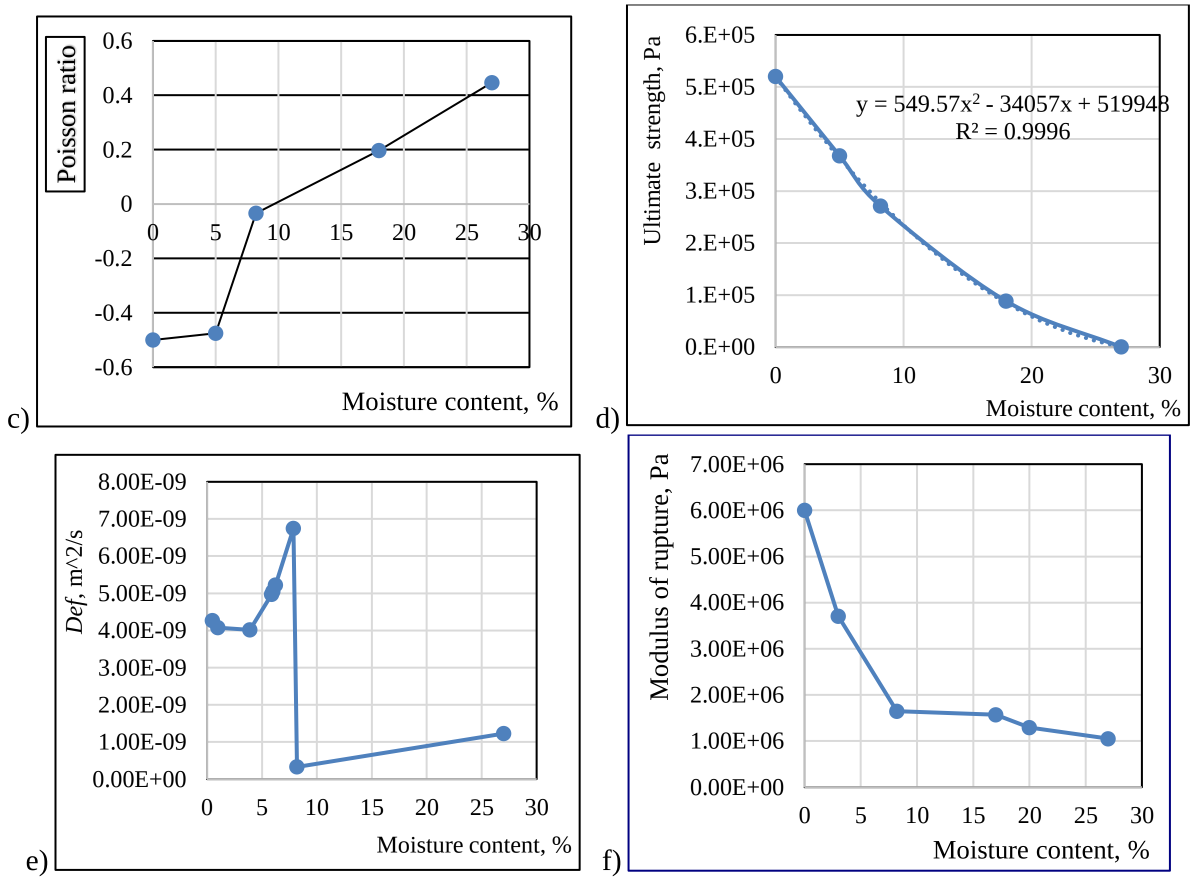


Figure 4: Material properties of the wet ceramic mass as function of moisture content
a) Bigot relation; b) Modulus of elasticity; c) Poisson ratio; d) Compressive strength; e) Effective coefficient of diffusion; f) Modulus of rupture

The material properties are used as function of the moisture content at the numerical analysis below.

3.3. Numerical simulation of structural – diffusion fields in the dried bodies.

Transient modeling investigations are implemented at a geometrical model of a typical article (Fig. 5). It is divided by a symmetry plane. The geometrical model is discretized by a finite element mesh. High order (20 nodes) element Solid 226, available at ANSYS Mechanical APDL for thermal- structural-diffusion analysis is used (Fig. 6).

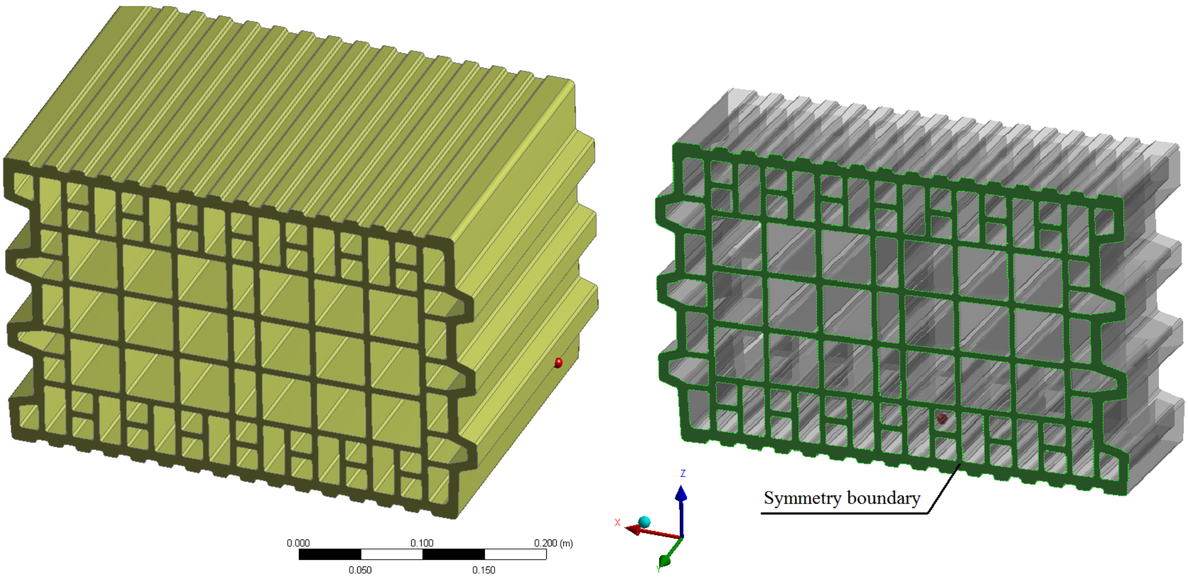


Figure 5: Ceramic brick (on the left) and geometrical model (on the right)

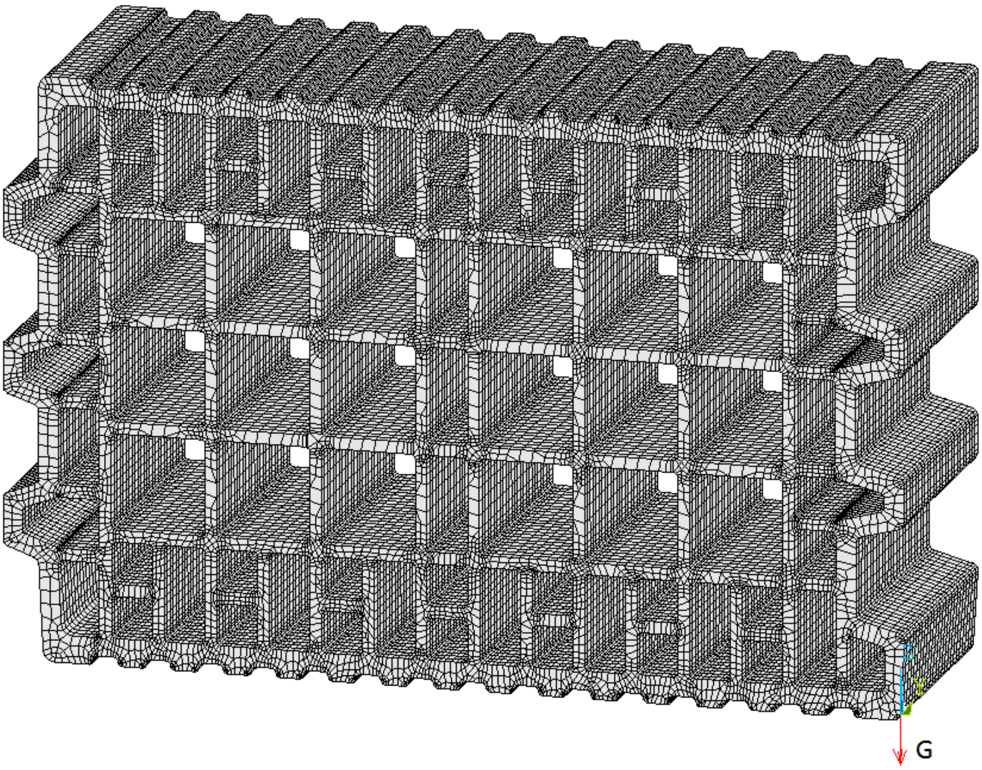


Figure 6: Finite element mesh

The analysis is performed using the analogy between the heat and mass transfer, described above. The time-histories of the moisture content, stresses and strains at the drying process are obtained. Fields of moisture content and first principal stress at a moment from the first part of the CDRP are shown on the figures bellow. The maximal values of the first principal stress does not exceed the modulus of rupture of the material, corrected by a safety coefficient during the process. So fractures of the production due to non-uniform shrinkage are not expected at the maintained drying regime. That corresponds to the facts and observations at the dryer.

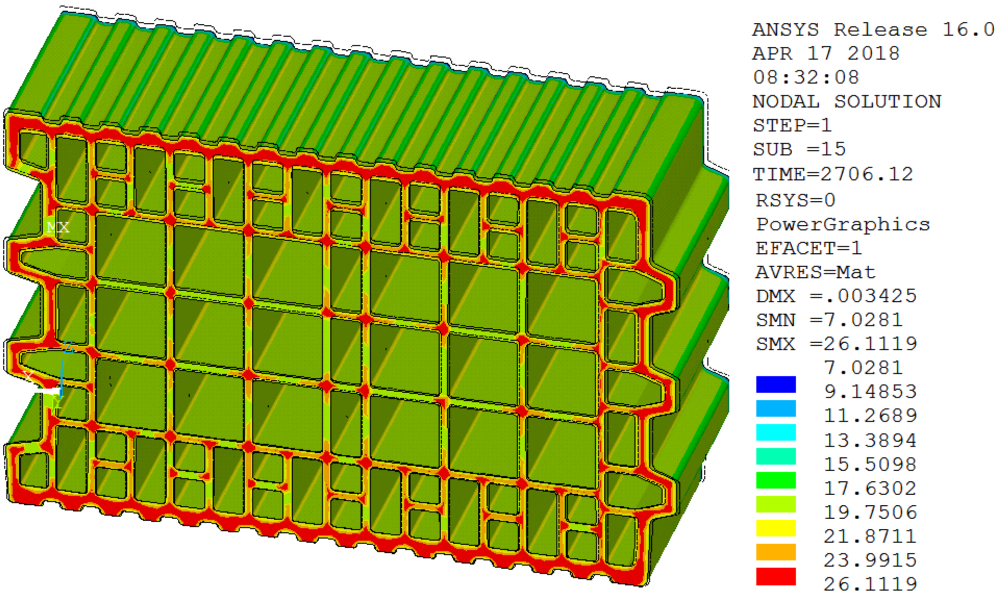


Figure 7: Moisture content W, % with deformed shape and unreformed edges

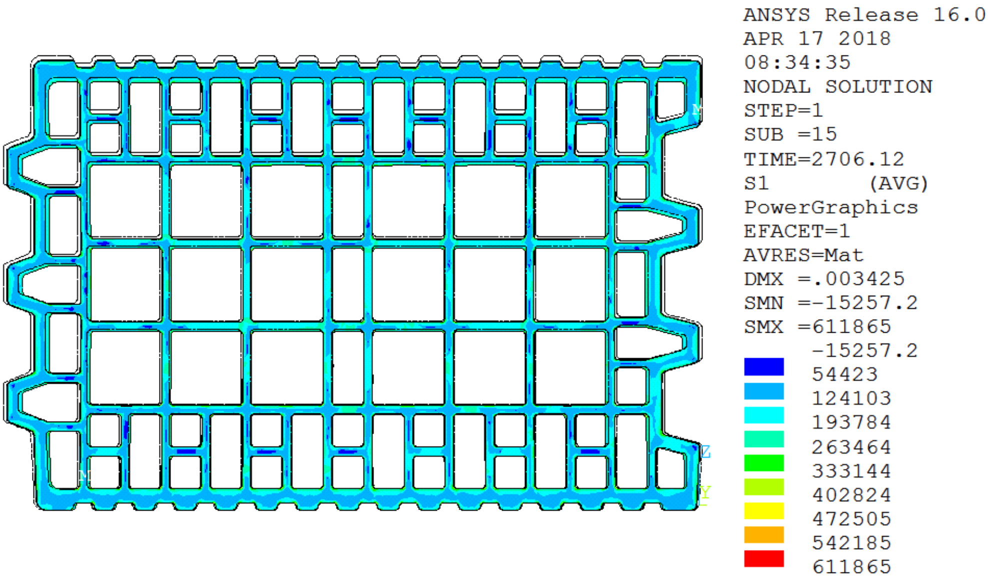


Figure 6: First principal stress with deformed shape and unreformed edges

The models are validated comparing the deformations after the simulation to the established ones after the drying. Additional validation is performed by comparison of final average moisture content, obtained at the real conditions and the numerical simulation. Differences below 4 % are established.

4 CONCLUSIONS

An algorithm for numerical investigation of the structural-diffusion processes in ceramic ware at drying in industrial condition is composed, tested on a real object and validated. It is open for development in order to investigate the possibility for improving of the energy efficiency of the dryer installation by reduction of the time duration of the process. That is possible if the local stresses, obtained at the numerical simulations at different drying regimes don't exceed the strength, reduced by safety coefficient of the material.

ACKNOWLEDGEMENTS

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