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NUMERICAL ANALYSIS BASED ON HEAT TRANSFER IN THE DRYING PROCESS OF SOLID BRICKS

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Abstract. Being the ceramic a widely used material and with great economic importance, its process of drying has been studied due to the occurrence of numerous phenomena, beyond a high energy consumption that happens in this stage of manufacturing. The use of numerical simulation technologies can alter the operating conditions and geometric of the drying object, all of this at low cost and relatively easy. Therefore, this job was carried out with the purpose of studying the drying process of massive ceramic bricks, considering it a solid means by Computational Fluid Dynamics (CFD), under the following experimental conditions: drying temperature of 60 ° C and 80 ° C, initial moisture content of 0.001734 and 0.00158 (kg / kg, bs) and relative humidity of 10.1% and 5%, respectively. The massive brick drying phenomenon was studied isolately, considering the drying model by liquid diffusion. The results of the temperature and volumetric fraction of water inside the brick obtained by the ANSYS CFX software package ® 19.2. Comparing the moisture and temperature simulated with experimental data can validate the numerical results, estimating the coefficient of mass diffusion and coefficient heat transfer from the surface of material. The results obtained in simulations show with the existence of important temperature and humidity gradients, which areas can shed cracks and deformations.

Keywords: Numerical simulation. solid brick. heat and mass transfer. CFD.

1 Introduction

Drying is one of the most complex and energy-intensive unit operations steps. It is assumed the importance of using and creating new technologies in order to optimize the drying of ceramic products, aiming to reduce the time to reach the ideal humidity, energy costs and guarantee the quality of the product. Numerical simulation is an example of a technology in which it is possible to reproduce the experimental study of drying, with greater advantages over work carried out in laboratories and in pilot plants [1].

In order for it to happen uniformly and thus prevent high temperature and humidity gradients inside the material, the drying process must occur in a controlled manner. During drying, physical and chemical properties of the material are changed, regardless of whether it is done by conduction, convection or diffusion, it is of paramount importance to know and control such effects [2].

The clay mass which is used to manufacture red ceramics is obtained from its conformation, in which it undergoes a slow drying process in order to remove much of the water [3].

Within the manufacturing process of ceramic pieces, one of the most complex steps is drying, since the last process, which is firing, depends on it. It is in this phase that moisture losses and changes in structure and composition occur, which are responsible for obtaining the final properties of the pieces, such as color, brightness, porosity, resistance, bending, cracking and high temperatures, in addition to attacks of chemical agents [4].

The water, which is distributed almost homogeneously in the ceramic mass after the piece is formed, needs to be removed also homogeneously, because due to this, there is a decrease in the volume of the piece, because the particles of the mass approach with the exit of the water. If this decrease does not occur evenly, the piece may show cracks or even break. Evaporation starts at the most superficial part, and then the water inside migrates to the surface and evaporates [5].

In the drying process, mathematical models that simulate it with great physical realism are extremely necessary, considering that this process involves complex phenomena of heat transfer, mass, momentum and dimensional variation. For this, it is of great importance to put in the drying model, as much information as possible, such as heat and moisture transport mechanism within the solid, diffusion coefficient, shrinkage, coupled heat and mass transfer, conditions of the close external environment of the solid, among others, making it possible to correctly relate the model to the real situation. The transport of moisture from the interior to the surface of the material can occur in the form of liquid and/or vapor, depending on the type of product and the percentage of moisture present. It is essential to control the dehumidification step and to know the mechanism of moisture movement, where through simulation and/or experimental data, it is possible to obtain optimal conditions in the process, reducing product losses and energy consumption [6].

In the literature it is possible to find analytical and/or numerical solutions of the diffusion equation, for different geometries, boundary conditions and constant or variable diffusive coefficients, but there are few studies with scientific results obtained through three-dimensional geometries. Through one-dimensional and two-dimensional analysis to describe the three-dimensional process, it is possible to find discrepancies in drying kinetics, moisture content distribution and temperature inside the solid, when comparing with the experimental results.

In order to have commercial quality products, controlled drying is necessary, because a very slow drying becomes economically unfeasible, but if the product does not dry uniformly, it will have distortions in the end [7].

ANSYS CFX is a commercial software based on the finite volume method capable of discretizing conservation equations and constitutive relationships to simulate fluid flow and heat transfer in two/three-dimensional geometric shapes [8].

In the drying process, CFD is one of the most suitable tools to expand knowledge regarding fluid flow, in addition to the fields of temperature and humidity in drying systems. This knowledge is used in the design and optimization of drying equipment and in processing strategies [1].

There is some research on drying bricks with CFD; however, works involving industrial solid ceramic bricks are scarce. This work aims to study the drying of an industrial solid ceramic brick using the liquid diffusion theory and the Ansys CFX software.

2 Methodology

For the simulations, an Intel Core i5 – 8265U 1.80 Ghz computer and 8 GB of RAM and the following computer applications were used: ANSYS ICEM CFD® and ANSYS CFX® 19.2. From points, curves and surfaces, geometry was created in ICEM-CFD®. Overlapping the geometry, the numerical mesh was built, which is the subdivision of the spatial domain into small spaces, called elements. In other words, it is the discretization of a continuous domain so that the equations of the phenomenon that is occurring can be solved by the computer.

Having possession of the geometry created in ICEM-CFD®, a blocking strategy was defined (Blocking > Create Block > InitializeBlocks), where this procedure ensures the refinement or distribution of elements in the vicinity of the solid walls and in regions where the gradients of speed, pressure and/or temperature are important. Thus, several blockings were performed in order to obtain a mesh of good quality and density of nodal points compatible with the computational limit of the machine (computer) available for the simulations. For the work in question, an unstructured mesh with hexahedral elements was chosen.

Figure 2.1 ilustrates the numerical mesh for the solid brick. The mesh consists of 157,209 elements and 168,000 nodes.

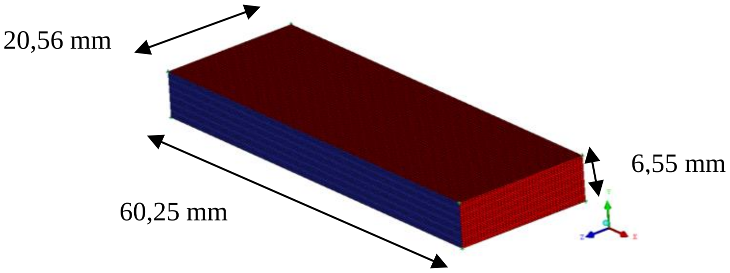

Figure 2.1 Representation of the numerical mesh of the solid brick.

For the studies of fluid dynamics and mass and heat transfers during the drying process of the brick, a mathematical modeling was used. In order to carry out the numerical simulations, some considerations were made:

- Water migrates inside the solid in liquid form and evaporates on the surface;
- Through convection on the surface and conduction inside it, heat is transferred to the material;
- Internal generation of negligible mass and heat;
- Fluid flow regime over the brick is transient and not isothermal;
- The effect of shrinkage of the ceramic piece was not considered;
- Constant thermophysical and mechanical properties;
- The convective heat and mass transfer coefficients are constant for all faces of the solid.

2.1 Governing equations

The solid brick drying phenomenon was studied based on the mass and energy conservation equations, Equations (1) and (2). Such equations are presented below considering the adopted hypotheses.

a) Conservation of mass

$$\frac{\partial \mathrm{M}}{\partial \mathrm{t}} + \nabla.\,(D\nabla M) = 0. \tag{1}$$

b) Energy conservation

$$\frac{\partial}{\partial \mathrm{t}}\,(\rho + \nabla.\,(k\nabla T) = 0. \tag{2}$$

Thus:

P = specific mass
H = enthalpy of air
k = thermal conductivity
T = temperature

M = moisture content
D = mass diffusion coefficient
t = time

c) Initial and boundary conditions

Initial conditions:

$(x, y, z, = 0) = To.$ (3)
$(x, y, z, = 0) = Mo.$ (4)

As boundary conditions were adopted on all brick faces:

$k\nabla T = hc\,(Te - T), > 0.$ (5)
$D\nabla M = hm\,(M - Me), > 0.$ (6)

d) Average moisture content

From the following equation, the average moisture content was determined at each instant of time:

$$\bar{M} = \frac{1}{V}\int_{v} M\ V\ DV \tag{7}$$

Thus: V = volume of the brick.

2.2 Experimental cases

This research is applied to the drying of solid bricks. The data used in the simulations were reported by [7], who proceeded experimentally to obtain these data.

Table 2.1 summarizes all experimental conditions used by [7] and analyzed in this study.

Table 2.1 Experimental parameters used in numerical simulations.

Case	Drying air		Structural brick			
	T (°C)	UR(%)	Mo (kg/kg, b.s.)	Me (kg/kg, b.s.)	To (ºC)	Te (ºC)
1	60	10,1	0,101	0,001734	27,94	60
2	80	5	0,214	0,00158	27,42	80

For the domain under study, which refers to the solid brick, a clay material was initially created whose physiochemical properties of the air and the product are shown in Chart. 2.2.

Table 2.2 Thermophysical properties of the air and clay used in the simulations.

Properties	Air	Clay
Thermal conductivity k [W $m^{-1}k^{-1}$]	2.61E-02	1.675
Specific heat sh [J kg^{-1} k^{-1}]	1,00E+07	1673
Densidade ρ [kg/m3]	1.185	1985.8

The estimation of the mass coefficient was made by minimizing the minimum error between the experimental and numerical data. Table 2.3 presents the values for the effective diffusion coefficients (D) used by [7] and those found as a function of temperature for each case studied.

Table 2.3 Mass diffusion coefficient.

Experimental of birth			Found for simulation
Cases	Temperature [°C]	D [m²/s]	D [m²/s]
1	60	$0{,}233\text{x}10^{-8}$	$0{,}07\text{x}10^{-8}$
2	80	$1{,}296\text{x}10^{-8}$	$0{,}155\text{x}10^{-8}$

3 RESULTS AND DISCUSSION

Figure 3.1 illustrates the evolution of the average moisture content over the drying time, at a temperature of 60° with RH = 10.1% and 80°C with RH = 5%, respectively. This figure indicates that the numerical results of the drying of the solid brick adequately fit the experimental data reported by [7], where we can see a marked evolution of the moisture content in a short time, and soon after it remains constant.

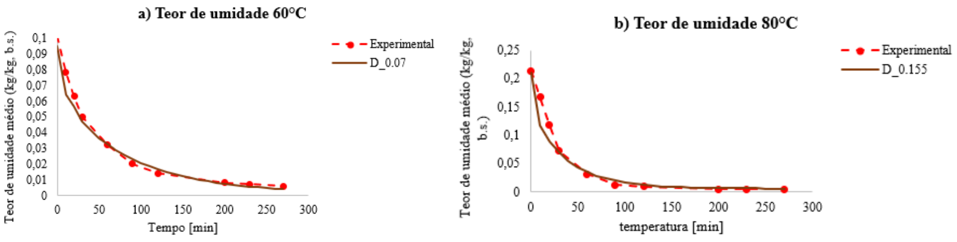

Figure 3.1 Average moisture content of the brick as a function of drying time.

Figure 3.2 illustrates in a comparative way the study carried out with the different temperatures indicated in Table 2.1. It is noticed that the increase in the drying temperature strongly influences the drying process, decreasing the moisture content of the brick more quickly and, with this, the final drying time [7]. This fact occurs due to the increase in the availability of energy for the vaporization of water and the increase in the mass transfer coefficient with the increase in the drying temperature. In all cases studied, there is a good fit between the numerical results and the experimental data. In addition to this, the results also show consistency with the physical phenomenon expected for the transport of heat and mass inside the brick, in the analyzed situations.

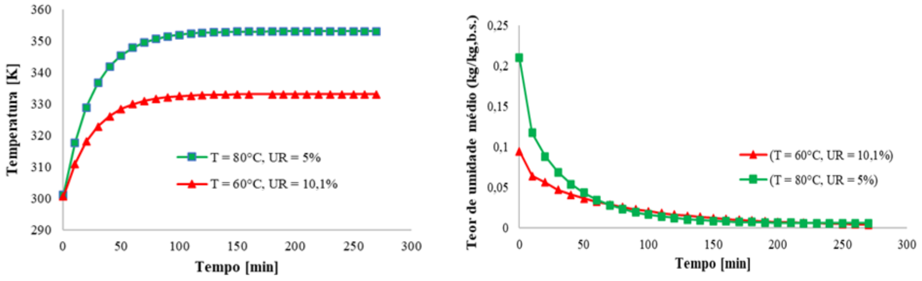

Figure 3.2 Temperatures and average moisture content of the brick as a function of time in the brick for different drying conditions.

3.1 Brick temperature and moisture content distribution

From the simulations, it was possible to study the phenomena involved during the drying process of the solid brick at temperatures of 60 and 80°C. In order to analyze the behavior of temperature and moisture content during this process, three planes were taken on the xy axis at positions 0 m; 0.01 m; 0.02m, in this way it was possible to see a pattern regarding the behavior of temperature and moisture content in the brick for both cases as seen in Fig. 3.3 and Fig. 3.4.

In view of the images presented, we can verify that the temperature gradients are located in the region close to the apex of the solid in all illustrated cases, since they are in contact with the drying air. These regions are more susceptible to the appearance of defects in the part, which agrees with the statement reported by [7]. However, in this analysis, there is an apparent uniformity of temperature inside the brick, due to a slower heating ($h = 1$ W/m^2.K).

The temperature gradients in the external layer of the brick, can cause the appearance of cracks, deformations and reduction of dimensions. This is due to the drying being more intense and faster outside the brick than in its internal parts. These observations are also reported by [5] and [9].

In this way, we can see that it is of great importance that there is a previous drying, where it is controlled and uniform. But this procedure cannot be done slowly, as it can become uneconomical. Thus, some factors such as air pressure, relative humidity, temperature, dimensions and specific gravity of the material are used to properly control the drying intensity.

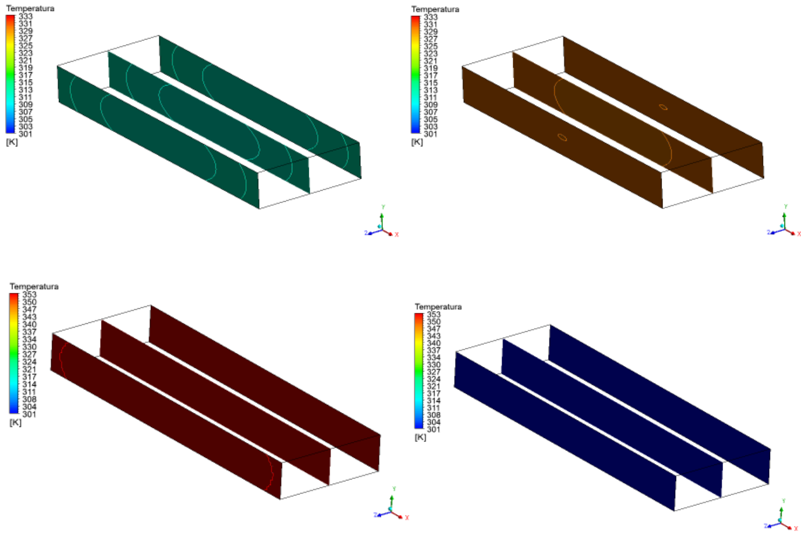

Figure 3.3 Behavior of the temperature distribution inside the brick in different planes of the XY axis, in the drying times of 0 min, 10 min, 1h and 4.5h.

In Figure 3.4 we have the gradients referring to the moisture content for the temperatures of 60° C and 80° C, in the instants of time for 0, 10 min, 1 hour and 4.5 hours. It is worth mentioning that, as the prescribed boundary condition, an equilibrium humidity equal to 0.001734 (kg/kg, b.s) for 60°C and 0.00158 (kg/kg, b.s) for 80°C was considered, over all the brick faces, which is equivalent to an instantaneous hygroscopic equilibrium condition.

Figure 4.9 shows the moisture content fields on the xy planes for the instants t = 0.0 and 10 minutes, for a temperature of 60°C.

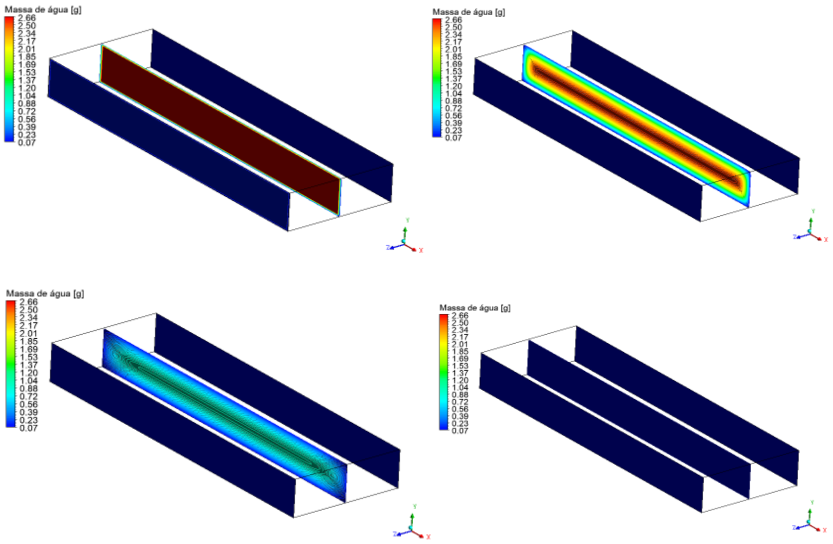

Figure 3.4 Behavior of the moisture content distribution inside the brick in different planes of the XY axis, in the drying times of 0 min, 10 min, 1h and 4.5h.

It is observed that the highest humidity gradients in the region close to the apex of the solid at all times illustrated, due to the fact that this region is in more intense contact with the drying air. Moisture content, has the highest results in the center of it at any time. It is also possible to observe the decrease in the moisture content with time, in any position, tending towards its equilibrium moisture content, for sufficiently long drying times.

Because the temperature at the wall is higher than the temperature inside the brick, heat flow occurs from the surface to the center of the brick, and the opposite for mass flow. These coupled phenomena can generate high stresses inside the brick, giving opportunity for the appearance of broken, cracks and deformations. Such defects, generated by the humidity and temperature gradients, can cause unacceptable tensile and compressive stresses, which drastically reduce the quality of the product at the end of the process [10].

4 Conclusions

In view of the data obtained for the drying of the solid brick, it is concluded:

- The mathematical modeling proposed was adequate, and the numerical results of the temperature of the brick and the mass of water lost showed a good agreement with the experimental data;
- The higher the drying air temperature, the faster the heating and drying rates;
- There is a good approximation between the curves referring to the experimental and numerical data, the average moisture content and surface temperature, enabling the use of the applied computer program;
- The mathematical modeling used is adequate and generalized, and can be used to obtain solutions in cases of drying, cooling, heating and humidification;
- The humidity and temperature fields make it possible to verify the regions of higher gradients, which are the regions where there is a greater probability of cracks and deformations, which can reduce the quality of the product after the drying process;
- From the point of view of heat and/or mass transfer, the humidity and temperature gradients are greater in the surface planes and in the vertices of the solid, which is in direct contact with the drying air. Therefore, such regions are more susceptible to the occurrence of thermal shocks, cracks and deformations, which compromise the quality of the product obtained.

References

[1] ARAÚJO, Morgana de Vasconcellos. **Simulação numérica via CFD da secagem de tijolos cerâmicos industriais.** 2019. 239 f. Tese (Doutorado em engenharia de processos) – Universidade Federal de Campina Grande, 2019.

[2] SANTOS, J. P. S. **Secagem de Materiais Cerâmicos com Forma Complexa: Um Estudo Teórico Via CFX.** 2018. 103 p. Tese (Pós-Graduação em Engenharia de Processos) – Universidade Federal de Campina Grande, Centro de Ciências e Tecnologia, 2018.

[3] MEDEIROS, M.H.F.; SOUZA, D.J.; FILHO, J.H.; ADORNO, C.S.; QUARCIONI, V.A.; PEREIRA, E. **Resíduo de cerâmica vermelha e fíler calcário em compósito de cimento Portland: efeito no ataque por sulfatos e na reação álcali-sílica.** Revista Matéria, v. 21, n. 2, p. 282 – 300, 2016.

[4] PAULETTI, M. C. **Modelo para introdução de nova tecnologia em agrupamentos de micro e pequenas empresas: estudo de caso das indústrias de cerâmica vermelha no Vale do Rio Tijucas.** 2001.Universidade Federal de Santa Catarina. Programa de pósgraduação em engenharia de produção, 2001.

[5] SILVA, Joselito Barbosa. S**imulação e experimentação da secagem de tijolos cerâmicos vazados.** 2009. 199 f. Tese (Doutorado em Engenharia de Processos) - Universidade Federal de Campina Grande, 2009.

[6] ALMEIDA, G. S**. Transferência de calor e massa em sólidos heterogéneos com geometria arbitrária: uma análise concentrada.** 2003. p. 52. Dissertação (Mestrado em Engenharia Mecânica). Departamento de Engenharia Mecânica, Centro de Ciências e Tecnologia, Universidade Federal da Paraíba.

[7] NASCIMENTO, José Jefferson da Silva. **Fenômenos de difusão transiente em sólidos paralelepípedos. Estudo de caso: Secagem de materiais cerâmicos.** 2002. 208 f. Tese (Doutorado em engenharia mecânica) - Universidade Federal da Paraíba, 2002.

[8] SANTOS, R. S. **Estudo do Processo de Secagem de Blocos Cerâmicos Estruturais: Modelagem e Simulação.** 2019. 215 p. Tese (Pós-Graduação em Engenharia de Processos) - Universidade Federal de Campina Grande, Centro de Ciências e Tecnologia, 2019.

[9] BRITO, M. K. T.; ALMEIDA, D. B. T.; LIMA, A. B. L. **Transferência de calor e massa durante a secagem de tijolos cerâmicos argilosos: um estudo analítico.** In: Congresso Nacional de Engenharia Mecânica, IX, Fortaleza – Ceará. P. 1 – 9, 2016.

[10] SILVA, J. B. **Secagem de blocos cerâmicos industriais: modelagem, simulação e experimentação.** 187 f. Tese (Doutorado em Engenharia de Processos) - Universidade Federal de Campina Grande, Campina Grande, PB. 2018.