Improvement of the Conjugate Heat Transfer in High Temperature Chamber Furnaces for Firing of Ceramic Ware

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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 walls 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 that conjugate heat transfer (CHT) in such thermal aggregates are developed. They are validated on the base of information, obtained by in situ measurements at a furnace for firing of technical ceramic. Non-uniform thermal and fluid flow fields in the furnace space that cause problems in the surrounding walls and wastes at the ceramic ware are ascertained in it. An impossibility to improve the furnace operation at the existing construction and combustion installation 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 different 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.

Key words: Ceramic firing, CHT, furnace design, topology optimization, combustion, computational fluid dynamics (CFD).

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 products are subjects of continuous improvements. The firing of the articles is an energy consuming high temperature treatment of the ceramic mass according to an assigned temperature and gas regime in order to ensure quality products with preliminarily defined physicochemical and mechanical properties. The firing process involves three stages—heating of the ceramic ware 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, geometry and ware arrangement in the furnace space [1, 2]. 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 appropriate fields of gas pressure, temperature and velocity.

In addition to the temperature regime there are restrictions to the gas mixture in the furnace. It is regulated by the combustion excess air ratio \( \alpha \) and can be reduction with carbon oxide in the gas space \( (\alpha < 1) \), neutral \( (\alpha = 1) \) or oxidation \( (\alpha > 1) \).

The temperature curve usually is monitored by thermocouples that conduct signals to a controller of automatic adjustment system to regulate the fuel and combustion air flows. It is set on the base of Differential Thermal & Calorimetric Analyses of the raw mass, literature review and experience of the responsible stuff. The refinement of the cooling and
heating rates according to the geometry of the fired articles can result in reduction of the wastes and energy economy [1]. The mathematical modelling and numerical simulation are the appropriate ways for the solution of these problems [3].

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

2. Mathematical Models and Conceptions for Numerical Simulation

The geometrical model of the chamber furnace is three dimensional and includes the solid and gaseous domains of the aggregate: walls, arch, floor, solid parts of the burners, gas space, auxiliary refractories and ceramic ware to be fired. The solid and fluid domains share common interfaces. For computational fluid dynamics (CFD) analysis they are discretized by a fine mesh of finite elements (volumes). To shorten the computational procedure the solid walls 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 for the gas mixture domain, surrounding the fired ceramic mass, includes:

* continuity equation;
* momentum equations;
* turbulence model: standard $\kappa$-$\epsilon$ model [5];
* energy equation;
* ideal gas equation;
* boundary layer model—wall functions [4];
* radiation model $\Pi_1$ to reflect the radiation heat transfer from the hot gases to the solid domain [5];
* computing of surface to surface radiation;
* eddy dissipation combustion model [5].

The temperature field and gradients in the solid domain are determined at a solution of the thermal conductivity equation. The endo- and exothermic reactions in the ceramic ware can be modeled by heat sources in it.

The heat exchange through the furnace envelops is modeled by a heat transfer coefficients, consisted of two parts, reflecting the heat transfer to the environment and the accumulated heat by the multilayer walls. A gage pressure is applied on the furnace outlet (opening boundary). 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 thermal balance equation at design stage.

3. Analysis of the CHT in Chamber Furnace for Technical Ceramics

The models above are applied to investigate a gas furnace for firing of technical ceramics with established problems, resulting in unsatisfactory firing of the production and subsequent wastes. Detailed information about the furnace and the production is not possible due to confidential rules. The temperature curve includes increasing of gas temperature to approximately 1,600 °C for 15 hours, keeping that temperature for one hour and cooling of the ware for 15 hours. The first two 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 (Figs. 1 and 2).

The ceramic articles (chocks with relatively small sizes) are arranged on a refractory floor structure
Improvement of the Conjugate Heat Transfer in High Temperature Chamber Furnaces for Firing of Ceramic Ware

Fig. 1 Geometrical model, including the fluid and solid domain in the furnace chamber.

(checker work). They are reflected in the geometrical models by increasing of the density and the roughness of the horizontal elements of the checker work.

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

(1) The distribution of air and fuel inputs at the burners is not logical—the fuel flows in the upper row of burners exceeds the flows in the lower row. In principle the fuel flow should decrease from top to the bottom. It also must be higher at burners number 1 and 4 compared to opposite burners at the same level (Fig. 1). But such regulation is impossible at the existing automation system with a common valve for all air flows regulation. The poorly organized combustion process causes non-uniform temperature, velocity and concentration fields in the furnace (Figs. 2 and 3). That results in a high thermal load at regions near the arch and the walls of the furnace and subsequent changes in the color of the refractory and cracks (Fig. 2). Dead zones are formed in separate regions of the furnace space where the ceramic production is not fired well and defects. Also incomplete combustion and nitrogen oxide formation (Fig. 4) are established.

(2) The total power of the burners is several times higher than the computed one on the base of thermal balance and temperature curve. The capacity of the burners during the heating period is 30% lower than their nominal operating capacity. That leads to difficulties at the regulation of the fuel flow and fuel/air ratio in that part of the process. As a result, a higher excess air ratio $\alpha$ than the recommended one for this type of fuel ($\alpha = 1.05$) is maintained to suppress the temperature rise into the chamber space in the start of the process. That result in undesirable thermal loses.

The models are validated by comparison between measured and computed temperatures at internal furnace walls. Satisfactory coincidences between the computed and measured temperatures are obtained.
Improvement of the Conjugate Heat Transfer in High Temperature Chamber Furnaces for Firing of Ceramic Ware

Fig. 2  Views of the furnace arch (a), walls (b) and computed temperature fields on the internal surfaces (right) in a moment of the heating period.

Fig. 3  Temperature field (a and b) and streamlines (b) in a moment of the heating period.
The conducted numerical studies proved the inappropriate topology and capacity of the burners and the inability to maintain uniform temperature fields in the furnace chamber by adjusting the combustion process. Variants for reconstruction of the furnace, changing the burner installation and auxiliary refractory checker work are accepted for modeling investigation.

4. Improvements and Effects

Two relatively cost-effective and easy for realization activities are accepted in order to improve the combustion and firing process: changes in the combustion installation and ceramic mass in the furnace space.

Different type, number and topology of burners are assumed (Fig. 5). Their total heat power and fuel flow are obtained by a thermal balance. The air flows are determined on the base of accepted excess air ratio $\alpha = 1.05$, suitable for that kind of furnaces. Also modification of the geometry of the checker work that allows increasing of the mass of the fired ware in the furnace space is accepted.

Numerical simulations of the transient combustion process, temperature, velocity and pressure fields are implemented at the accepted reconstructions. Temperature differences between the lowest and highest temperatures on the surrounding chamber walls, lower than 100 K are established (Fig. 6b) as results. Decreases of the temperature gradients in the domain of the updated checker work in comparison to the existing variant are also obtained. The maximal temperature differences on the refractory floor layers in the last stage of firing period are 8 K in the proposed variant. They are 3 times smaller according to 26 K at the existing furnace construction.

Fig. 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.

A reduction of the fuel consumption per firing cycle of 47.8% is estimated after the reconstruction of the furnace. That effects in energy savings of 2,343 MWh
Improvement of the Conjugate Heat Transfer in High Temperature Chamber
Furnaces for Firing of Ceramic Ware

Fig. 5  Meshed fluid domains of the burners at the current (a) and predicted (b) variants.

Fig. 6  Gas flows at a moment of the firing process at the current state (a) and after the proposed changes (b).
per firing cycle. A reduction of the specific fuel consumption (3 m³ natural gas per kg fired products) and correspondent energy consumption (29 kWh per kg fired products) are established as results.

A comparison between the computed temperature at a control point and the set values of the temperature curve is given in Fig. 7. The deviation is larger at the beginning and significantly decreases at the end of the firing process. It probably is the result of an inaccuracy of boundary conditions on the walls in the start of the process and can be reduced by the automatic adjustment system of the burner installation if really exists.

5. Conclusions

Modeling and numerical simulation of the combustion and CHT allow obtaining of detail information about the transient thermal and fluid flow fields in the industrial thermal aggregates at operating conditions and design stages.

That approach is used successfully to analyze 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 the exhaust gases. The realization of the suggested reconstruction is expected to effect on higher technological, energy and ecological efficiency of the furnace due to increasing of the productivity and reduction of the wastes, specific fuel consumption, possibilities for incomplete combustion and NOx formation.

Acknowledgments

This study has been financially supported by the Operational Programme “Science and education for smart growth” 2014-2020 of the European Union cofounded by the European Social Fund through the project BG05M2OP001-2.009-0015 “Support for the development of capacity of doctoral students and young researchers in the field of engineering, natural and mathematical sciences”.

The authors acknowledge the research ideas of National Program Young scientist and postdoctoral students, funded by Bulgarian Ministry of Education.

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Improvement of the Conjugate Heat Transfer in High Temperature Chamber Furnaces for Firing of Ceramic Ware

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