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# Novel baking concept based on the Volumetric Ceramic Burners VCB

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## ABSTRACT

Food industry is world-wide one of the most energy demanding sectors, commonly with the overall primary energy demands among top five industrial branches. Due to the constant population increase, it is reasonable to assume that this tendency will reflect to the future energy demand of the food industry as well. Within the food processing industry, baking processes are among most energy demanding in the whole production and processing chain. For example, from the total energy demand of one bakery more than the half energy is required by the baking oven. Furthermore, less than one third of the energy flowing into the baking ovens, contributes to the baking process itself, while more than two thirds dissipate into the environment [1]. Therefore, despite its long tradition, the baking industry still seeks for optimization of both the production equipment and the baking process.

The efficiency of the baking process can be increased by introducing novel advanced thermal energy sources, which would provide better thermal regulation and more efficient (direct) heat transfer to the baked goods. Using the concept of the hybrid virtual engineering, for the first time applied in the development of the baking oven prototypes, a unique, highly dynamic, energy efficient and low pollutant emission baking oven concept, based on volumetric ceramic burner (VCB) technology was developed from the pure theoretical idea up to the full size industrial deck oven prototype.

Experimental characterization of the developed deck oven prototype under realistic working conditions showed that its main features are precise power control in the range 1:20, fast dynamic response and up to 60% of total energy exchanged in the form of irradiated thermal energy. Tests showed that this technology enables reduction of preheating and baking time of up to 20% for a full load of 12 pieces of 800 g white bread loaves, keeping or even improving the baked product quality [2-5].

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## 1. INTRODUCTION

Bread baking process, with the energy demand of approximately 4.8 MJ per kg of used flour, is far the most energy intensive processing step in the pastry production [1, 6, 7]. In the same time, baking process has a crucial influence on the final product quality that cannot be corrected afterwards. Only less than one third of the thermal energy input to the baking oven is used for the baking process, while the remaining energy dissipates into the environment [1]. The energy efficiency and internal energy management within the baking oven are thus a key factors for the optimization within the baking industry.

The efficiency of the baking process can be improved by introducing novel baking concepts, which are able to provide better regulation of the conditions within the baking chamber and a more efficient (direct) heat transfer to the baked goods, compared to conventional system. Furthermore, the fuel consumption and the accompanying pollutant emissions to the environment can be decreased in this way. This study, demonstrates that these goals can be reached using the newly developed baking oven system based on the integration of porous volumetric ceramic burner technology (VCB) as a core technology for the baking process thermal energy generation. Besides an extremely wide regulation range, this burner type possess a high ratio of near infrared (NIR) thermal radiation-to-convection heat transfer to the heated object. This is an advantage that no other combustion technology can offer. According to the available literature [8-13], baking process based on the direct heat transfer from NIR thermal radiation sources should have several positive effect on baking, e.g. reduced baking time, thinner crust, finer crumb, more uniform surface browning and improved product quality.

Major advantages of volumetric ceramic burner (VCB) technology, based on combustion of air/fuel mixture inside the cavities of inert, porous matrix, are well documented in the literature. Its compact design, high thermal radiation output, homogenous temperature distribution, extreme modulation range (max-to-min power) of 1:10 or more, etc., have still not found their application in the commercial baking ovens, where a product quality strongly dependents on the heat transfer mechanisms, temperature level and uniformity of the temperature field at the surface of the baked goods and within the oven.

This novel gas fired baking oven, based on VCB technology, has been developed and systematically investigated at the Institute of Fluid Mechanics in Erlangen, Germany in the scope of the research project financed by German Federal Ministry for Economic Affairs and Energy (BMWi) through the German Federation of Industrial Research Associations (AiF) and The Research Association of the German Food Industry (FEI). The main advantage of this novel baking system, intended in the first step for small-to-middle size companies, is its high controllability, fast dynamic response and unique heat transfer mechanism, i.e. a high and adjustable level of near infrared (NIR) heat radiation from VCB, especially in the wavelength range between 1300 and 1700 nm. This high energy thermal radiation band, corresponds to the one of the main absorption lines of water at app. 1400-1450 nm and can penetrate deeper in to the baking good then the infrared thermal radiation of the conventional ovens. Furthermore, the construction of the developed oven also enables to the certain extension unique adjustable ratio of the direct heat transferred through NIR radiation and other secondary heat transfer mechanisms like IR radiation from the walls, heat convection from the flue gas to the oven walls, heat conduction, etc.

The main goals of the presented research were to develop this new concept using hybrid virtual engineering, to design and build a full-scale size industrial deck oven prototype with the baking area of 1200 x 800 mm and to experimentally evaluate and validate the applicability of this technology in the baking process, based on its functional characteristics and the end-product quality.

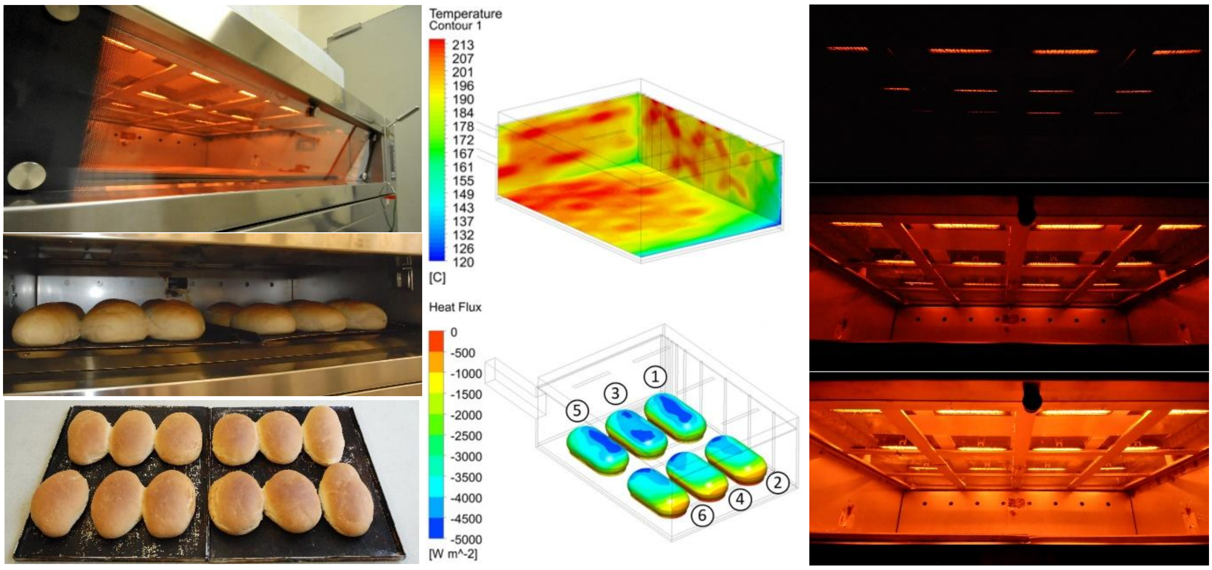


Figure 1. (a) VCBs in operation within the novel baking oven developed at LSTM (upper photo), view of the bread during the baking process (middle photo) and first bread baked within the novel baking oven (lower photo)

(b) Results of the numerical optimization of wall temperature distribution within the right side of an oven (upper picture) and heat flux leaving the oven (-) being absorbed by the bread (lower picture)

(c) Photo of the volumetric ceramic burners (VCBs) integrated within the novel baking oven, taken during the operation, through the front glass door at three different powers between 3 kW and 15 kW

This work offers an insight in the construction of a developed baking oven prototype and presents major results of conducted experimental and numerical investigation.

### *1.1 Volumetric ceramic burner (VCB) technology*

VCB technology is relatively new combustion technology based on combustion of premixed, gaseous air/fuel mixture inside the cavities of inert, porous materials, mainly ceramics [14, 15]. Development of the VCBs is characterized through the development of the different flame stabilization concepts, e.g. velocity stabilization [16], active cooling [17], etc. The latest development of this technology, done at the Institute of Fluid Mechanics in Erlangen, Germany, provides a safe to operate, simple construction and an application under a wide range of operating parameters is a two-layer stabilization, which is based on the modified Péclet-number [14]:

$$Pe = \frac{s_{lam} \ d_{eff}}{a_f} = \frac{s_{lam} \ d_{eff} \ \rho_f \ c_{p,f}}{\lambda_f} \tag{1}$$

In the equation (1), $s_{lam}$ stands for the laminar flame speed, $d_{eff}$ is the effective diameter of the pore size, and $a_f$ is the gas thermal diffusivity (eq. (2)):

$$a_f = \frac{\lambda_f}{\rho_f \ c_{p,f}} \tag{2}$$

where $\lambda_f$ is thermal conductivity, $\rho_f$ is density and $c_{p,f}$ is specific heat capacity of the gas mixture. Defined as in eq. (1), the *Pe* number characterizes the ratio between the thermal energy released during the combustion process within the flame front and the energy taken out from the flame front due to the thermal diffusivity of the gas.

Will the flame propagation within the porous structure take place or the flame will be extinguished, depends is the *Pe* number of the observed structure higher or lower than the critical *Pe* number for that air/fuel mixture (65 in case of methane/air mixture). If the *Pe* number is higher than the critical ($Pe > 65$), the flame will propagate though the structure (combustion zone). Otherwise ($Pe < 65$) the flame propagation will be prohibited due to the quenching (flame trap).

Figure 2. shows a two-layer porous burner, consisting of the flame trap (small pores) and the combustion zone (big pores), each having a different *Pe*-number. Besides the prevention of the flame flash-back through the flame quenching, the flame trap provides preheating of the incoming mixture [18].

In the left hand side of the Figure 2, the burner is in operation when no open flame can be seen, but a strong thermal radiation of the ceramic foam occurs, while the right hand side of the Figure 2. shows the VCB out of operation.

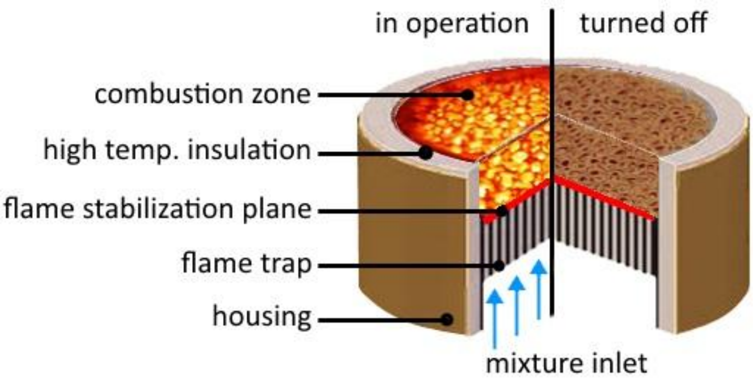


Figure 2. VCB in-and-out of operation with the list of its main components

Porous VCB technology offers a number of advantages in comparison to conventional free flame combustion, i.e. stable operation over a wide range of power loads (up to 1:25) and air ratios, a very small and compact design due to high power density, a high near-infrared thermal radiation (NIR) output, and preserved operation quality independent of burner orientation. Due to the presence of a porous material in the combustion zone, the effective heat transfer is much higher compared to the free flame combustion, which leads to homogenization of the temperature field, intensive heat coupling and lower pollutant emission (CO, NOx) [19-22].

The thermal radiation output of this burner type is significantly higher compared to open flame burners, due to the high temperature of the porous material of 1000 – 1400 °C. Experiments [21] showed that the contribution of thermal radiation to the total exchanged thermal energy between the target object, comparable to a food product (stone HIPOR [23]), and the burner within a model backing oven can reach up to 60%. VCBs are usually produced in different shapes and from various porous ceramic materials (Figure 3.), which can stand high operating temperatures and high thermal stresses (e.g. occurring during the ignition phase), e.g. SiSiC and $Al_2O_3$, etc. [24, 25].

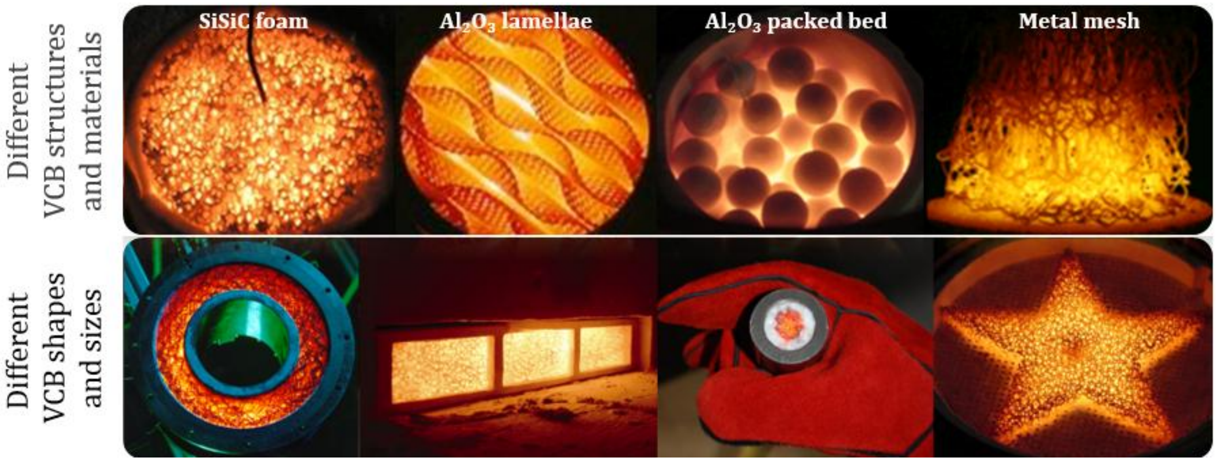


Figure 3. Different VCB forms, structures, shapes and sizes.

VCB technology was successfully applied in different, mainly high temperature applications, e.g. in glass and steel industry [16, 19, 22, 26, 27]. On the other hand, this technology was so far not applied in food industry, even though it can provide significant reduction of thermal energy input, and consequently economic benefits to the production process.

## 2. DESIGN OF THE VCB-BASED BAKING OVEN

The novel VKB-based baking oven, shown in Figure 4. consists of an inner (baking) chamber (left hand side in the Figure 4.), and the outer chamber, which directs the flue gas flow (right hand side in the Figure 4.). In order to heat the baking plates (Figure 4. - ④ 1200 mm x 800 mm), twelve fully premixed, porous VCBs (Figure 4. - ①) are used.

Thermal radiation, coming from VKBs (placed in the outer chamber ceiling - Figure 4. - ①), heats the baking chamber directly through its top wall, made of quartz glass (Figure 4. - ③). The thermal energy of the flue gas (red arrows) is transported to the baking product by convection, through the walls of the baking chamber (Figure 4. - ⑤).

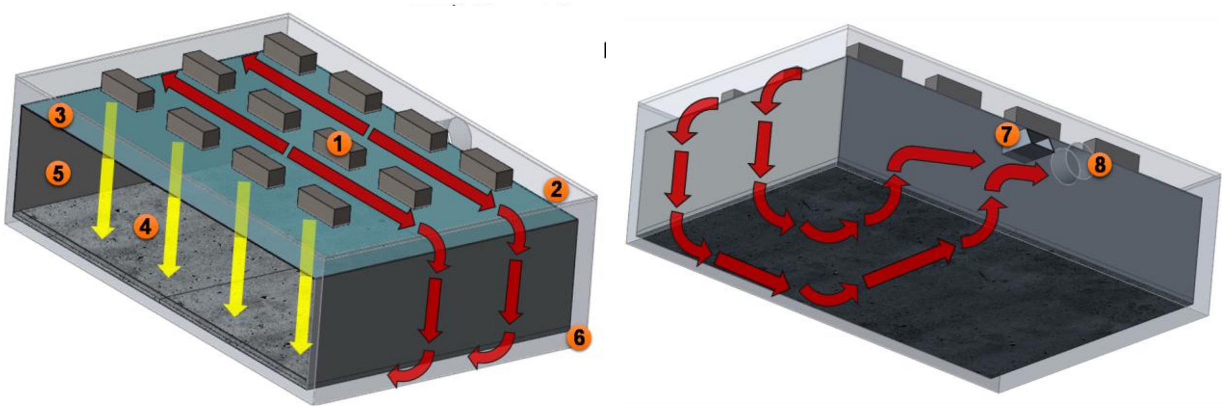


Figure 4. Concept of the new VCB-based oven prototype with its main component: ① VCB, ② VCB carrier plate, ③ quartz glass plate, ④ baking plates, ⑤ baking chamber walls, ⑥ double (sandwich) wall with flue gas guiding channels, ⑦ steam inlet and ⑧ flue gas outlet [28, 29].

This final construction of the demonstrator baking oven was developed based on the hybrid virtual engineering process described in the next chapter.

### *2.2 Hybrid Virtual Engineering*

After initial investigation development of a novel, full size industrial deck baking oven prototype with integrated highly radiative, volumetric ceramic burners (VCBs), was intensively supported by hybrid virtual engineering based on computational fluid dynamic (CFD) numerical simulations and simulations of virtual control system. Use of hybrid virtual engineering is an innovative approach for the baking oven design which interactively combines analytics, semi-empirical and empirical values, obtained results of the pre-tests, numerical simulations of the scaled-up system and results of the tests in the prototype oven. As the development of the prototype baking oven and various novel concepts integrated in this system progresses, simulations develop with it in parallel. In this way, the whole hybrid virtual engineering concept becomes iterative and develops together with the physical prototype and its control system. This approach, used for the first time in the oven prototype design, resulted in significantly shorten development time and almost eliminated conventional expensive and time consuming try-and-error procedures.

For this purpose, commercial software package ANSYS Fluent was use as a basic tool for the CFD simulations and LabView and ProLite software were used for the simulations and development of the virtual baking oven control system. All the simulations were based on a prototype geometry with twelve, celling mounted VCBs used as a source of the near-infrared (NIR) radiation to bake bread placed in the baking chamber below the quartz-glass windows. Consequently, NIR radiation emitted by the VCB surfaces, convectively transferred thermal energy, exchanged between the hot flue gas flowing around baking chamber and the air within the baking chamber and finally conductively exchange thermal energy between hot baking plate and the baked goods within the baking chamber influence significantly overall baking process. Therefore, all three major heat transfer mechanisms were essential parts of each conducted numerical simulation. For the generation of the steam injected at the beginning of the baking process into the baking chamber, commercially available steam generator for deck baking ovens of this size was selected and integrated into the prototype. Therefore, development of this sub-system was not of interest in this work and the thermal energy transferred to the baking goods by the injected steam during the real baking process was excluded from numerical simulations conducted within this research in order to speed up the calculation process.

In a main virtual scenario half of the prototype backing oven (Figure 1. (b)), heated by the thermal radiation of VCBs through the semi-transparent quartz-glass from one side and convectively by the flue gas flow, was used. Radiation was modelled using the Discrete Ordinates Model. Combustion and baking processes were not considered. The goal was to evaluate the optimal burner layout, operating parameters and the flue gas flow pattern to obtain a uniform temperature distribution over the baking plate.

## 3. NUMERICAL CHARACTERIZATION AND OPTIMIZATION

Numerical simulations done in the frame of the hybrid virtual engineering of the prototype were investigating two main cases of interest. First one is the case of the empty oven at different working conditions (thermal loads, excess air rations, etc.) and the second one is the case of fully loaded baking oven with 12 pcs. (6 pcs. in the simulated half of the oven) of 800 g bread loaves.

Obtained results were used to characterize flow fields of the air within the baking chamber, flow gas speeds through the sandwich walls of the oven, temperature fields across the oven walls and baking plates, etc. In addition, for the case of the fully loaded oven, thermal fluxes through the bread crust were investigated in the stationary baking regime using semi-empirical literature data regarding the surface bread temperatures and crust properties.

Figure 5. shows an example of the simulation results conducted for half of the empty oven at the power of P = 1.3 kW, $T_{set}$ = 200 °C and λ = 1.5.

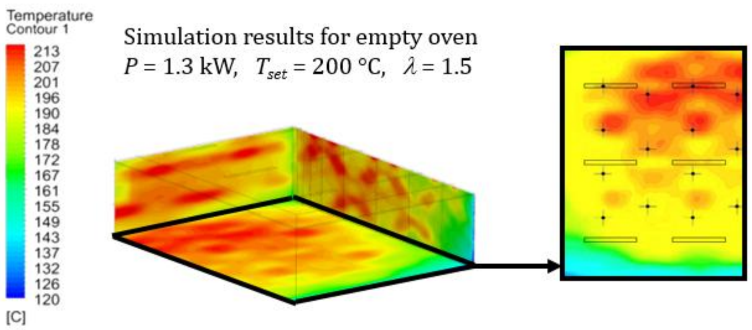


Figure 5. Temperature distribution over the baking chamber walls in an empty half-oven at the power of P=1.3 kW, $T_{set}$=200°C & λ=1.5

In the similar way, the numerical simulations were used to determine effects of the product in the baking chamber. Figure 6. shows example of the simulation conducted for the fully loaded oven at P = 2.5 kW, $T_{set}$ = 200 °C and λ = 1.5.

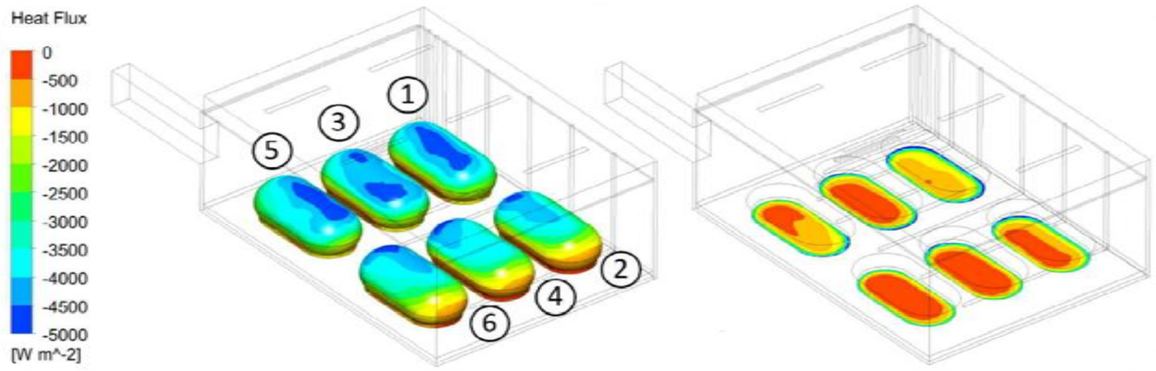


Figure 6. Thermal flux through the upper and lower crust of the bread in a fully loaded oven half at P=2.5 kW, $T_{set}$=200°C and λ=1.5 [30]

Results of these simulations showed the presents of the radially shaped temperature contours with the hot spot in the central region and cold zone closed to the oven's door. In general, numerically obtained results were in very good agreement with the experimentally measured values in the prototype. In the next iterative step of the hybrid virtual engineering oven development, similar calculations were conducted in order to investigate and optimize, VCB position adjustment, individual power modulation for each VCB, influence of the glass oven door on the temperature distribution, effects of flue gas recirculation, etc.

## 4. EXPERIMENTAL CHARACTERIZATION AND DISCUSSION

In order to evaluate the results of the hybrid virtual engineering, and to quantify suitability of the novel VCB-based demonstrator oven for the baking process, its operational properties (e.g. start-up behavior and operational stability), the temperature distribution within the oven and especially over the baking plate, and the quality of the baked goods were extensively experimentally tested using the oven prototype shown in the Figure 7.


Figure 7. Developed and experimentally tested full-size baking oven prototype [2, 3].

The temperature field inside the baking chamber and the quality of the baked goods were additionally compared to a reference electrical deck oven of the same size.

Experiments showed that the baking process demands not more than 500 $kW/m^2$ during the heat-up phase, and ca. 100 – 150 $kW/m^2$ during the baking phase, although it is possible to achieve much higher thermal load with VCB (based on the previous experience, up to 1 – 2 $MW/m^2$).

Uniformity of the temperature field over the baking plate, evaluated through the maximum measured temperature difference and the standard deviation of the temperature measurements, was identified as one of the most crucial parameters in this evaluation process. Temperatures over the baking plate were measured using fourteen K-type thermocouples, integrated within one of the baking plates.

The differences between the minimum and the maximum recorded temperature were found to be less than 15°C, with the standard deviation of 6°C. On the other hand, the maximum temperature difference, measured in the reference electrically heated deck oven with the set temperature of the baking plate of 200°C was detected to be 8°C. Although the temperature difference in the novel oven is higher compared to the reference oven, its relatively low value indicates that the thermal radiation is uniformly distributed over the plate. Further optimization like e.g. the recirculation of the flue gas flow pattern below the baking plate, decreases the maximum temperature difference over the baking plate.

The baking process inside the demonstrator VCB-based oven was characterized using the reference baking goods, i.e. 800g white bread loafs, with twelve loafs per batch. The quality analysis (crust thickness, color, texture, pore distribution) showed that the developed oven delivers products with similar sensory properties (similar crust color and crumb properties, thinner crust) as the reference electrical deck oven (Figure 8). The overall process time was reduced up to 20%, both in the preheating phase and the baking phase. As a result, reduced fuel input and increased production capacity can be expected.

Figure 8. Quality of the obtained product (upper and lower crust, and crumb), obtained for total burner power P = 3 kW [2, 3, 30].

The influence of the power and the excess air ratio on the reference baking good was additionally characterized. The upper and lower crust color are directly influenced by the burner power load, with the optimal power being in the range 2.5 – 3.5 kW. The air excess ratio has an influence on the specific expansion of the goods, due to the intensification of the convective heat transfer from the backing chamber walls. Finally, the novel baking oven possess a high controllability and the fast dynamic response, which enables an implementation a wide range of temperature/baking programs, i.e. production of a wide variety of pastries.

The presented experimental campaign showed that the VKB technology not only applicable for the baking process, but also brings a number of advantages to the baking process.

## 4. CONCLUSIONS

Volumetric ceramic burner technology, previously implemented in various, mainly high temperature applications, e.g. in glass and steel industry was for the first time successfully used as a core technology and the thermal energy source for an innovative baking oven - one of the most important processes in the food industry. The goal of the project, which is partly presented in this study, was to evaluate and quantify the applicability of the VCB technology for highly energy demanding baking process. In this work, the design, construction and characterization of the VCB-based demonstrator deck baking station was shortly overviewed.

Using the concept of the hybrid virtual engineering, for the first time applied in the development of the baking oven prototypes, a unique, highly dynamic, energy efficient and low pollutant emission baking oven concept, based on volumetric ceramic burner (VCB) technology was developed from the pure theoretical idea up to the full size industrial deck oven prototype.

Experimental characterization of the developed deck oven prototype under realistic working conditions showed that the novel gas fueled oven combines the advantages of the uniquely high radiation-to-convection thermal energy transfer (up to 60%) with a unique regulation dynamic - precise power control in the range 1:20. The experimental investigation demonstrated its stable operation over a wide range of burner operating parameters, i.e. thermal loads and excess air ratios, which consequently provides a wide range of baking plate/baking atmosphere temperatures. The combination of the wide operating range and a fast response enables the implementation of a wide range of baking programs, and consequently allows very fast product adjustment.

Tests showed that this technology enables reduction of preheating and baking time of up to 20% for a full load of 12 pieces of 800 g white bread loaves, keeping or even improving the baked product quality. Achieved temperature distribution over the baking plate was homogeneous and satisfying in comparison to the reference, commercial electrically heated oven of the same size and geometry. Visualization of the temperature field showed satisfactory browning grades and a uniform browning of the toast bread layer, indicating a homogeneous distribution of thermal radiation over the baking plate. The quality of the baked goods, i.e. 800 g-white bread loaves, and 50 g-white buns, was in the same level as the products prepared in the reference electrical oven, in terms of browning, structure and porosity.

The obtained results demonstrated a huge potential of the VCB technology for the food industry in general, and for the baking process in particular.

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