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Methodology for modeling browning of biscuits in CFD

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Abbreviations

CFD	Computational Fluid Dynamics
P	Power
V	Voltage
I	Current
MRF	Moving Reference Frame
Massw, evap	mass of water content that is evaporated during baking, i.e., mass lost from the initial mass
Massinitial	mass of total composition dry matter and water content
R&D	Research and Development
gms	grams
mV	Milli volts
rpm	Rotations per minute
3D	Three dimensional

Introduction

Biscuit baking is a form of cooking process done in an oven, where heat transforms semi-solid dough spread on trays into eatable biscuits. Initially, moisture is removed, followed by water evaporation, volume increase, development of porous structure and crust texture of biscuits, protein denaturing and starch gelatinization. In the final stage, browning occurs. This study however, focuses solely on the evenness of browning on the top surface of the biscuit.

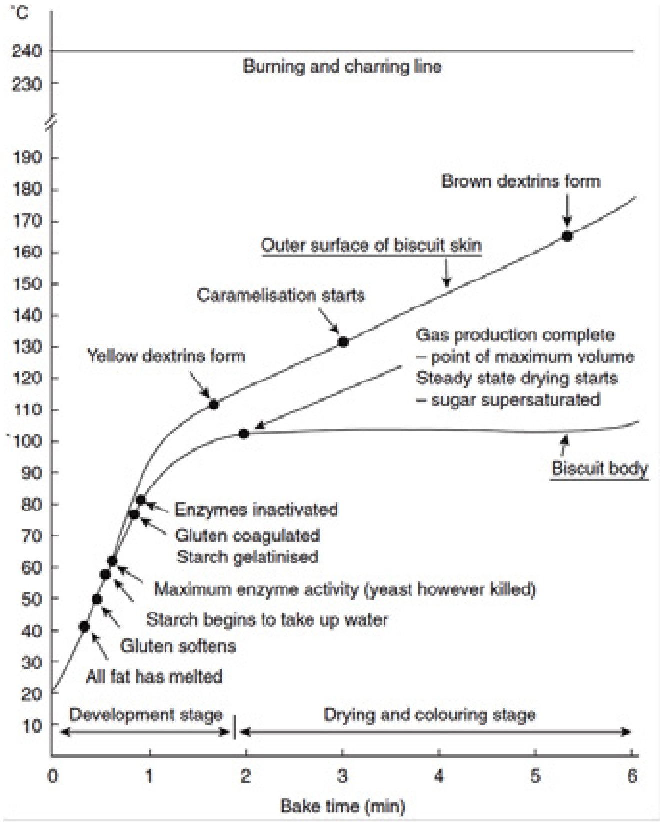

Figure 1: Biscuit baking stages illustration adapted from (Mowbray, 1981) [10].

Biscuit baking can be divided into two main stages: development stage and the drying and coloring stage. During the development stage, the fat in butter biscuits begins to melt and water absorbed by the starch causing the dough to expand. This stage transforms the dough from foam-like structure to a porous one, allowing water vapor to evaporate in the following stage. The drying and coloring stage, which is the longest stage, involves evaporation, browning due to Maillard reactions and caramelization of sugar.

Convection plays a crucial role in heat transfer during biscuit baking. Heat is conducted from the oven to the base of the dough, while convection circulates hot air from the heating element, impacting both the top of the dough pieces and the bottom of the tray metal surface. This process efficiently dries and browns the dough, giving them a brown color.

Business challenges

The surface color is one of the first impressions consumers have of a baked product. During the baking process, biscuits are typically baked at around 180^{0}C and the browning index for each biscuit is measured using Chroma meters after they are removed from the oven. The R&D team dedicates a tremendous amount of time and cost during this testing. However, understanding the hot airflow inside the oven cavity, which contributes to the browning of the biscuits, poses considerable challenges in laboratory testing.

- Food modeling
- Improve browning evenness
- Airflow visualization
- Food temperature prediction

Problem statement

The browning of biscuit crust is influenced by several operational factors, including baking air temperature and baking time, as well as chemical reactions such as the Maillard reaction and sugar caramelization. The primary components of biscuit dough – proteins, carbohydrates, fat and water – serve as the reactants in these reactions, resulting in the formation of acrylamides. Since the surface color is one of the first impressions consumers get of a baked product (Clydesdale 1991), the browning of biscuits is a critical quality parameter [1].

The study aims to conduct an in-house baking test using a domestic oven to track the temperature curve on biscuits and estimate their mass fraction at various time intervals during baking. Additionally, it will determine the thermal properties of biscuits made with selected ingredients and develop a browning function in Computational Fluid Dynamics (CFD) to correlate with the experimental browning index. However, this paper does not examine the evaporation and condensation of moisture, dough expansion, porous texture formation, protein denaturing or starch gelatinization.

Methodology

Lab experiments in baking biscuits: Measurement of temperature on biscuits and operating logs

Lab experiments has been conducted to measure the biscuit's center, mid and bottom temperatures, which will be utilized in CFD to derive thermal properties of selected dough ingredients.

For in-house experimental testing, a domestic cooking range was employed. The oven's 'Convection Bake' function allows the user to set both the preheat or set temperature and cooking time. The minimum circuit size and voltage rating are 40 amps and 240 volts, respectively. The cavity has an internal volume of 5.4 cubic feet. The dough for baking biscuits has been prepared from all the ingredients listed in the table below.

Ingredients	Quantity(gms)
Refined wheat flour	250
Butter(Unsalted)	120
Sugar (Powdered)	80
Egg(whole)	46
Baking Soda (1/2 tablespoon)	5
Salt	1
Lemon	1
Total	503

Table 1 Ingredients for biscuit dough

All the ingredients are mixed in a well-balanced manner and need to be refrigerated for 30 minutes before rolling out. The selection of cavity temperature and baking time depends on the oven's construction and operating mode.

The baking process in a domestic oven consists of three-stage: preheating, loading and cooking. During preheat, the empty cavity is heated to the desired temperature (for biscuits, this can range from 180°C to 300°C). Next, in the loading phase, a tray filled with dough is placed into the cavity at the appropriate rack position. The cooking phase encompass the entire baking time set by the user. In this test, the biscuits are baked for 30 minutes.

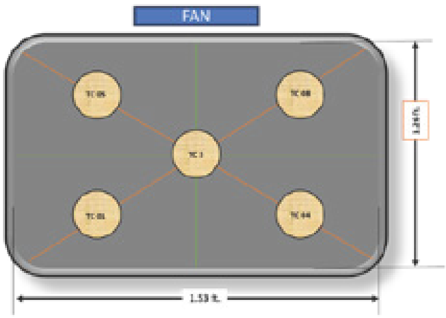

Figure 2: Placement of thermocouples to probe temperature

T-type thermocouples are used to measure the variation of biscuit temperature.

Thermocouples are placed at various locations on the rolled dough to understand the temperature variation during the cooking cycle. This process consumes more time and requires careful handling of the dough. The temperature on the top surface of the dough is monitored in five prominent places in the tray. The dimensions of the tray and the locations of the biscuits placed are shown in figure 3.

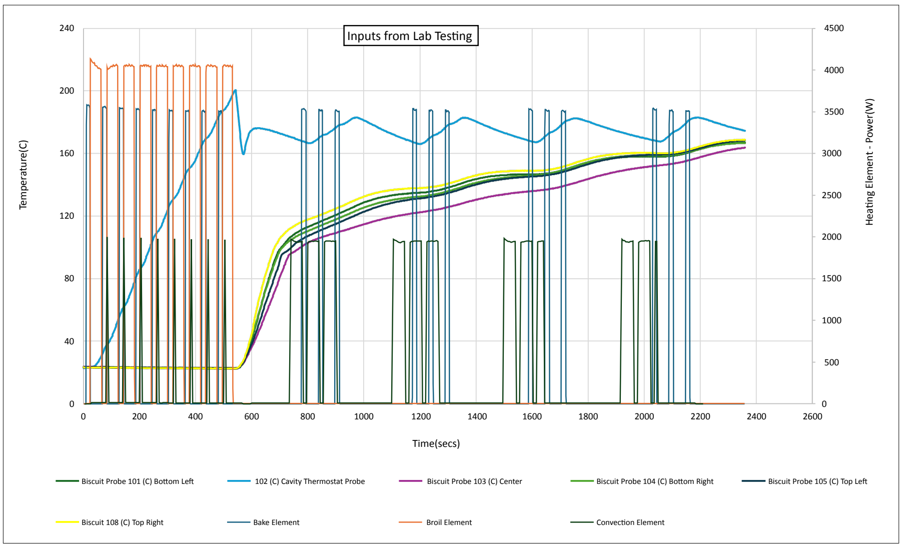

Figure 3: Biscuits temperature curve, Cavity air temperature, Heating cycle – baking cycle.

Thermocouples are wired and connected to a digital data acquisition system that reads temperature data as mV and converts it to temperature values in degrees Celsius. Other than measuring the temperature on biscuits, the convection bake heating element cycle should be measured to implement the same during CFD simulation. This requires measuring the amount of current flowing to the heating elements (bake, broil and convection) during the baking cycle. The current flowing through the heating elements is measured using an ammeter, which has a maximum input capacity of 20 amp and outputs a DC voltage of 5V. This data from the ammeter is fed to the data acquisition system and converted to current. From this data, the Power(W) of heating elements is calculated using the known formula, P =V*I.

Fan speed is measured using a digital tachometer. The fan is fully ON whenever the door is closed. This is verified from the ammeter readings of the fan motor.

Baking cycle	Bake	Convection	Broil	Fan
Preheat	3500W	2000W	4000W	2800rpm
Loading	OFF	OFF	OFF	OFF
Cooking	3500W	2000W	OFF	2800rpm

Table 2 Operating log of convection bake function

Moisture content analysis and effect of parchment paper on Baking

To analyze the total moisture content and density at each timestep within the volume of dough, a moisture analysis was conducted. This test was performed in the same oven using the convection bake function, with a tray placed in the middle rack. The baking time was varied up to 60 minutes to assess the total moisture content in the dough volume. Mass loss at each timestep was considered as the mass of moisture evaporated. When the mass of the volume stabilizes, it indicated that no further moisture remains in the mixture.

CH no	Time in min	Mass in grams	Mass fraction (g/g)	Fraction of moisture loss	Density (kg/m^3)
8.00	0.00	18.97	1.00	0.00	1117.12
8.00	5.00	18.06	0.95	0.05	1063.53
4.00	10.00	17.57	0.93	0.07	1034.68
4.00	15.00	17.05	0.90	0.10	1004.06
4.00	20.00	16.68	0.88	0.12	982.27
4.00	25.00	16.45	0.87	0.13	968.72
4.00	30.00	16.30	0.86	0.14	959.89
4.00	35.00	16.23	0.86	0.14	955.77
4.00	40.00	16.13	0.85	0.15	949.88
4.00	45.00	16.09	0.85	0.15	947.52
4.00	50.00	15.99	0.84	0.16	941.63
4.00	55.00	15.96	0.84	0.16	939.87
4.00	60.00	15.89	0.84	0.16	935.75
4.00	65.00	15.81	0.83	0.17	931.03

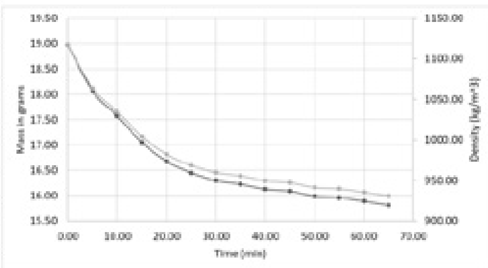

Figure 4: Study of moisture content in biscuit

Hence, the difference between this final mass and the initial mass gives the mass of moisture. The images of biscuits are captured for each time interval to study the variation of lightness. Figure 5 shows the change in color of the biscuit for more than 60 minutes of baking.

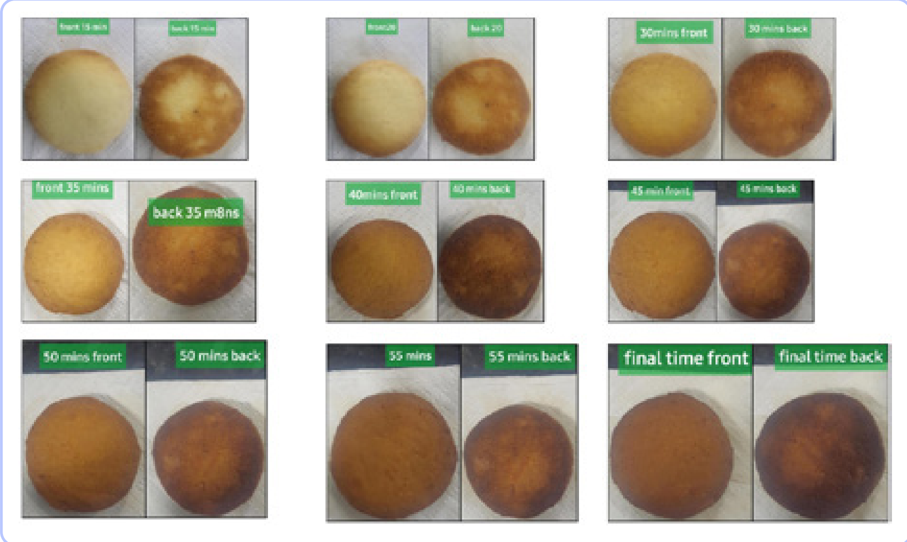

Figure 5: color change of biscuits during 60 mins baking

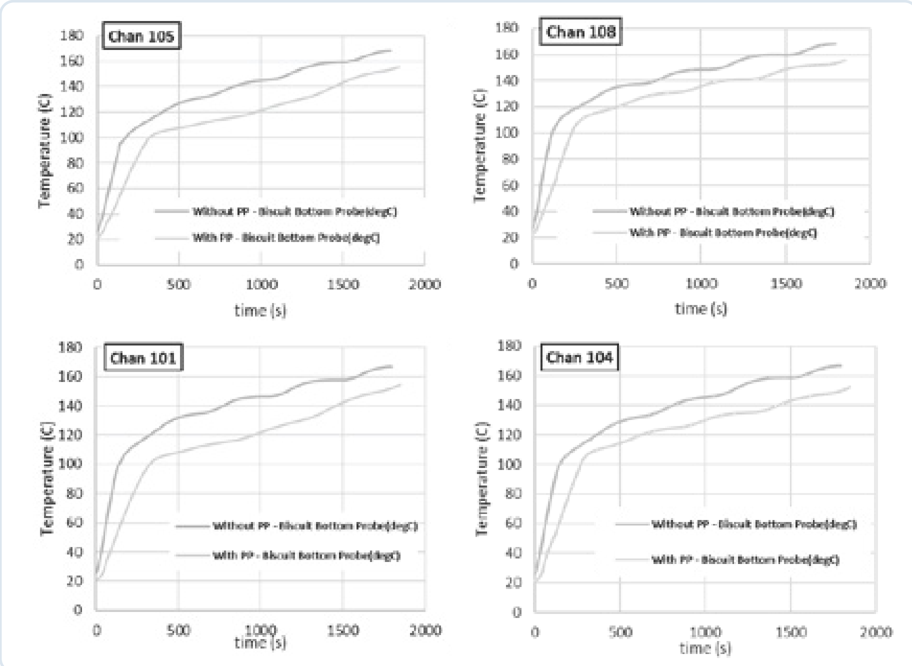

Figure 6: Effect of parchment paper on biscuits bottom temperature

Further, the presence of parchment paper between the biscuit bottom and tray has the effect of temperature distribution on the biscuit, which can be seen from the plots in figure 6. Two tests were conducted (with and without parchment paper) to study the variation of heat distribution on the biscuit's bottom surface. Figure 6 shows the difference observed on the bottom probe during the baking process with and without parchment paper.

Simulation methodology

Heat transfer inside the oven occurs by conduction, convection and radiation. Hence, the conjugate heat transfer model was used for this simulation. STAR-CCM+ tool was used for pre-processing, solving and post-processing the solution, while multipart imprint methodology was used to create interfaces for conjugate heat transfer. Polyhedral mesh was generated for the computational domain with prism layers. The computational mesh size generated is about ~25 million. The k-epsilon turbulence model was used. Moving Reference Frame or MRF model was used for fan rotation at constant speed. The initial solution to the cooking phase was assigned from the final solution of the loading phase using the data mapping method. Cavity heat loss was modeled by assigning convection heat transfer coefficient values of 3 W/m^2K and 5 W/m^2K on the cavity walls and door glass respectively, as door glass is transparent and heat loss will be more than cavity heat insulation.

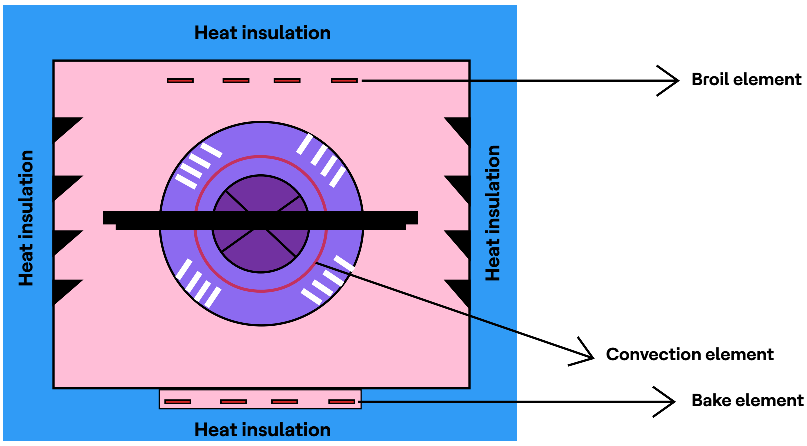

Figure 7 Geometry setup considered in simulation

Thermal properties of biscuits

For the calculation of density, the volume of the biscuit is assumed to be constant. However, in real-time, the volume of biscuits increases due to the expansion of dough at the initial stage. The mass of dough decreases at each timestep due to evaporation. The decrease in mass is the mass of moisture content evaporated. Hence, the density of biscuit dough at any instant is given by

$$\text{Density} = \text{Mass initial} - \text{Mass w, evap} / \text{Volume}$$

The specific heat of the biscuits plays a crucial role in CFD. It is known from the experimental biscuit temperature curve that around 108°C-110°C, the temperature stagnates due to the evaporation of moisture content. To model this stagnation of temperature, specific heat for this temperature range was set to be higher values so that the rise in temperature of the biscuit would be hindered for this temperature range. After this stage (evaporation), the temperature slope is very low as the remains are mostly dry matter of biscuits. To account for this, the slope of the specific heat curve is gradually reduced, as shown in figure 8.

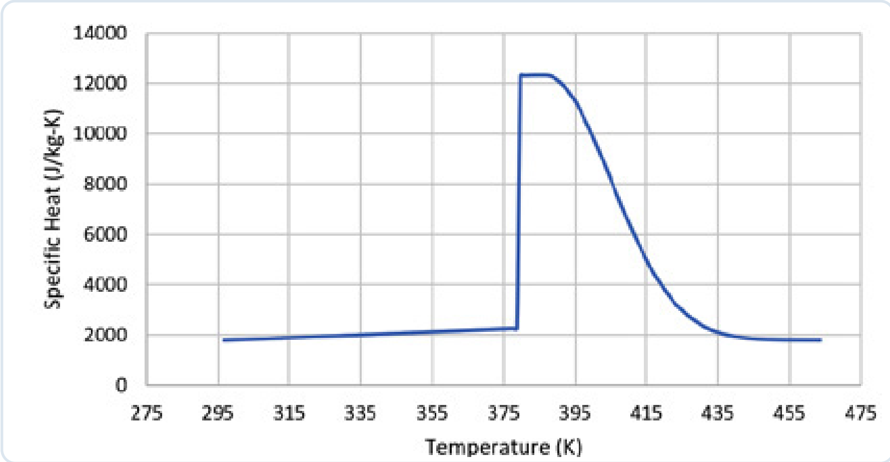

Figure 8: Specific heat curve varying with temperature

The thermal conductivity of obtained ingredients of dough (Table 1) as a function of temperature is empirically obtained as below. Seen from the temperature curve of the center, the biscuit in the experiment almost stagnated between 108 °C and 110 °C. . From Figure 9, it can be observed that the mass fraction(g/g) of dry matter becomes constant after 10 minutes of baking time, which means that the evaporation of moisture content takes place before that. After this stage, most of the moisture content from the biscuit dough would have been evaporated from the dry matter. Hence, thermal conductivity tends to decrease after this stage due to a reduction in moisture content (Figure 9).

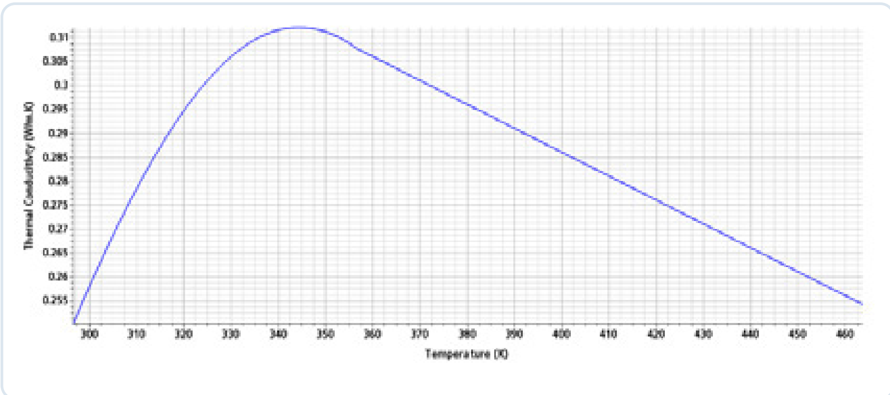

Figure 9: Thermal conductivity curve varying with temperature

Biscuit temperature validation

The biscuits' mid-probe temperatures are validated with CFD results using empirically derived thermal properties. The probe measurements were done during the cooking phase, which was simulated for 30 mins physical time with a one sec time step. Probe monitors were created at the centroid of the biscuit region. In experimental testing, thermocouple probes were inserted into the dough from the sides to position its tip at the center of the dough. From Figure 10, it can be seen that the temperature curve of biscuits from the CFD simulation matches with the experimental temperature curve. The stagnation temperature at mid of the biscuit is attained in CFD simulation by obtaining a specific heat curve.

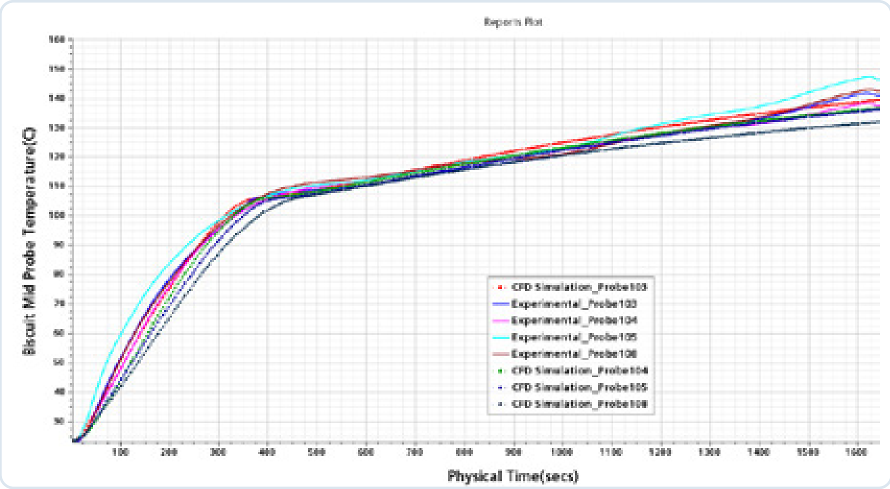

Figure 10: Validation of biscuit center temperatures with experimental data

Browning evenness

CFD browning evaluation – Temperature time integral function:

- Browning is influenced by both biscuit's temperature and baking time.
- The time integral report of monitored surface temperature provides a stronger correlation with the browning index.
- It is essential to monitor the average temperature of the top surface biscuits during the cooking phase.
- A monitor integral report integrates the input monitor (integrand) over another monitor (variable). This can be achieved using overall N samples or the most recent N samples. It is recommended that both the integrand and variable data be collected at the same frequencies. In this study, the integral monitoring report of temperature over physical time was recorded for all N samples.

Plots in figures 11 and 12 show that the trend between the experimental browning index and simulation temperature time integral predictions are in good agreement.

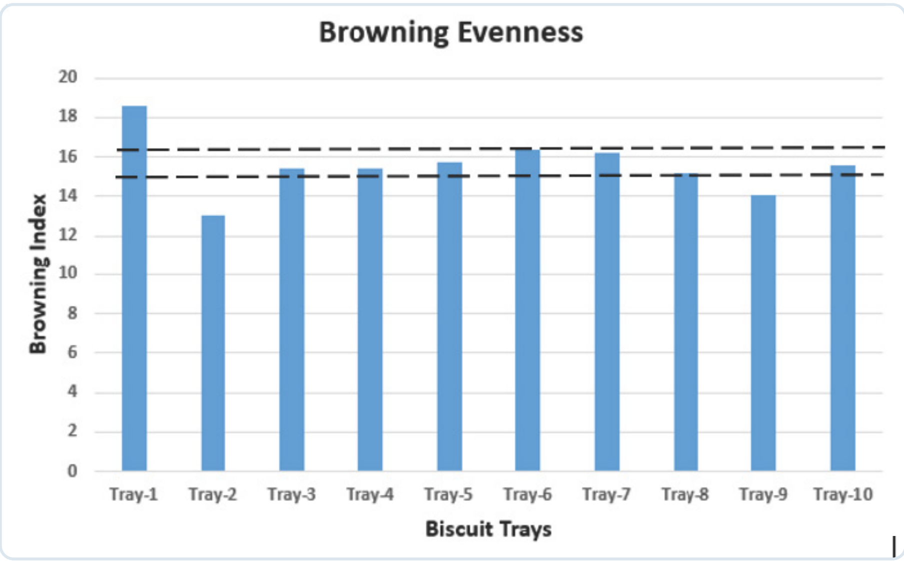

Figure 11: Browning evenness data of multiple trays – Experimental

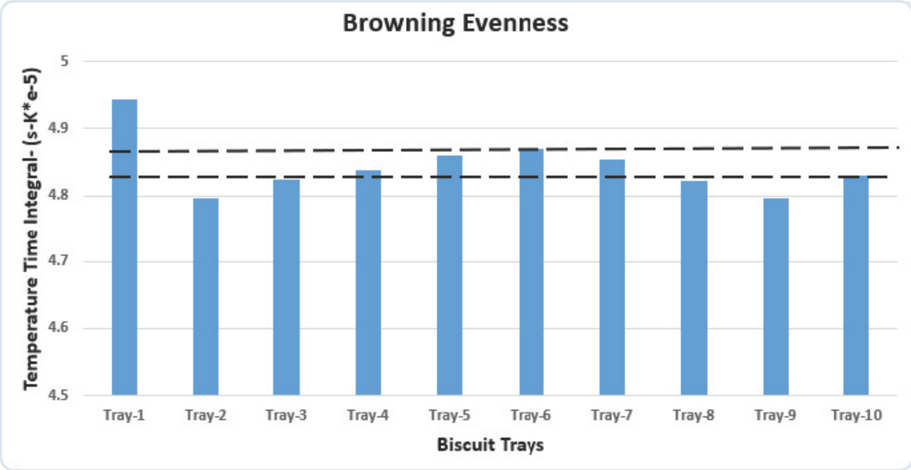

Figure 12: Browning evenness data of multiple trays – Simulation

Benefits

- CFD simulations were performed to predict the biscuit temperature and were validated against experimental data, enhancing browning evenness through various design iterations.
- 3D airflow streamlines provide a clearer visualization of airflow within the oven cavity, helping to identify areas of low airflow and facilitating appropriate design modifications to improve airflow.
- By implementing the solution derived from CFD studies, achievement of the browning target in a shorter time frame can reduce cooking duration, which in turn saves energy consumption, minimizes water usage for steam generation and results in operational cost savings for consumers.

Hence, sustainable solutions for problems in consumer products can be found through CFD simulations.

Conclusion

The comparison between CFD simulation and experimental data demonstrates that CFD is effective in predicting the temperature and browning evenness in baked goods by determining their thermal properties. These thermal properties can be empirically derived using experimental temperature curve data, reinforcing the value of CFD in the bakery industry.

CFD simulation made it feasible to visualize the hot airflow inside the cavity in a convection. Multiple design changes for improving airflow around biscuit dough can be made through CFD model and cooking evenness can be optimized in a quick turnaround time.

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Mathiyalagan V

Mathiyalagan is working in HCLTech since 2016. He has close to 9.5 years of industry experience in the CFD domain. He has a Bachelor's in Aeronautical Engineering from Anna University, Chennai, with a specialization in aerodynamics. He has handled a wide variety of industrial problems involving conjugate heat transfer, multiphase simulations, food modeling, external aerodynamics, internal flows, etc. At HCLTech, he is a part of the MCOE CFD and thermal team, working across verticals such as industrial, consumer products, medical devices, etc.

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Vipin joined HCLTech in 2023 and has over a year of industrial experience in the CFD domain. He holds a bachelor's degree in Aeronautical Engineering from the Aeronautical Society of India and a master's degree from IIT Madras. He has worked on various academic projects, including marine propeller wake characteristics and noise analysis, external aerodynamics of warships and generic aircraft carriers and multiphase simulations of ship motion to estimate engine installed power. Moreover, he has addressed numerous industrial problems related to thermal and airflow analysis of different oven cavities. At HCLTech, he is part of the MCOE CFD and Thermal team, working across sectors such as industrial and consumer products.

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