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The Validation of Numerical Methodology for Oven Design Optimization Using Numerical Simulations and Baking Experiments

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*In this paper, we will present the validation of numerical methodology for the improvement of baking performance of a forced convection oven. The baking performance will be assessed as the degree of uniformity between browning and temperature distribution in the oven. We found a linear relationship between the experimentally measured grade of browning and the simulated temperature distribution. Six different designs of oven fan cover were compared through numerical simulations, where a time-dependent 3D numerical model with radiative and convective heat transfers mechanism was used. The results were used in a linear model to estimate the grade of browning. The results were validated with the experimental measurements of baked shortbread using an old and improved-upon oven design. The grade of browning was determined experimentally by the colour contrasts method, based on the colour space CIE L*a*b. The results show that the improved fan cover performs better than the existing fan cover.*
Keywords: computational fluid dynamics, baking, oven, heat transfer, shortbread, optimization

Highlights
- *Numerical model for the determination of the grade of browning was used in the improvement of baking results.*
- *Six different fan cover designs are presented and analyzed.*
- *The improved fan cover decreases the difference in the grade of browning by 25.9 %.*
- *The numerical calculations were validated and match the experimental results very well.*

0 INTRODUCTION

The improvement of existing products and technologies is one of the main global aims of manufacturers and research and development (R&D) teams. In the field of cooking appliance design, baking performance, energy consumption and noise levels are the main features of the product that engineers constantly strive to improve.

The improvement of an existing product usually requires a lot of effort, time and resources for the preparation of prototypes and measurement of different solutions. In order to reach an improved solution with a minimal amount of effort, the use of numerical simulations, such as computational fluid dynamics (CFD), is becoming essential as it helps engineers to understand the processes and to prepare solutions.

The aim of this paper is to prepare and validate a methodology for the improvement of the baking performance of a forced convection oven. We propose the combination of a flow and heat transfer simulation coupled with a model for the grade of browning followed by experimental validation. In order to enable the comparison of experimental and simulation results, we will introduce a model, which is able to use CFD results for the prediction of the browning grade during the baking process. The improvement of the oven fan cover was selected as a case study. In the study, we considered the position of the tray, which is most commonly used in baking.

The use of numerical simulations to study flow and heat transfer in oven cavities has been proposed by researchers [1] to [3]. They considered natural convection ovens, where radiation is the main heat transfer mechanism. Forced convection ovens, where the fan is included, were considered by [4] to [6]. In this paper, we will optimize the baking performance of a forced hot air convection oven. In this case, the fan, the circular heating element, the fan cover and the cavity itself are the potential parts that could be optimized. Since the circular heating element and fan are standard components and because the changes in the oven cavity result in huge costs, we decided to perform the improvements on the fan cover, which is screwed into the oven cavity. The new fan cover design should not affect the other parts of the oven.

The simulation of temperature and air flow in a forced convection oven cavity was studied by [6] and [7]. They report that the performance of the fan, the shape of the fan, and the oven cavity geometry are the most important parts in the oven cavity. The difference between the numerical simulation and experimental measurements were 4.6 °C at a setting

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of 200 °C. They used the k-ε turbulence model, where the average error in the velocity field was 22 %.

A transient simulation with heating elements turning on and off was performed by [8]. The heating elements were modelled as a volume heat source. They reported that the emissivity of the heating element has a big influence on the results. If the emissivity of the heating element is reduced by 30 %, the oven wall temperature is reduced by 10 %. When the oven wall emissivity is reduced by 20 %, the temperature of the oven wall is reduced by 0.2 %. They performed a natural convection simulation of a bake cycle, where the comparison to experimental measurements showed a 4 % difference. Furthermore, they considered a natural convection simulation, where only the upper heating element was working, and the deviation to experimental measurements was 10 %.

Rek et al. [4] performed three dimensional (3D) numerical simulations of the oven cavity and the fan cover with forced convection. In the numerical model, the following two simplifications were used: the fan, which is the air flow generator, and the heating element were not included in the model. These simplifications were not made in our work.

The experimental measurements are needed to verify the improved design, which was obtained using simulations. When designing an oven cavity, the appropriate experimental method is the baking of food, where the uniformity of browning is a good indicator of how well the oven bakes. The experimental measurements were performed according to the standard EN 60350-1 [9], which prescribes how to verify and evaluate baking performance.

Researchers [1], [3] and [10] used temperature measurements and browning method for the evaluation of numerical results of the bread baking process. They report that all applied radiation models, discrete transfer radiation models, surface to surface, and discrete ordinates gave similar results.

The authors [11] used the computerized determination of the browning of baked bread. The method is based on colour space CIE L*a*b. The authors report that the change in the browning of bread is in linear correlation with its weight change.

The browning process consists of the simultaneous process of mass transfer, heat transfer and chemical reactions of caramelisation and Maillard reactions. The browning process starts when the temperature is above 120 °C and water activity is below 0.6 [12].

In our previous work [13], we developed the numerical model for the prediction of the browning grade according to the standard EN60350-1 [9]. The average shortbread temperature was used to define R_y. The averaging process starts when the surface temperature of the shortbread reaches 120 °C. In the numerical model, radiative, convective and water evaporation mechanisms are taken into account. The model was based on a 3D, time dependent numerical calculation. The model was validated through experimental measurements of the browning of baked shortbread.

The objective of this research was to validate the applicability of the developed numerical model for the determination of the browning grade of baked shortbread, and to present the use of time-dependent 3D numerical simulations for the improvement of baking performance and the design optimization of a forced convection oven.

The results of the numerical simulations were validated through the experimental measurements of baked shortbread. The grade of browning was determined for baked shortbread with the use of the reference browning measurement system (RBMS) [14], which is based on the CIE L*a*b colour space.

The paper is organized as follows: in section 1, our methods will be presented. In section 2, we will present the experimental part. The numerical model will be presented in section 3. In section 4, the results of several simulations of various fan covers and the validation with experimental results will be presented. The main conclusions and results will be summarized in section 5.

1 METHODS

The experimental and numerical methods for improving the baking performance of a forced convection oven will be developed in this paper.

To assess the baking performance of the oven, experimental measurements were performed according to the standard EN 60350-1 [9]. Furthermore, we took additional temperature, weight and heater operation measurements. The baking of shortbread was performed to assess the heat distribution of the oven cavity. The experimental results were used in two ways: firstly to determine the boundary conditions that were used to setup the simulation and secondly to validate and confirm the numerical results.

The numerical calculations for several fan cover designs were performed with commercial computational fluid dynamics software ANSYS CFX 15. 3D time dependent simulations of air flow along with convection, conduction and radiation heat transfer mechanisms were modelled. In addition, a water evaporation model was included, since during baking an important amount of heat is used for the evaporation of water from the dough. Finally, based on the CFD results, a model was implemented to estimate the grade of browning and facilitate the comparison between the simulation and the experiment.

2 EXPERIMENTAL SETUP

The experiments were performed in two steps: the first during the baking of shortbread (temperature and mass measurements) and the second after the baking process was finished (grade of browning measurement). The experimental set up is presented in Fig. 1.

The shortbread was baked according to the standard EN 60350-1 [9] using the following mass portions: 49.9 % white wheat flour, 19.9 % margarine, 19.9 % sugar, 10 % eggs, and 0.3 % salt. The total mass of the shortbread at the start of the baking procedure was 356 g and the dimensions of the shortbread on the baking tray were 400 mm in length, 20 mm in width and 5 mm in height.

The baking was performed at a stabilized voltage of 230 V obtained by means of a stabilizer by Gorenje Orodjarna, Slovenia.

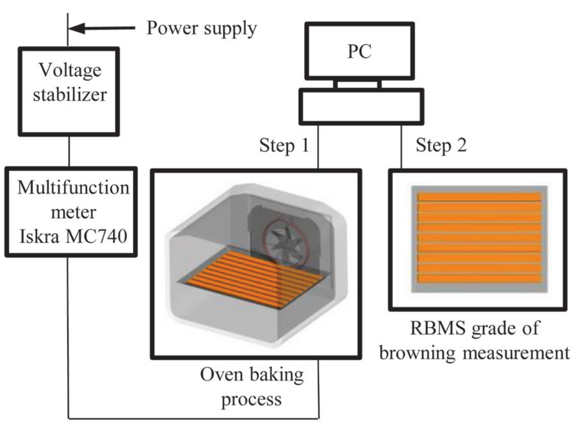

Fig. 1. *Experimental set-up of measuring system*

During the baking process, the operation of the heating elements was recorded using an Iskra MC740 multifunction meter to measure power. Fig. 2 shows the operation of the heating element during the baking process. The oven was set in such a way that both the round heating element and the fan operated. The oven fan rotation speed was measured with a digital stroboscope tachometer by Extech instruments, USA.

The temperature setting of the oven was 175 °C and the baking process lasted for 780 seconds. These parameters were reused in the setup of the numerical model.

The shortbread thermal properties before baking were: thermal conductivity λ = 0.195 W/(m·K), specific heat capacity c_p = 1921 J/(kg·K), and density ρ = 1075 kg/m^3, calculated according the portions of the ingredients added [15]. During the baking process, the water evaporates and the shortbread properties changed. The dry shortbread thermal conductivity λ was 0.128 W/(m·K), the specific heat capacity c_p was 1526 J/(kg·K) and the density ρ was 1088 kg/m^3.

The browning measurement took place 1 hour after baking due to the requirements of the standard. The sample was taken out of the oven and left on the baking tray, which was placed on a table. The measurements of the grade of the browning R_y were carried out by applying the RBMS [14]. The R_y parameter is used by the manufacturer of the browning measurement device and is the reflection density color scale based on the CIE color space. It is defined as $R_y = Y_{10}$. 63 points on the shortbread were measured (matrix 7×9).

The RBMS method is based on the optical measurement system, which is composed of a measurement chamber, a charge coupled device (CCD) camera, and lamps. The RBMS was developed in compliance with the ISO 7724 standard [16] and CIE 15.2., which is based on the CIE L*a*b colour space.

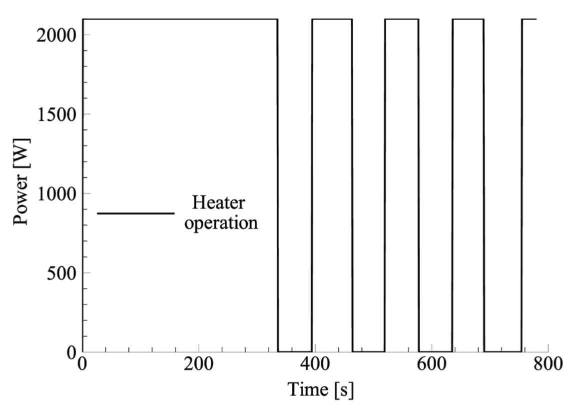

Fig. 2. *The operation of the round heating element during the baking process*

3 CFD MODELING

Simulations of air flow and heat transfer were performed using the commercial software ANSYS CFX 15 [17]. ANSYS CFX is a CFD software, which is based on the finite volume method.

The complete domain dimensions were: width 500 mm, depth 450 mm, and height 380 mm. The numerical model included radiation, conduction and convection heat transfer mechanisms. Eight solid domains were included: the insulation of the oven cavity, the oven cavity, the door glass, the fan cover, the fan, the round heating element, the shortbread, the baking tray as well as two fluid domains including stationary and rotating air. The rotating fluid domain was set as a transient rotor stator interface boundary condition within the stationary fluid domain. The conservative interface flux boundary condition was used for all connections between the domains. Fig. 3 shows all domains.

The mesh sensitivity analysis was performed in our previous work [13], where a similar oven cavity was studied. For this study, we designed the meshes in a similar fashion, keeping the number of elements and the structure of the mesh at the same level for all fan cover designs. The final mesh was designed with 4.5 million elements.

The air in the oven cavity was treated as an ideal gas for temperature dependent density, thermal conductivity, specific heat capacity and dynamic viscosity [18]. The air-flow inside the domain was assumed turbulent, with the Reynolds number 9.7 ×10^4, which is based on a domain length of 0.4 m and a velocity of 3.71 m/s. There are several URANS turbulence models in the ANSYS CFX [17]. Because of the coupled flow and heat transfer within the complex geometry of the numerical model and based on our previous experience with the use of the SST turbulence model [13], we chose the SST model for the analysis. We have validated the use of the SST turbulence model for oven baking in our previous work [13]. The turbulence model settings used an automatic wall function, with an initial high intensity (10 %) boundary condition. The $y+$ values on the wall ranged from 0 to 71.

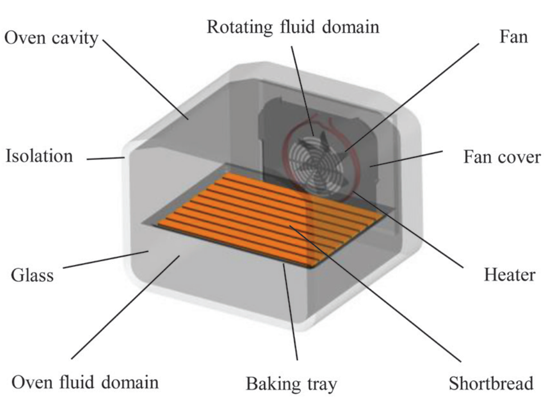

Fig. 3. *Domains of the numerical model*

The following unsteady Reynolds averaged Navier-Stokes equations for flow and heat-transfer were solved:
the continuity equation:

$$\frac{\partial \rho}{\partial t}+\nabla\cdot\left(\rho\vec{v}\right)=0, \quad (1)$$

the momentum equation:

$$\frac{\partial \vec{v}}{\partial t}+\left(\vec{v}\cdot\nabla\right)\vec{v}=-\frac{1}{\rho}\nabla p+\mu_0\nabla^2\vec{v}+\frac{1}{\rho_0}\nabla\left(\overline{\tau}_{ij}+\tau_{ij}^R\right), \quad (2)$$

the energy equation:

$$\rho c_p\frac{DT}{Dt}=\lambda\nabla^2 T+S_r-S_e, \quad (3)$$

the turbulent kinetic energy equation:

$$\frac{\partial k}{\partial t}+\overline{v}\left(\nabla k\right)=\frac{P_k}{\rho_0}-\beta' k\omega+\nabla\left[\left(\mu_0+\frac{\mu_t}{\sigma_k}\right)\left(\nabla k\right)\right], \quad (4)$$

the turbulent frequency equation:

$$\frac{\partial \omega}{\partial t}+\overline{v}\left(\nabla\omega\right)=\alpha_3\frac{\omega}{k}\frac{P_k}{\rho_0}-\beta_3\omega^2+$$
$$+\nabla\left[\left(\mu_0+\frac{\mu_t}{\sigma_{\omega 3}}\right)\left(\nabla\omega\right)\right]+\left(1-F_1\right)\frac{2}{\sigma_\omega\omega}\left(\nabla k\right)\left(\nabla\omega\right), \quad (5)$$

and the turbulent viscosity equation:

$$\mu_t=\frac{a_1 k}{\max\left(SF_2,a_1\omega\right)}, \quad (6)$$

where p is the pressure, $\vec{v}$ is the air velocity field, T is the temperature, S_r is the radiation and S_e is the heat sink due to evaporation. τ_{ij} are viscous stresses, τ_{ij}^R is the Reynolds stress tensor, μ_t is the turbulent viscosity, k is the turbulent kinetic energy, ω is the turbulent frequency, P_k is the production of turbulent kinetic energy, F_1 and F_2 are blending functions, S is an invariant measure of the strain rate and β', σ_k, α_3, β_3, σ_ω, a_1, are constants [17]. The air density ρ_0 was obtained by the ideal gas state equation. The thermal conductivity λ and the viscosity μ_0 of the air as well as the specific heat c_p were considered temperature dependent [18]. All solid material properties, except for the shortbread, were considered to be constant. We simulated 780 seconds of baking using time steps of 10 seconds. The time step was defined and validated by our previous work [13].

The simulation was set up to mimic experimental conditions. The experiments revealed that the heating element can be modelled as a volume energy source at a power of 2100 W. The oven fan rotates at a speed 1350 min^{-1} at a temperature of 20 °C in the oven and 1800 min^{-1} at a temperature of 175 °C. The oven speed varies because of the air property change due to its heating up the oven. In the simulation, the fan rotation speed changed as a linear function of temperature.

Since the heating element reaches up to 700 °C during baking, radiation plays an important role in the numerical model. The optical thickness is a good indicator for the selection of the radiation model. In our case, the length scale was L = 0.45 m and the absorption coefficient was 0.01 m^{-1} yielding the optical thickness which is much smaller than the unity. The optical thickness defines which radiation model should be used. P1 and Rosseland models are best suited for optically thick materials (where radiation absorption is important), while the Monte Carlo model, which we used, is appropriate for media, where the absorption of radiation is minimal [17]. The Monte Carlo radiation model is capable of modeling radiation through the glass door and transparent materials. In our case, the glass was treated as a transparent material with the absorption coefficient a = 89.15 m^{-1}, calculated using Eqs. (7) and (8) and the refractive index of 1.51 [17].

$$I = I_0 e\left(-\alpha x\right), \tag{7}$$

$$a = -\frac{1}{x}\ln\left(T\right) = 89.15\ m^{-1}. \tag{8}$$

The radiation properties and emissivity of the enameled elements were prescribed 0.9 [2], [8] and [13] and were considered composite materials of steel and enamel with thermal conductivity λ=45.7 W/(m·K), a specific heat capacity c_p = 513 J/(kg·K), and density ρ = 6515.5 kg/m^3 [13]. The emissivity of the heating element and the fan, which are made of steel was 0.85 [2], [8] and [13].

The no-slip velocity boundary condition was applied to the walls of the model. Due to the natural convection of the air outside of the domain, a low value of the heat transfer coefficient was prescribed at the insulation, h = 5 W/(m^2·K). A heat transfer coefficient of 5 W/(m^2·K) was used for cases where natural convection cooling took place under quiet ambient conditions [19]. Such conditions were set up in our laboratory when experiments were conducted, thus we have used this value in the numerical model. Furthermore, the outside heat transfer coefficients were defined by comparing the experimentally measured temperatures in an empty oven with a simulation.

Due to the slightly forced convection of the cooling system at the door glass, a higher value of the heat transfer coefficient was prescribed there, h = 13 W/(m^2·K) [13].

The experiment showed that during the baking process, water evaporates and the shortbread mass is reduced by 14.89 %. The results of mass measuring experiments are presented in Fig. 4. In the numerical model, the evaporation was modelled as a heat sink of, $S_e = mH_w/t$ = 249.7 W [13]. Here m = 42 g is the mass of evaporated water, H_w = 2260 kJ/kg is the water vaporization heat and t = 380 s is the duration of the evaporation process, which causes linear shortbread mass loss, see Fig. 4. Evaporation was modelled as a temperature dependent heat sink imposed on the shortbread. This kind of evaporation model was developed in [13] and was adopted here.

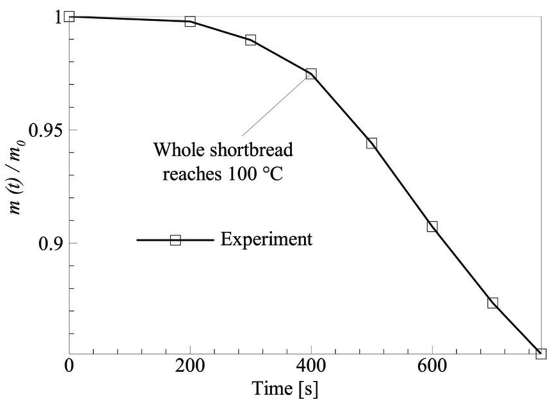

Fig. 4. *Shortbread mass change due to the evaporation of the water; the mass at the start of the baking process was m_0 and the mass as a function of time during the baking process was m (t)*

Due to the evaporation process, the change in shortbread properties has also been included in the numerical model. Since the shortbread mass changes linearly over time (Fig. 4), we calculated the shortbread properties using a linear model interpolating between the wet shortbread properties before baking and the dry shortbread properties after baking.

4 RESULTS AND DISCUSSION

The results of the numerical simulations and experimental measurements have been compared to the grade of browning method. For comparison, a different grade of browning fields of baked and simulated results have been used. The experimental grade of browning has been established through the RBMS system according to the standard EN 60350-1 [9]. For the evaluation of numerical results, the numerical grade of browning model was developed [13]. In our previous work, we evaluated the empty oven cavity with numerical simulations where the average difference between the experimental measured and numerically calculated temperature at the center of the oven was 2.8 K and 5.6 K in the shortbread. For development of the model, we used the boundary condition that the browning starts when the first measurement point on the shortbread exceeds 120 °C [20].

Secondly, we compared the experimental results of the browning grade of baked shortbread and the temperatures of the numerical calculation and found a linear relationship. For the determination of the numerical browning grade, the following model was proposed [13]:

$$R_y = \alpha T + \beta. \tag{9}$$

After adopting the model for the present case, we found that the constants of the model are: and . Based on our experimental data and simulation results, the equation is valid for the temperature range from 100 °C to 150 °C. The Eq. (9) was used to predict the browning grade based on the CFD simulations of different fan cover designs.

We simulated the existing and five additional fan cover designs. The CPU time was 28 hours and using 12 processors / simulation.

All designs of the fan cover along with descriptions of their modifications are presented in Fig. 5. The existing fan cover is marked with a). Detailed descriptions of the modifications are given in Table 1.

Table 1. *Modifications of various fan covers*

	Modifications
a)	Existing fan cover
b)	Closed opening 1
c)	Closed opening 1 and 2
d)	Closed opening 1, 50 % closed upper opening
e)	Closed opening 1, 50 % open corner
f)	Closed opening 1, 20% closed upper opening

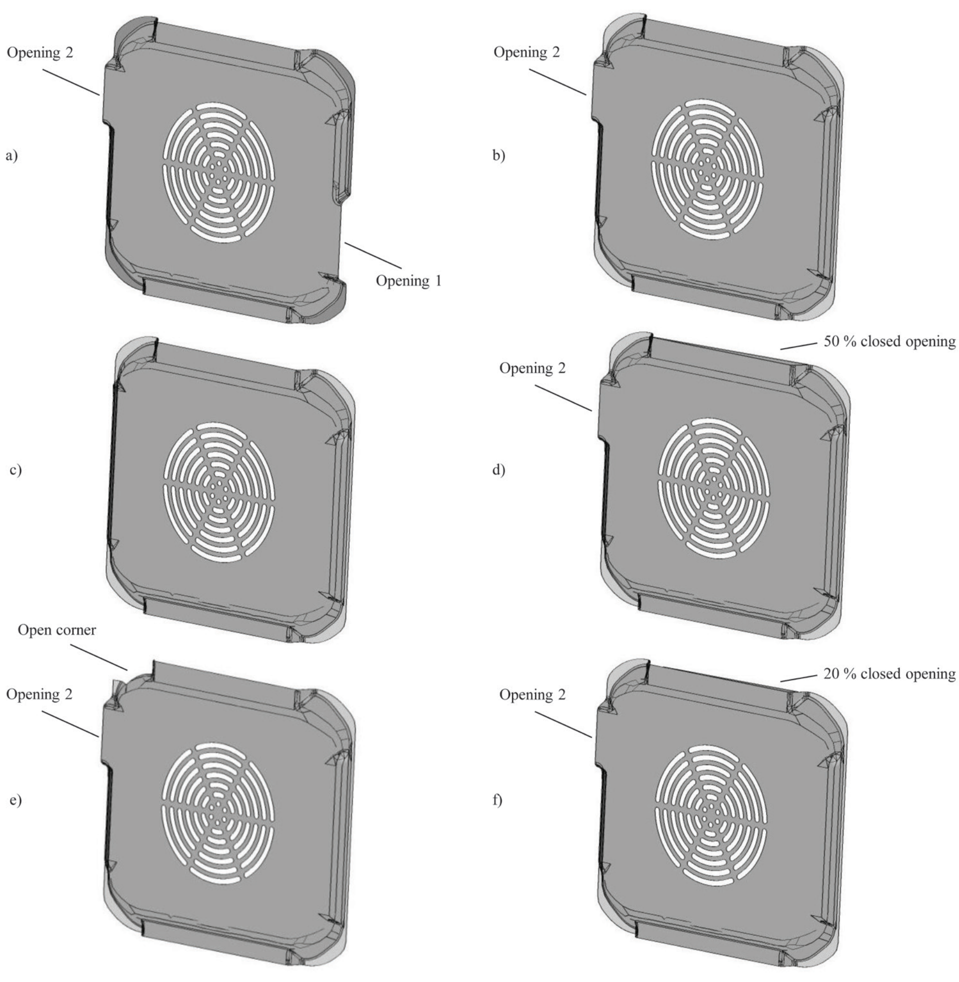

Fig. 5. *Existing fan cover a) and modifications b), c), d), e) and f)*

The results of the numerical simulations of different fan cover models are presented in Table 2 and in Fig. 6. The R_y contours were obtained by the interpolation of 7×9 R_y measurements. Two different criteria were used: the difference in the maximum and minimum grade of browning ($R_{y\,max} - R_{y\,min}$) and the standard deviation σ of the field of the browning grade, which was estimated using the following equation, Eq. (10):

$$\sigma = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(R_{yi} - \overline{R_y}\right)^2}, \tag{10}$$

where $\overline{R_y}$ is the average grade of browning and $n = 63$ are all of the measurement points.

The reason for introducing the two criteria is twofold: From an oven user point of view, an important indicator of oven quality is the difference in browning along the whole baking tray as well as the uniformity of browning of the baked food.

Table 2. *Numerical results of various fan covers*

	$R_{y\,max} - R_{y\,min}$ [%]	σ
a)	22.21	4.82
b)	13.46	2.99
c)	26.16	7.65
d)	33.92	8.27
e)	21.10	5.56
f)	15.57	3.66

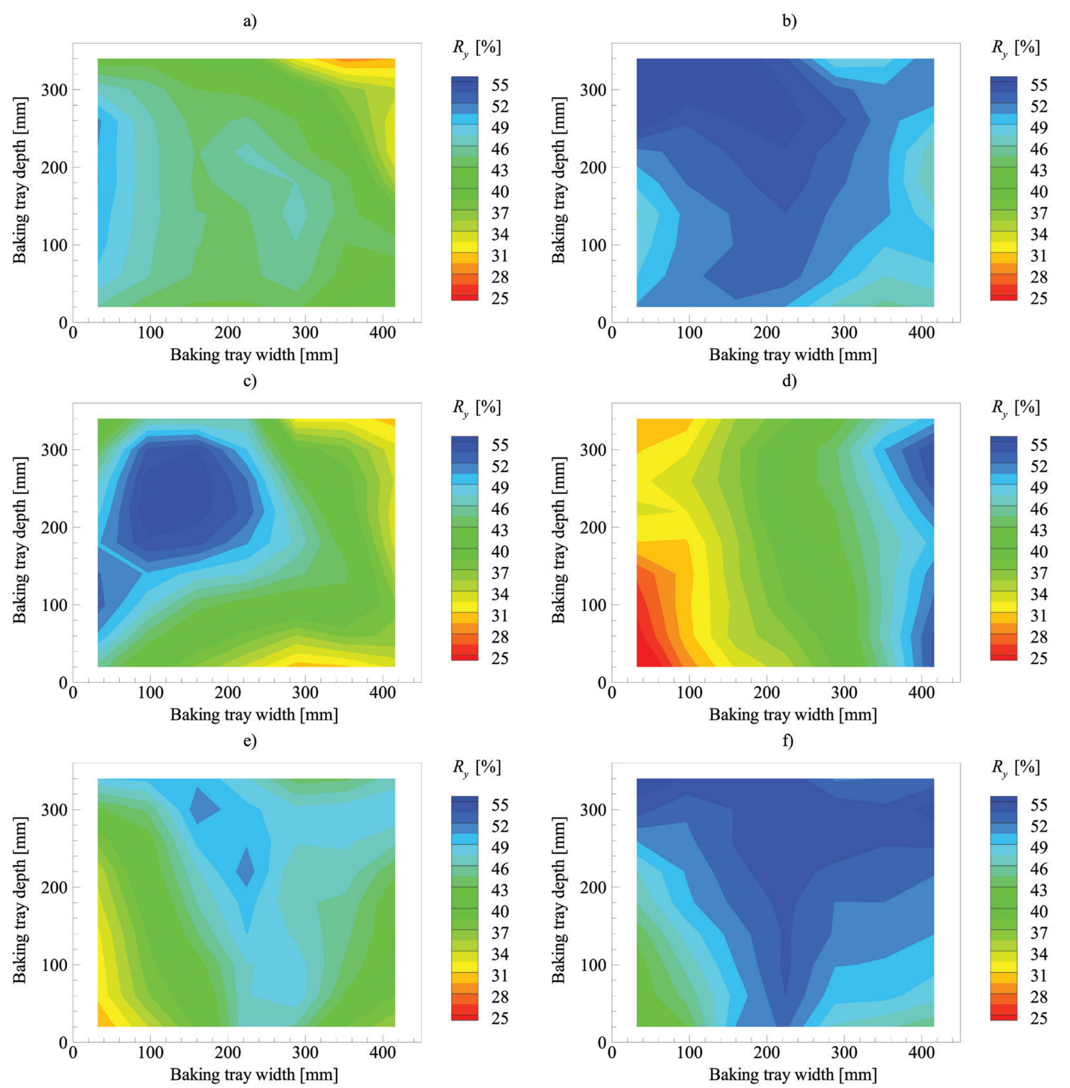

Fig. 6. *Results of numerical simulations of the six fan covers: a) existing fan cover, b), c), d), e), f) new designs; the numerically estimated grade of browning R_y is also presented*

Considering all of the fan cover designs (Table 2), we have observed that the lowest difference in the grade of browning, 13.46, and the lowest value of standard deviation, 2.99, were found for fan cover design b).

In order to visualize the results of numerical simulation, Fig. 7 shows the full numerical domain where the temperature contours on the shortbread at the end of the numerical simulation for variant b) are presented.

The existing fan cover a) and the improved version b) were verified by an experimental test of baking shortbread and evaluated through the grade of browning based on the RBMS method. The results of the experimental measurements are presented in Fig. 8. The results are presented on a common scale of the grade of browning, so it is easy to visualize the improvement of fan cover variant b). With design b), the intensive browning on the rear right part of the baking tray disappears.

In Table 3, the difference in the grade of browning between the existing and improved fan cover is shown, which was obtained experimentally.

Table 3. *Experimental results of a) existing and b) improved fan cover*

	$R_{y\,max} - R_{y\,min}$ [%]	σ
a) Existing	31.10	6.64
b) Improved	23.06	5.13

The new design of the fan cover decreased the difference in the grade of browning R_y between the maximal and minimal value for 25.9 % and improved the uniformity of baking performance by 22.7 %. In comparison with the numerical estimation the difference in the grade of browning R_y was predicted to improve by 39.3 % and the equality of baking performance by 37.9 %. These values were obtained by using the following equation: (new design/old design - 1) ×100. The numerical simulation predicted the improvement of the fan cover well, even though the model is a simplified version of the experimental set-up. This results prove, that the proposed CFD model alongside with the grade of browning model are capable of verifying oven design changes.

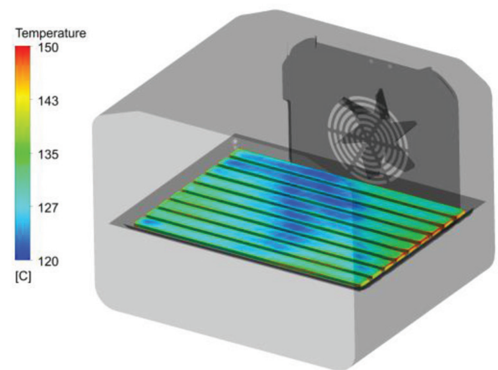

Fig. 7. *Temperature distribution of numerical simulation for fan cover version b)*

The velocity field, 20 mm above the baking tray, is shown in Fig. 9. The impact of the new proposed fan cover on browning is very visible in the right rear corner of the oven cavity, where the velocity decrease is significant in comparison to the existing fan cover. The decreased velocity leads to improvement in the uniformity of the baking in this corner.

This means that with a lower forced convection heat transfer originating from the fan cover openings, we are able to reduce browning in this area. Furthermore, Fig. 9 also shows the low velocity field area in the left rear corner, which means that the browning in this area starts later on.

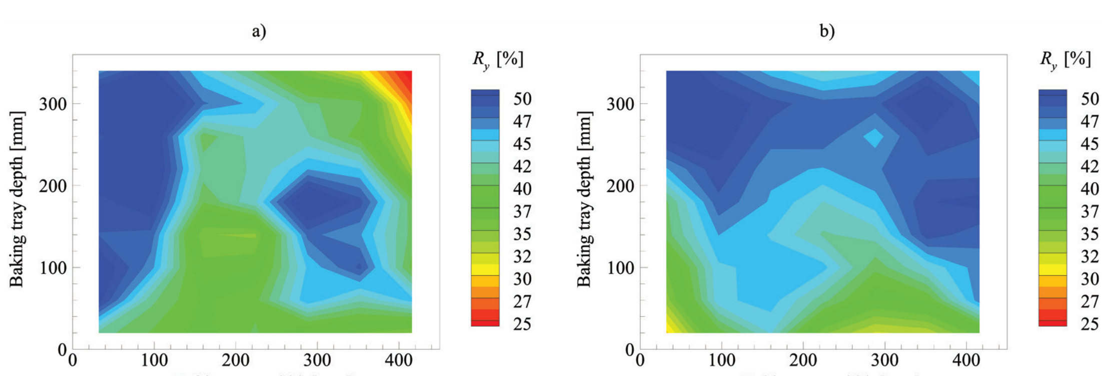

Fig. 8. *Grade of browning of experimental results of a) existing and b) improved fan cover*

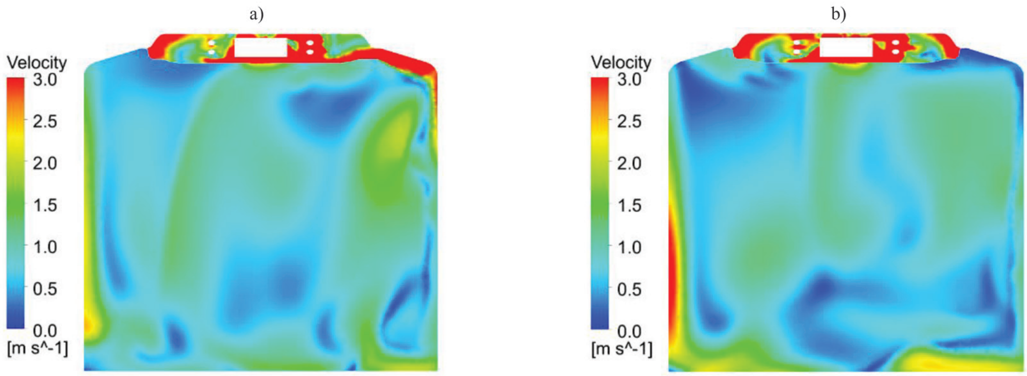

Fig. 9. *The velocity field of a) existing fan cover and b) improved fan cover*

The results of the velocity field, 20 mm above the baking tray, are presented in Table 4. The standard deviation $\sigma_{(x,y,z)}$ of the velocity field was estimated by using the following equation, Eq. (11):

$$\sigma_{(x,y,z)} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(v_{(x,y,z)i} - \overline{v_{(x,y,z)}}\right)^2}. \qquad (11)$$

Table 4. *Results of the velocity field 20 mm above the baking tray*

	$v_{average}$ [m/s]	σ_x	σ_y	σ_z
a) Existing	0.98	0.49	0.39	0.25
b) Improved	0.79	0.41	0.35	0.29

5 CONCLUSIONS

The objective of this study was to propose and validate the methodology, which uses computational fluid dynamics combined with additional models for evaporation and grade of browning to improve the baking performance of the oven cavity.

We focused our attention on the design of the fan cover. Several designs were considered using the proposed numerical methodology. Based on the uniformity of the grade of browning, we identified the optimal design. The optimal fan cover design was confirmed and validated by the experimental measurements of baking performance, where the measurements of the grade of browning R_y were carried out. The results of the numerical calculation correspond very well to the experimental measurements.

This satisfactory agreement between the experiment and simulation validates the proposed methodology. Using the simulation methodology in the design process will enable engineers to quickly and efficiently verify new design ideas and thus speed up the design process. Furthermore, the use of the developed methodology will help the engineers avoid the preparation of a large number of expensive prototypes.

6 ACKNOWLEDGEMENTS

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