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IMPROVEMENT OF THE CONJUGATE HEAT TRANSFER IN HIGH TEMPERATURE CHAMBER FURNACES FOR CERAMIC FIRING

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Abstract. The firing of ceramic ware in chamber furnaces is a transient multiphysical process, including turbulence combustion and fluid flow in the gas space, convective and radiation heat transfer from the flue gases to the furnace wall and ceramic ware, surface to surface radiation between the solid surfaces and conduction heat transfer in combination with endothermic or exothermic processes in the ceramic body.

Models and conceptions for numerical analysis of the conjugate heat transfer in such furnaces are developed. They are applied for analyses of the thermal processes in a chamber furnace for firing of technical ceramics. All mathematical models are validated on the base of information, obtained from in situ measurements of parameters of the real object. Non-uniform thermal and fluid flow fields in the thermal aggregate that cause problems in the furnace walls and wastes at the ceramic ware are ascertained. An impossibility of improving the furnace operation at the existing construction, topology and parameters of the burners is established.

A variant for reconstruction of the furnace is investigated numerically. It includes changes of the number, power and topology of the burners and the arrangement of the ceramic ware in the furnace space. Uniform temperature fields and reduction of the specific fuel consumption at the suggested configuration of the thermal aggregate are established. They are prerequisites for quality and economical firing of the ceramic ware.

1 INTRODUCTION

Ceramic production is closely related to the development of human culture and life. The technologies for processing of the raw materials and semi-manufactured are subject to continuous improvement. The firing of the articles is an energy consuming high temperature treatment of the ceramic mass according to the assigned temperature and gas regime in order to ensure quality products with preliminarily defined physicochemical properties.

The firing process involves three stages - heating the ceramic products to a firing (maximal) temperature, keeping this temperature during a fixed time and cooling of the products. It is expressed by so-called temperature curve that depends on ceramic materials and ware arrangement in the furnace space [1, 2]. In addition to the temperature regime there are restrictions to the gas composition in the furnace space. It is regulated by the combustion excess air ratio α and can be reduction with carbon oxide in the gas space (α <1), neutral (α = 1) or oxidation (α> 1). In order to achieve a uniform heat transfer in the furnace space and a homogeneous temperature field in the ceramic ware it is necessary to maintain an appropriate gas flow field (gas pressure, temperature and velocity).

The time duration of the heating, keeping maximal temperature and cooling periods depend on the ceramic geometry, material and arrangement in the furnace space. The temperature curve usually is monitored by thermocouples that conduct signals to the controller of automatic adjustment system to regulate the fuel and subsequent air flows. The heating and cooling rate are setting on the base of experience of the responsible stuff and the literature. The refinement of the time duration of the processes results in reduction of the wastes and energy economy [1]. The mathematical modelling and numerical simulation are the most appropriate ways for improvement of the firing efficiency at the high temperature industrial furnaces.

So far a complex study of transient conjugated heat transfer with numerical simulation of combustion process, temperature, concentration and hydrodynamic fields in gas chamber furnaces is not published. Such analysis requires solving of multi-physical models for fluid and solid domains at relatively low time steps, which is a difficult and time consuming problem. But that approach allows detailed information of the temperature and fluid flow fields that can be a base for proper correction of the maintained temperature regimes and improvements of the thermal aggregate. An algorithm for modeling investigation of the conjugate heat transfer in high temperature gas furnaces is presented in this study. It is validated and applied for analysis and improvement of the transient firing process of technical ceramics.

2 MATHEMATICAL MODELS AND CONCEPTIONS FOR NUMERICAL SIMULATION

The complex model of conjugated heat transfer in high temperature chamber furnaces is based on geometrical model, including the solid and gaseous domains of the furnace aggregate: walls, arch, floor, solid parts of the burners, gas space, auxiliary refractories and ceramic ware to be fired. The solid and fluid parts share common interfaces. Such complex analysis requires large computer resources and computational time at a mesh with a large number of finite elements (volumes). To short the computational procedure the solid parts of furnace and burners envelopes can be excluded from the model. Their influence on the heat transfer can be modeled by the boundary conditions.

The system of equations describing the combustion and heat transfer in the multicomponent gas domain surrounding the fired ceramic mass includes:

- continuity equation;
- momentum equations;
- turbulence model: standard κ-ε model [5];

- energy equation;
- ideal gas equation;
- boundary layer model – turbulent wall functions [4];
- P1 radiation model - a simplification of the radiation transport equation [5];
- eddy dissipation combustion model [5].

The temperature field and gradients in the solid domain are determined at a solution of the Fourier's law. In the presence of endo- and exothermic reactions in the ceramic ware their influence on the temperature distribution can be modeled by a heat source: heat generation rate per unit volume in the conductivity equation.

The solution of the above system of equations is performed at conditions and loads, reflecting the specific features of the particular object by finite volume method FVM [5]. The heat exchange through the furnace envelops is modeled by a heat transfer coefficient, consisted of two parts, reflecting the heat transfer to the environment and the accumulated heat by the multilayer walls. The boundary conditions on the burner inlets reflect the non-stationary fuel and air velocities.

The moment values of the fuel flow B is measured at working aggregates or can be determined by heat balance equation in matrix form [1]:

$$\left(\left[Q_i^r\right]+V_\alpha\left[h_{air}\right]+\left[h_f\right]-V_\alpha^{fg}\left[h_{fg}\right]\right)\left[\dot{B}\right]=\left[\dot{Q}_{prod}\right]+\left[\dot{Q}_{furn}\right]+\left[\dot{Q}_{CW}\right]+\left[\dot{Q}_{chem}\right] \quad (1)$$

where:

- $[Q_i^r]$, $[h_{air}]$, $[h_f]$, $[h_{fg}]$, $[\dot{Q}_{prod}]$, $[\dot{Q}_{furn}]$, $[\dot{Q}_{cw}]$- vector-matrix with elements equal to the moment values correspondently of lower heating value of the fuel, combustion air, fuel and flue gases enthalpies and the heat flows to the ceramic ware, furnace envelopes and auxiliary refractory (checker work);
- $[\dot{Q}_{chem}]$ - heat flow for chemical reactions in the ceramic ware;
- $[\dot{B}]$- diagonal matrix of the moment values of the fuel flow, m^3s^{-1} or kgs^{-1};
- V_α – combustion air /fuel ratio, m^3m^{-3} or m^3kg^{-1};
- V_α^{fg} – flue gas/fuel ratio, m^3m^{-3} or m^3kg^{-1}.

3 ANALYSIS OF THE CONJUGATE HEAT TRANSFER IN CHAMBER FURNACE FOR THECNICAL CERAMICS

An object of investigation is a chamber gas furnace for firing of technical ceramics with established problems, resulting in unsatisfactory firing of the production and wastes. The heating period includes increasing of gas temperature to approximately 1600°C for 15 hours and keeping that temperature for an hour. These processes are realized by subsequent rising of the fuel (natural gas). The fuel and the combustion air are conducted in the furnace by six burners (Figure 1 and 2). The ceramic articles (chocks with relatively small sizes) are arranged on a refractory floor structure (checker work). At the modeling investigations below the articles don't presence in the geometrical models: they are modeled by increasing of the density and the roughness of the horizontal checker work elements. Detail information about the furnace and the production is not possible due to confidential rules.

On the basis of inspections, in situ measurements, thermal balance and numerical analyses of the existing regime in the furnace the ascertainments and conclusions below were made.

1. There are not systematic approach and logic in the distribution of air and fuel flows by burners - the fuel consumption in the upper row of burners exceeds the consumption in the lower row. That results in a high thermal load at certain places in the arch and the walls of the furnace, a change in the color of the refractory and occurrence of cracks (Figure 2). The ineffective combustion process and the irrational organization of the gas dynamic flows and fields are expressed in incomplete combustion and azote oxide formation (Figure 3). The fuel flow should decrease from top to the bottom and must be higher at burners #1 and #4 compared to opposite burners at the same level at the existing topology of the burners and furnace outlet (Figure 1). But such regulation is impossible at the existing burner installation.

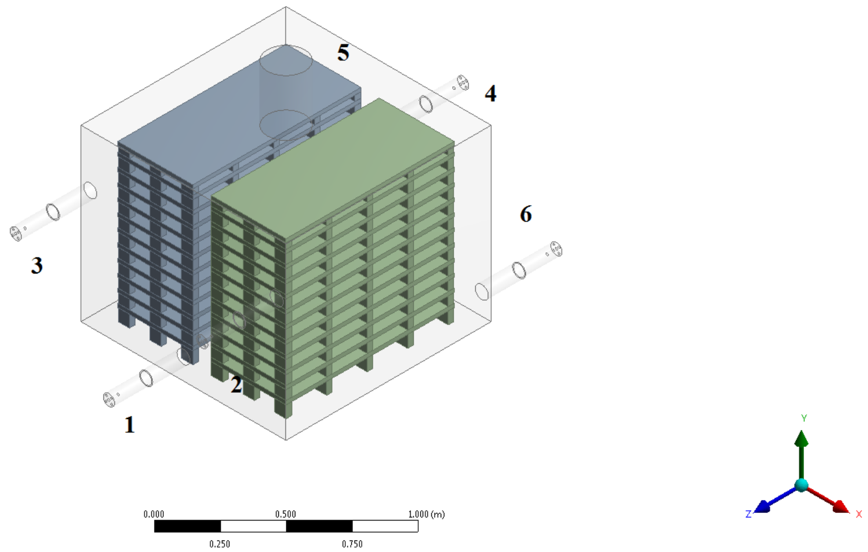


Figure 1: Geometrical model comprising the fluid and solid domain in the furnace chamber

2. The total power of the burners is several times higher than the computed one on the base of thermal balance for the existing furnace unit and temperature curve. The capacity of the burners during the heating period is lower than 30% of their nominal operating capacity. That leads to impossibility for regulation of the fuel flow and fuel / air ratio in that part of the process. A higher excess air ratio α than the recommended one for this type of fuel (α =1.05) is maintained to suppress the rate of temperature rise into the chamber space in the start of the process. That results in undesirable heat loses.

3. The organized combustion process causes the non-uniform temperature, velocity and concentration fields in the furnace (Figure 4). Dead zones are formed in separate regions of the working space where the ceramic production is not fired well and has defects. The

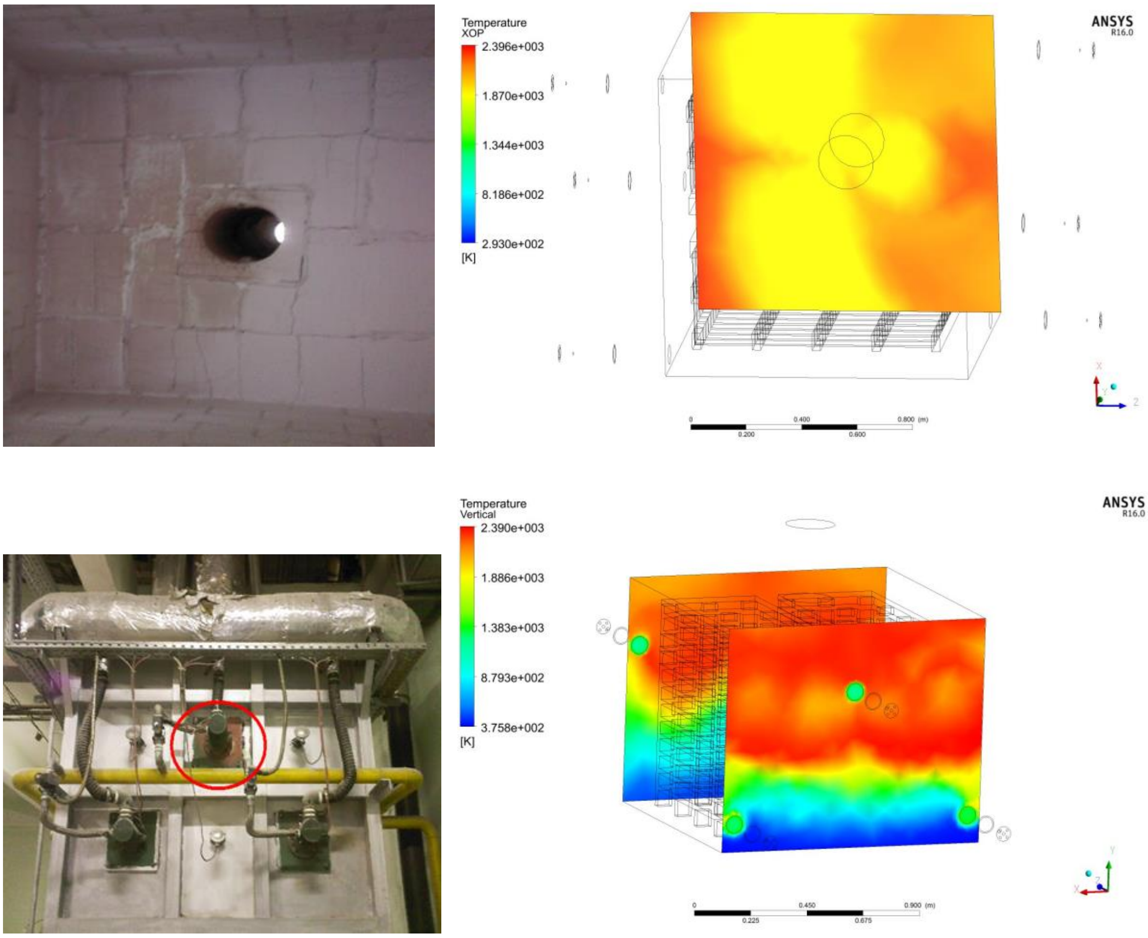
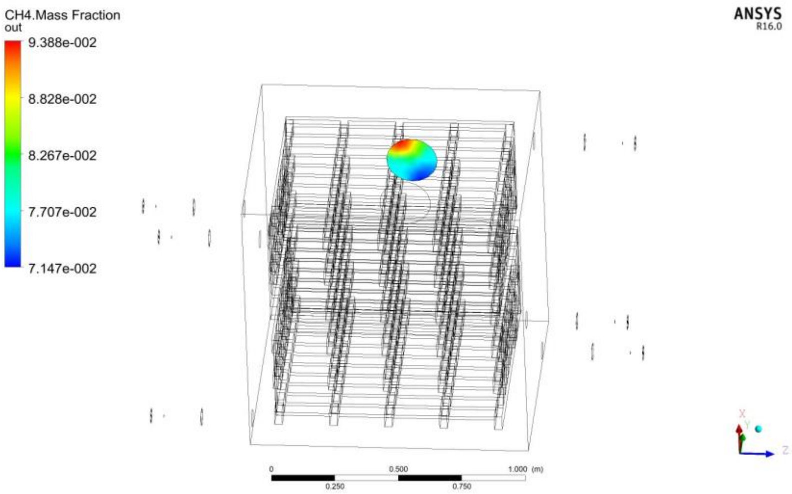
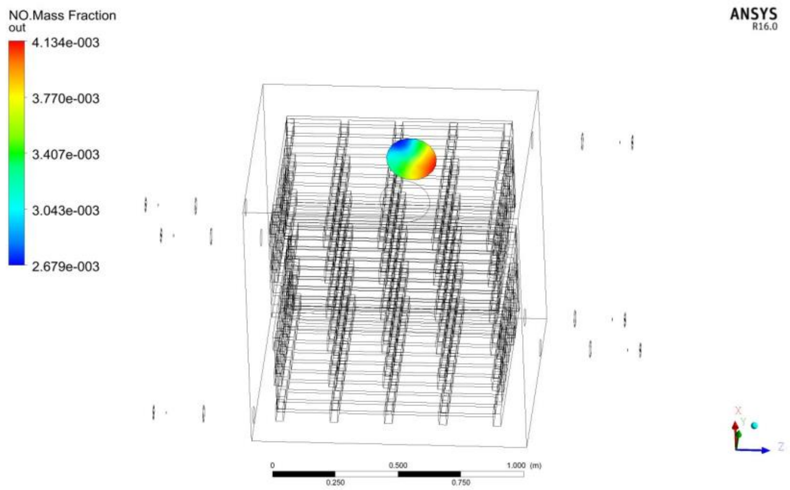


Figure 2: Views of the furnace walls and computed temperature fields on the internal surfaces (right).

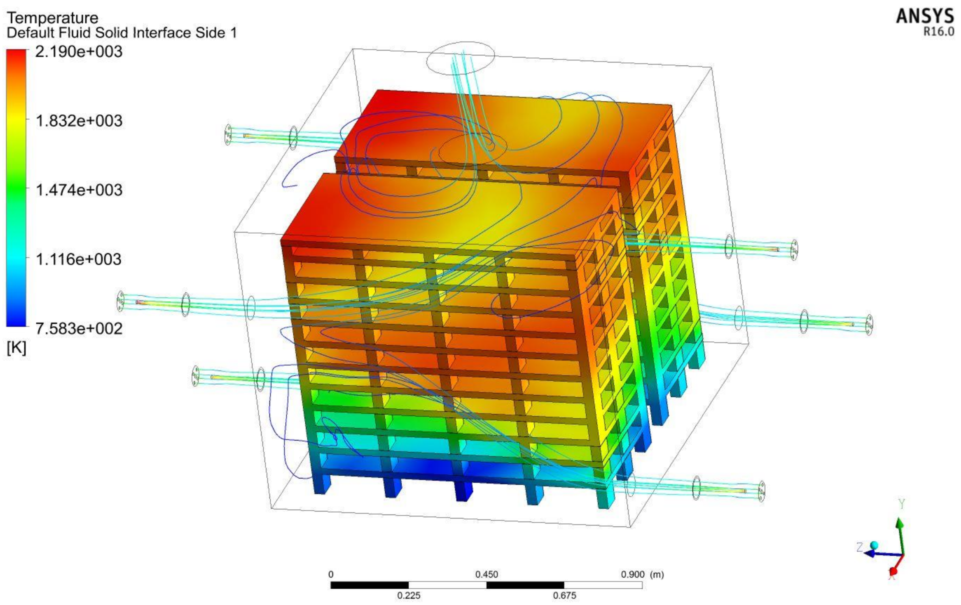


a)



b)

Figure 3: CH_4, (a) and NO_x mass fractions (b) at the outlet of the furnace



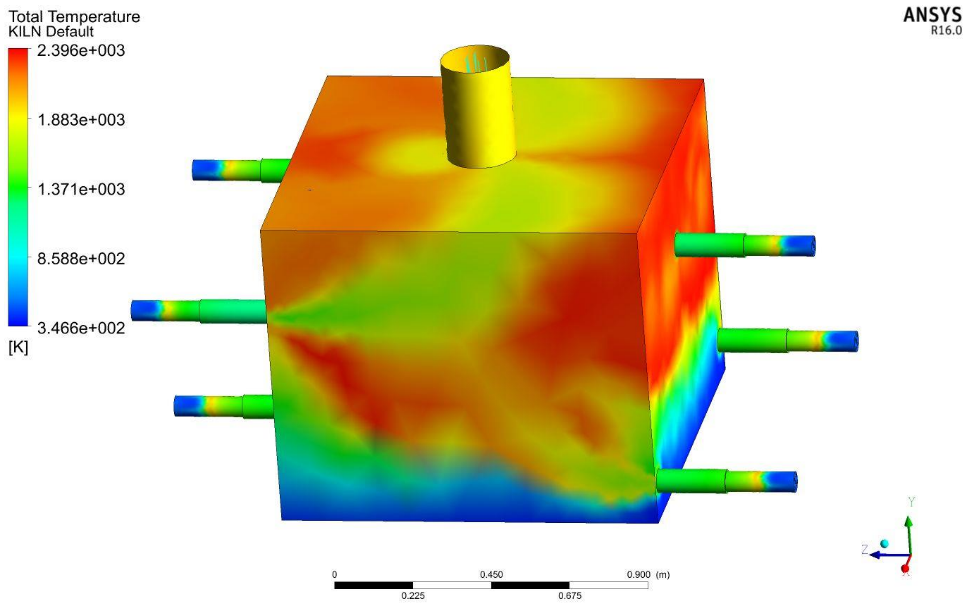


Figure 4: Temperature fields and streamlines at the end of the heating period

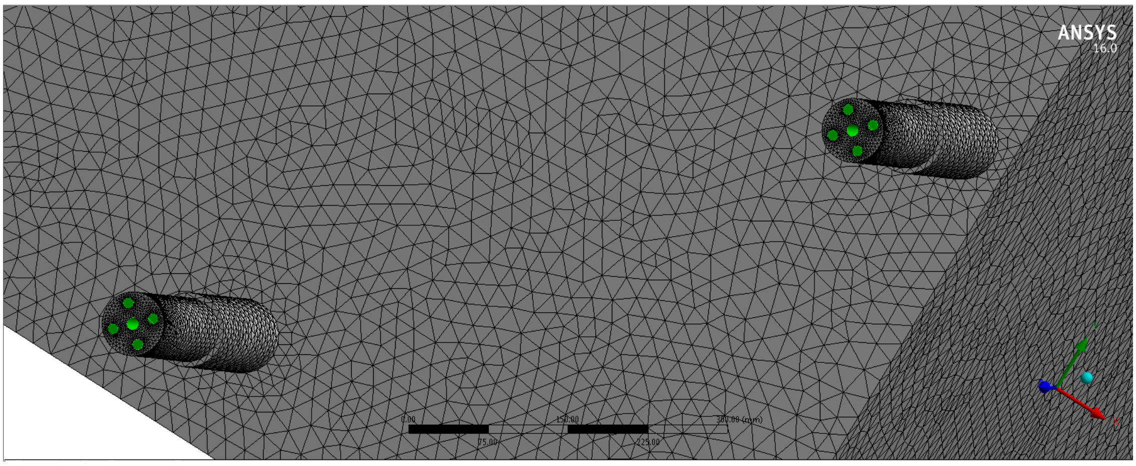
The models are validated by comparison between measured and computed temperatures at internal furnace walls. Satisfactory coincidence of the regions with computed and real higher and lower temperatures are obtained.

The conducted model studies proved the inappropriate topology and capacity of the burners and the inability to maintain a uniform temperature field in the furnace chamber by adjusting the combustion process. The powerful burners and their positions on the relatively small furnace volume lead to unequal thermal loads to the refractory envelopes and the ceramic ware. Variants for reconstruction of the furnace, changing the burner installation and auxiliary refractory checker work are accepted for modeling investigation.

4 ANALYSIS OF IMPROVEMENTS OF CHAMBER FURNACE

Different type, number and topology of burners (Figure 5) are assumed. The total heat power of the new burners is obtained at thermal balance. Modification of the geometry of the auxiliary checker work refractory and an increase in the mass of the fired ceramic ware for one firing cycle are accepted. The thickness, structure and properties of the refractory of the furnace are retained.

The fuel flow variation with the time is computed by the thermal balance (1). The excess air ratio is accepted $\alpha=1.05$. It is use to determine the air flow. Numerical simulations of the transient combustion process, temperature, velocity and pressure fields are implemented in accordance with the concept of reconstruction.



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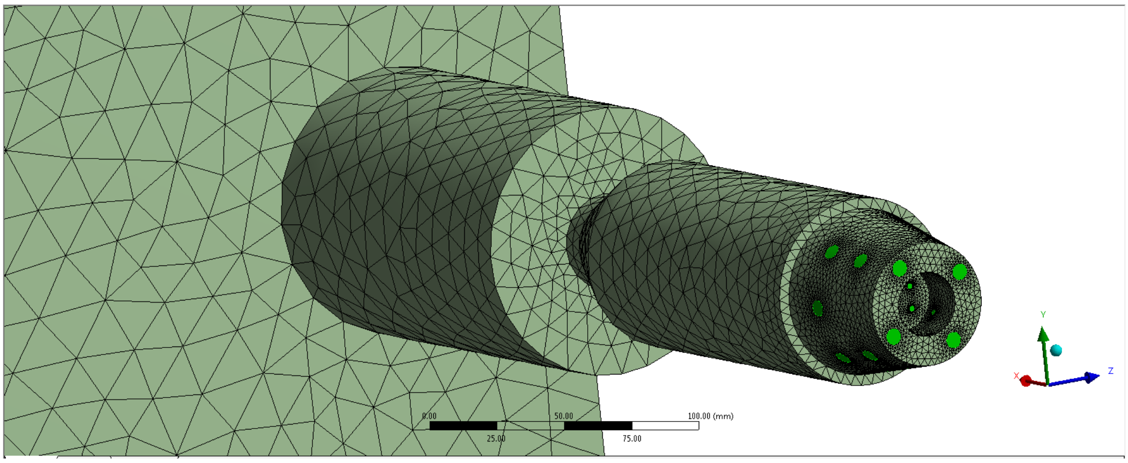
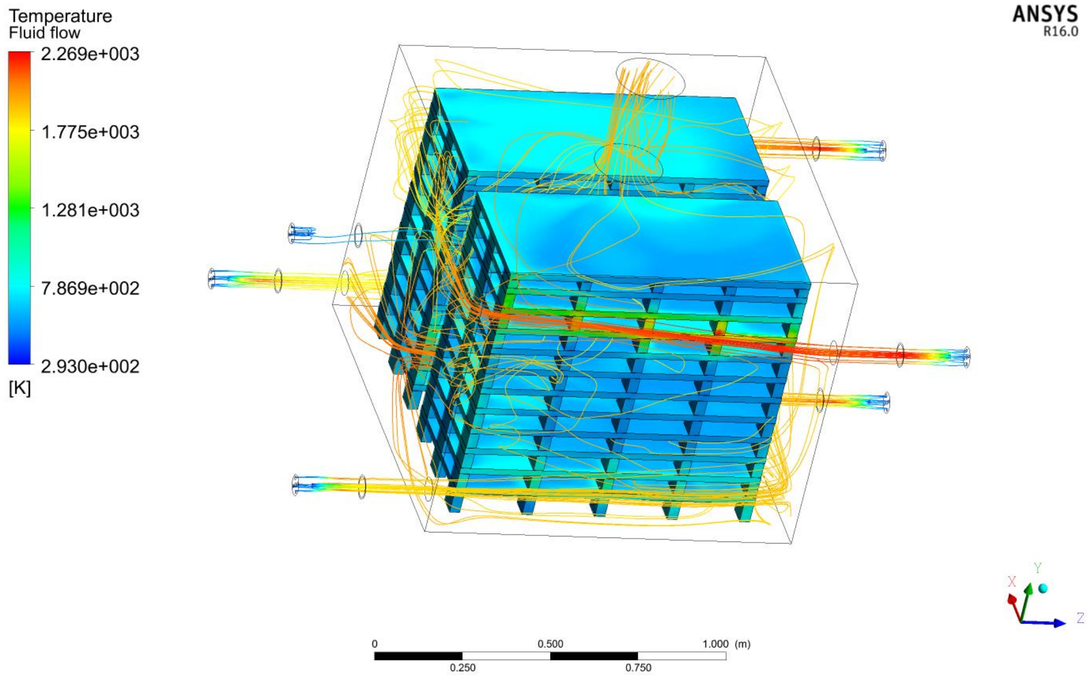


b)

Figure 5: Fluid domains of the burners in the current (a) and predicted (b) variants

Temperature differences between the lowest and highest temperatures on the surrounding chamber walls lower than 100 K were established. A decrease of the temperature gradients at the new checker work in comparison to the existing variant is obtained. The temperature difference between the minimum and maximum surface temperatures of the refractory floor structures in the last stage of firing period are 26K (1.5%) at the existing furnace and 8K (0.5%) in the predicted construction. Figure 6 shows a comparison of the distribution of gas streamlines in the actual and virtual furnace chamber.

An increase of time for circulation of hot gases in chamber space about 30-35% at the new burner topology in comparison to the current state is established. It is due to the extended flow path in the circulating gas flows provoked by the countercurrent action of the lower and upper burners. As results complete combustion of the fuel is observed.



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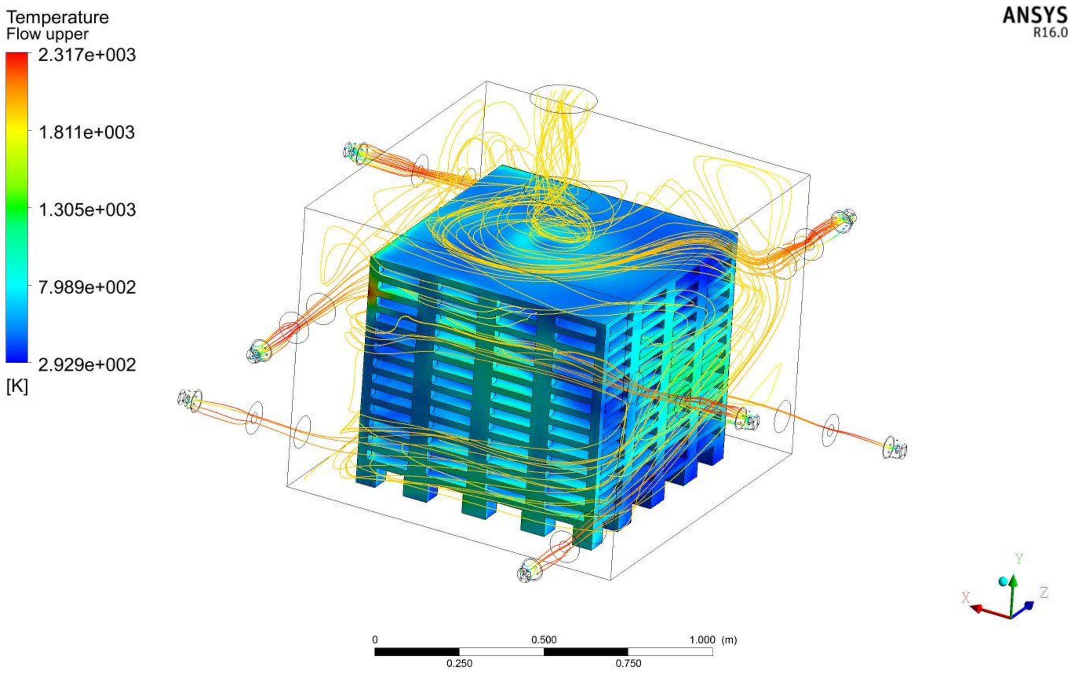

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Figure 6: Comparison of the gas flow at the moment of the firing process at the current state (a) and after the proposed changes (b)

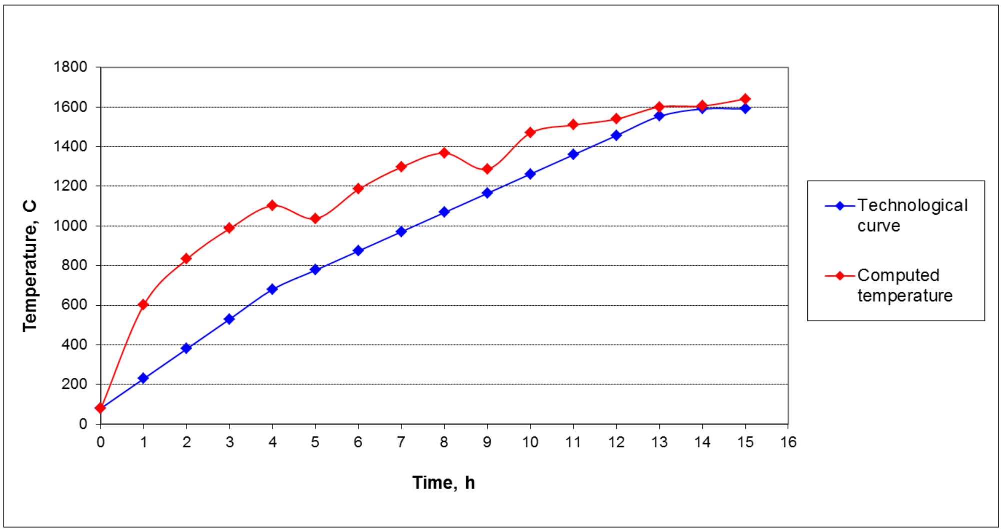

Figure 7: Differences between the technological temperature curve and the computed temperatures in a control point with temperature sensor.

The comparison between the computed temperatures at the control point and the set values of the temperature curve are given in Figure 7. The deviations are larger at the beginning and significantly decrease at the end of the firing process. They probably are caused by inaccuracy of accumulated heat prediction in the model of heat exchange through the furnace envelopes and can be reduced by the automatic adjustment system of the burner installation.

It was estimated that after the reconstruction of the furnace the fuel consumption per firing cycle is reduced by 47.8%. That results in energy savings of 2,343 MWh/firing cycle. The reduction of the specific fuel consumption is 3 m^3 of natural gas per 1 kg of fired production. It corresponds to a reduction of the specific energy consumption of 29 kWh/kg. In determining this saving, the increase in the mass of fired produce for one working cycle was taken into account.

5 CONCLUSIONS

Modeling and numerical simulation of the combustion and conjugate heat transfer allow obtaining of detail information about the transient thermal and fluid flow fields in the high temperature furnaces at operating conditions and design stages.

That approach is used successfully to analysis the heat transfer in a high temperature chamber furnace for technical ceramic and to investigate the possibility for increasing of its efficiency. Improvements of the combustion equipment and production arrangement in the chamber space are suggested that result in smaller gradients in the thermal fields, reduction of the heat losses due to incomplete combustion and loosed heat with exhaust gases. The realization of the suggested reconstruction is expected to effect in higher technological, energy and ecological efficiency of the furnace due to increasing of the productivity, reduction of the wastes, specific fuel consumption, possibilities for incomplete combustion and NO_x formation.

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