Optimization of Heat Transfer in Cassava Flour based Cake Baking: A Computational Fluid Dynamics Approach

DIANA NEKESA, REBECCA M NALULE, ANNET KYOMUHANGI, ASAPH K MUHUMUZA,
ANSELM O OYEM*
Department of Mathematics,
Busitema University,
P.O. Box 236, Tororo,
UGANDA

Corresponding Author

Abstract: - Cassava flour cake baking entails changes in temperature, moisture content, and volume, which are closely linked aspects in the heat and mass transfer phenomena that take place during the baking process. This process of baking is often faced with challenges related to texture and structure. Computational Fluid Dynamics is therefore utilized in this study to determine the temperature and moisture content profiles during cake baking using cassava flour in dough preparation. A mathematical model was applied in the baking process and solved using the CFD technique employing the Finite Element Method (FEM) to optimize baking conditions, that is baking temperature, time, and moisture content. Using COMSOL Multiphysics software (version 6.2), simulation results showed that as the oven temperature and temperature within the dough increase, moisture content reduces. Additionally, results also reveal that the temperature distribution within the dough increases with baking time. Moreover, simulated results conquered those in different studies on baking using wheat flour. Based on the findings, we recommend the adoption of CFD simulations in standardizing cassava cake baking and integrating value-added ingredients for improved nutritional value to give cassava a much bigger market value.

Key-Words: - Cassava flour, Cake Baking, CFD, Multiphase Flow, FEM, Pasteurization, Drying.

Received: June 9, 2024. Revised: September 14, 2024. Accepted: November 15, 2024. Published: December 31, 2024.

1 Introduction

Food processing plays a crucial role in transforming agricultural products into safe, nutritious, and market-ready items. Defined as the series of mechanical or chemical processes applied to food, it encompasses methods such as pasteurization, drying, and freezing, [1], [2], [3]. However, the complexities involved in food processing, particularly regarding fluid dynamics, present significant challenges of which many traditional methods lack efficiencies and may not fully address the nutritional needs of consumers. One promising area of innovation is the use of cassava flour in cake baking. Cassava, a staple food in many regions, can be processed into high-quality flour that serves as a versatile ingredient in various baked goods. The baking process involves some chemical, biochemical, and physical changes in the interaction of ingredients, thermophysical properties, and moisture content inducing the final quality of the product. To further bring the process of baking to the fore, requires developing a mathematical model to handle all aspects similarly, by the concept of computational fluid dynamics (CFD), several researchers have looked into the convective heat and mass transfer processes, and possible optimized techniques to improve product quality and safety, [4], [5].

[6], consider the relationship between temperature, moisture content, and volume expansion in bread baking, heat transport, and change in volume. Their results revealed that temperature increases with a decrease in moisture content, and as baking time increases, the temperature within the dough also increases accordingly. Similarly, as the baking temperature increases, the baked bread volume also decreases.

Heat and mass transfer in industrial biscuit baking ovens was carried out by, [7], concentrating on the effect of temperature and baking time. From the findings, the main medium of heat transfer was radiation (69%) in the baking process, while convection and conduction were 28% and 3% respectively with, the baking time directly dependent on the baking chamber temperature. The result further suggested that an increase in the baking chamber temperature tends to reduce the baking time required for the desired moisture content of the final product. Summarily, there is a relationship between heat transfer mechanisms, oven temperature, and baking time and this knowledge can be tapped into for improved efficiency and optimization of the production process.

Several researchers have considered the application of CFD to quality control through profiling the temperature and moisture content in baked products, [8], [9], [10]. These researchers identified temperature as the core of the baking process, making it the key determinant in the quality and value of the final product. The CFD model demonstrated effectiveness in predicting; the temperature of the crumb and crust based on heat transfer principles, validating the model's accuracy by measuring the heat and mass transfer profiles of the baked products. This paper, therefore, considers the application of CFD in the cake baking process, using cassava flour, and the thermophysical effects in addressing the various industrial challenges of today, and how to optimize them.

2 Problem Formulation

A two-dimensional steady, incompressible convective heat and mass transfer fluid flow on cassava cake using baking flour was considered, taking into review, temperature change and moisture content effects on the thermophysical properties using CFD techniques (Figure 1). The mathematical model under consideration is resolved using COMSOL Multiphysics software, version 6.2 (covering the geometry and domain configuration) with Finite Element Method (FEM) where cassava dough (which is the domain) is discretized into triangular computational mesh with initial and boundary conditions.

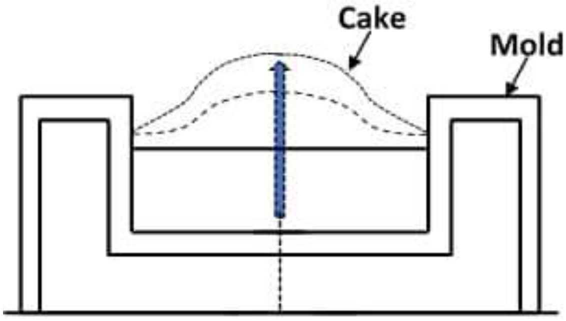

Fig. 1: Geometry of the Baking Process

2.1 Mesh Generation

The flow fluid behavior is represented in the computational space using a mesh diagram (Figure 2) and this is vital to this concept, [11]. After the meshing process is completed, the next step is solving the governing equations of fluid flow within individual mesh elements using numerical techniques, [12]. Meshing and numerical solving are interdependent in a way that the characteristics of the grid structure generated have an effect on the accuracy and stability of the numerical solution obtained, [13].

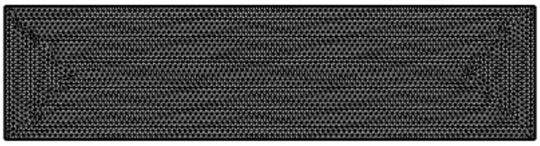

Fig. 2: Mesh diagram of the geometry

2.2 Governing Equations

The governing equations of the flow field for moisture content, mass conservation of carbon dioxide, conservation of energy, porosity, and predicting swelling (visco-elastic model) are given as

$$\rho_s\left(\frac{\partial w}{\partial t} + \nabla.(v_s\, w)\right) = -\nabla.\left(D_v^T + D_v^T\,\Delta T + D_v^W\,\Delta w + D_v^p\,\Delta p\right), \quad (1)$$

$$\frac{\partial \rho_c}{\partial t} + \nabla.(\rho_c v_s) = -\nabla.n_c + G_c\,, \quad (2)$$

$$\rho c_p \frac{\partial T}{\partial t} + \nabla.\left(\rho c_p v_s T\right) = -\nabla.(k\nabla T) - kL_v\,, \quad (3)$$

$$-\rho_s \frac{\partial \varepsilon}{\partial t} + \nabla\cdot(v_s\,(1-\varepsilon)\rho_s) = 0\,, \quad (4)$$

$$\nabla\cdot\sigma = \nabla p. \quad (5)$$

where, ρ_s is the density of the solid dough, w is the moisture content, v_s is the deformation velocity, p is pressure, ρ_c is the density of carbondioxide, n_c is the species flow, G_c is the generation rate, ρ is the density of the dough, c_p is the specific heat capacity, T is the temperature, t is time, k is phase change rate, L_v is the latent heat of vaporization, and ε is the porosity.

2.3 Initial and Boundary Conditions

Initial conditions and boundary conditions in CFD are key parameters which state the starting state of a system and constraints at the boundaries of the domain for accurate simulations.

2.3.1 Initial Conditions

Initial temperature, $T_0 = 293K$,

Initial moisture content is $0.68\ kgkg^{-1}$.

2.3.2 Boundary Conditions

For the moisture content equation, air/dough interface, water evaporation takes place at the surface of the cake. So, m_w is based on the difference between the partial vapor pressure between the surface of the cake and that of the hot air.

$$-n(n_{l+}\, n_v) = M\frac{k_m}{R}\left(\frac{p_{v,surf}}{T} - \frac{p_{v,\infty}}{T_\infty}\right) = m_w. \quad (6)$$

where, p_v is the vapour pressure (p_a), k_m is the mass transfer coefficient (ms^{-1}) and m_w is the water evaporation rate $(kgm^{-2}s^{-1})$.

For mold and dough interface, in this case, zero mass flux condition is put into account such that:

$$-n(n_{l+}\, n_v) = 0 \quad (7)$$

For energy equation, the air/dough interface heat is transferred to the cake surface by convection and radiation and balanced by conduction such that:

$$-K\nabla T = h(T_\infty - T) + \varepsilon\delta(T_{oven}^4 - T^4) - n_l L_v \quad (8)$$

while the Mold/dough interface is:

$$-n\left(-k_{eff}\,\nabla T\right) = -n(-k_{mold}\,\nabla T_{mold}) = T_{mold} \quad (9)$$

For the gas pressure equation, the total gas pressure is assumed to be constant and equal to atmospheric pressure such that:

$$p_g = p_{atm} \quad (10)$$

and the visco-elastic model is

$$\sigma = 0 \quad (11)$$

$$-n(v_s \rho_s) = 0 \quad (12)$$

3 Problem Solution

3.1 Temperature Profiles

During the baking process, the temperature distribution within the dough keeps on varying with baking time. This study illustrates time, $t = 0$, $t = 15$, $t = 30$ and $t = 45$ minutes respectively. As more heat is dissipated in the baking chamber, the temperature inside the dough begins rising, [14]. This is also shown by the temperature contours at times $t = 0$, $t = 15$, $t = 30$ and $t = 45$ minutes respectively in Figure 3(a – d).

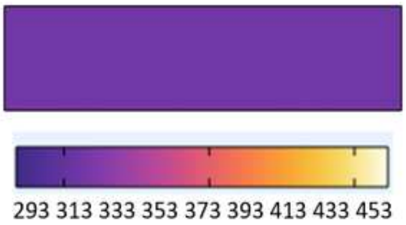

Fig. 3(a) Temperature profile at $t = 0$ mins

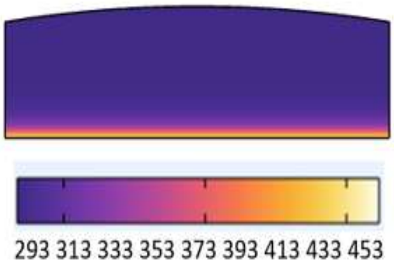

Fig. 3(b): Temperature profile at $t = 15$ mins

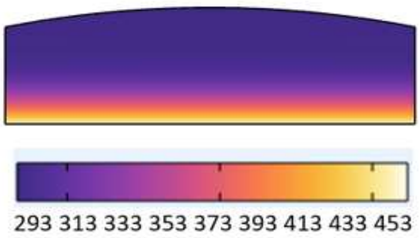

Fig. 3(c): Temperature profile at $t = 30$ mins

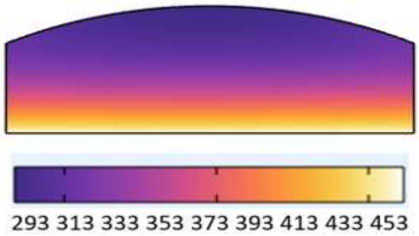

Fig. 3(d): Temperature profile for $t = 45$ mins

From Figure 3, initially, at $t = 0$ minutes, there was a uniform temperature distribution throughout the dough which is shown by the solid purple color. This is because the dough has not yet been subjected to any source of heat. After 15 minutes, there was an increase in the temperature of the dough which came as a result of heat supply from the oven or any other heat source. As temperature increases, a series of processes like gelatinization of starch, denaturation of proteins, leavening, and moisture evaporation begin to take place, which is in agreement with the results obtained in [6]. At $t = 30$ minutes, the temperature is higher since it increases with time, implying a faster rate at which the physical and chemical processes occur during the baking process. This reflects a higher rate of moisture evaporation, protein coagulation, and production of carbon dioxide which causes volume expansion. Between $t = 30$ minutes and $t = 45$ minutes, the temperature increases, which means that there is more moisture loss, and a faster rate of leavening which brings about more carbon dioxide production which causes dough expansion. Beyond $t = 45$ minutes, there is no more cake expansion implying that increasing baking time and temperature will affect the end product since all the baking stages have already been completed. Close to the end of the baking process, the surface of the dough is subjected to intense heat of the oven leading to the formation of a crust. The crust formed hinders moisture loss. In other words, at this stage, moisture is closed in the cake. In Figure 4, as baking time increases, it implies that there is still more heat supplied from the oven causing the temperature within the dough to also increase, [6], [15], [16].

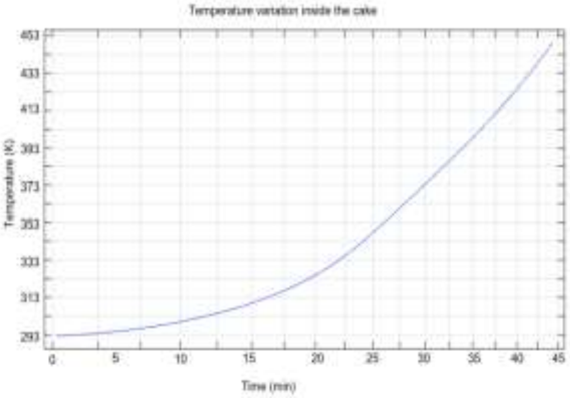

Fig. 4: Temperature profile against time

The graph above shows that temperature increases with time. It also indicates no fluctuations in temperature which shows that cake baking is uniform. The gradual increase in temperature reflects a gradual change of the dough into a baked cake. In general, the graph provides vital information on how the cake responds to heat during the baking process showing the usefulness of temperature control in order to achieve a quality cake. Temperature is a key element in the baking process since it influences different physiochemical changes that are the basis of the final texture, flavor and structure of any baked product.

3.2 Moisture Content Profiles

The moisture content scales in ascending order across the gradient as shown in Figure 5(a–d) by the color changes from blue to red (red indicates a higher moisture content while blue indicates a lower moisture content level). As the color gradient transitions from blue to red, it shows an increase in a temperature gradient. The middle colors like cyan, green, yellow, and orange reflect varying levels of moisture content as temperature changes.

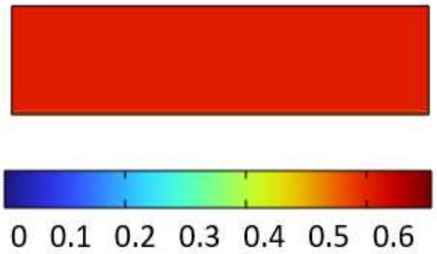

Fig. 5(a): Moisture content profile at $t = 0$ mins

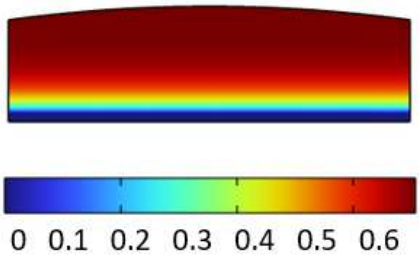

Fig. 5(b): Moisture content profile at $t = 15$ mins

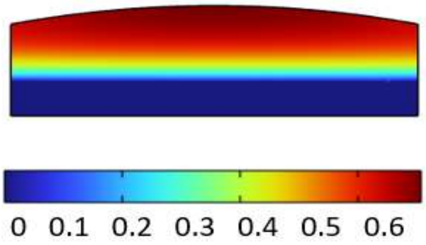

Fig. 5(c): Moisture content profile at $t = 30$ mins

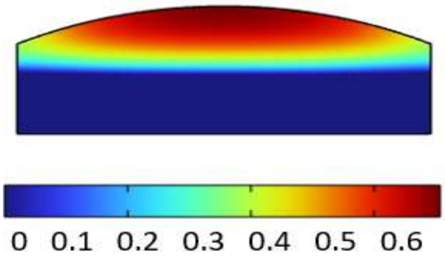

Fig. 5(d): Moisture content profile at $t = 45$ mins

At $(\mathrm{t} = 0 \text{ mins})$, the red colour alone is spread throughout the structure of the dough. This is because the dough is not yet subjected to any heat source. It means that the moisture content is the same throughout the dough. For $(\mathrm{t} = 15 \text{ mins})$, there is a reduction in the moisture content which is seen at the bottom (blue color) as a result of heat being applied during the baking process, more moisture content moves at the top (red color). There is also evidence of cake expansion in height. When

$\text{t} = 30\,\text{mins}$, it is evident that as baking time increases, the moisture content within the cake reduces. At this time, there is a more reduction in the moisture content level as compared to the previous times and a higher expansion of the cake in height. After $\text{t} = 45\,\text{mins}$, the moisture content is so low (reflected by a minimal red color as compared to other colors). The blue color dominates at this time implying there is a more reduced moisture content level. According to [6], and [16], their studies also portrayed that as baking time increases, the moisture content within the dough reduces.

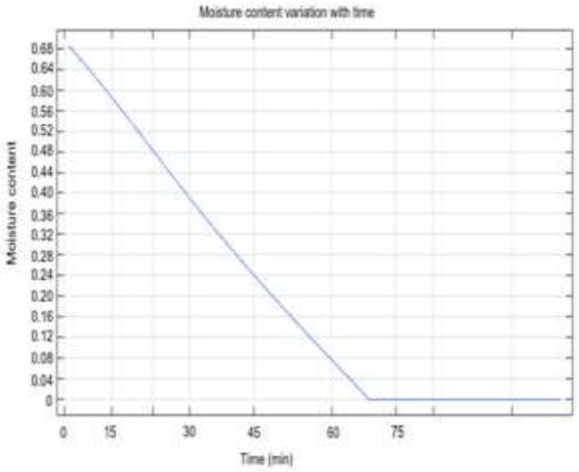

Fig. 6: Moisture content profile against time

Figure 6 shows the variation of moisture with time. It reflects a decreasing trend with time. Initially, the moisture content level was close to 0.68kgkg^{-1} but as time goes on, it constantly reduced to 0kgkg^{-1} after 60 minutes. Figure 7 shows the expansion in height of a cassava cake overtime during the baking process.

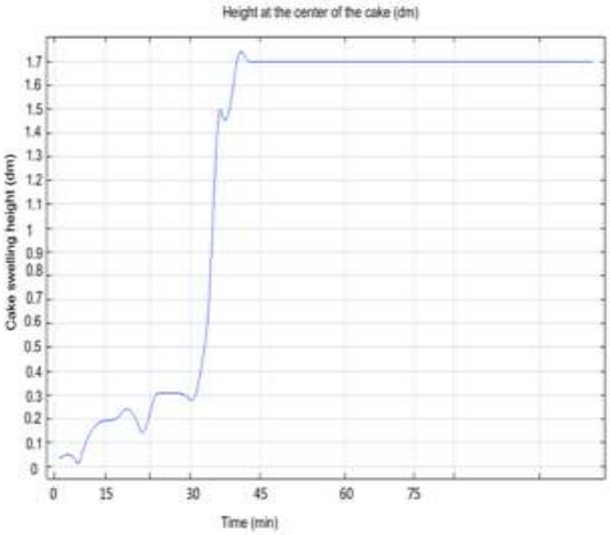

Fig. 7: Cake Swelling profile against time

Figure 7, indicates a gradual but (fluctuating) rise and fall in the height of the cake at the start because of the period when the yeast activation is still low, which is in relation with [6]. This is followed by a steeper incline shortly after 30 minutes to close to 45 minutes, reaching a peak slightly above 1.7dm. The levels indicate a constant height of the cake swelling until the end of the observation period. Initially, the increase in the height of the cake (expansion) is slow because, at this stage, the dough has just been subjected to heat implying that the physio-chemical reactions responsible for the swelling are also taking place at a relatively lower rate. The later on steeper incline shows a faster increase in the size of the cake which is caused by the higher rate at which the chemical and physical processes take place at this stage. This is due to higher activation of the leavening agents like baking powder, and the release of carbon dioxide which expands the cake batter, among others. When the cake reaches its maximum height, it then slightly drops back to a height of 1.7dm and remains constant throughout.

A similar occurrence was portrayed in, [16], which showed a maximum height of 26mm at an approximate of 16inutes after which the height of the cake remained constant. A large diffusivity also causes a faster loss in moisture content hence resulting in an increased cake expansion, [6].

4 Conclusion

A study into the cake-baking process, incorporating heat and mass transfer together with volume expansion has been considered. To obtain a solution to the governing equations (1) – (4) subject to the initial and boundary conditions (6) – (12), a CFD technique together with Finite Element Method (FEM) was employed and implemented using COMSOL Multiphysics software (version 6.2). The following conclusions were obtained:

1. At an interval of 15 minutes for 45 minutes showed an increase in temperature and a constant reduction in moisture content within the dough as baking progressed. It is also observed that shortly after 45 minutes, the cake's height stabilized.
2. The findings show the effectiveness of CFD in optimizing the key baking parameters such as; temperature, baking time, and moisture content hence improving the quality of the final product. This research highlights the significance of adopting innovative technologies like CFD

3. Also, the sustainable use of cassava flour in the baking process not only boosts its market value but also contributes to the stability of the food sector. In summary, integrating CFD into food value addition presents a promising avenue for enhancing product quality.

References:

[1] Therdthai N., Zhou W., Adamczak, T., Three-dimensional cfd modelling and simulation of the temperature profiles and airflow patterns during a continuous industrial baking process, *Journal of Food Engineering*, Vol.65, No.4, 2004, pp. 599–608, https://doi.org/10.1016/j.jfoodeng.2004.02.026.

[2] Anandharamakrishnan C., Anandharamakrishnan C., *Computational fluid dynamics applications in food processing*, Springer, 2013.

[3] Susan N., Awichi R.O., Kadedesya S., Oyem AO., Application of computational fluid dynamics in simulation and optimization of a fluidized sugar bed dryer, *WSEAS Transaction on Fluid Mechanics*, Vol.18, No.25, 2023, pp. 286-295, https://doi:10.37394/232012.2023.18.25.

[4] Scott G., Richardson P., The application of computational fluid dynamics in the food industry, *Trends in Food Science and Technology*, Vol.8, No.4, 1997, pp. 119–124. https://doi.org/10.1016/S0924-2244(97)01028-5.

[5] Xia B, Sun D.W., Applications of computational fluid dynamics (cfd) in the food industry: a review, *Computers and Electronics in Agriculture*, Vol.34, No.1, 2002, pp. 5–24. http://dx.doi.org/10.1016/S0168-1699(01)00177-6.

[6] Zhang J., Datta A., Mathematical modeling of bread baking process, *Journal of Food Engineering*, Vol.75, No.1, 2006, pp. 78–89. https://doi.org/10.1016/j.jfoodeng.2005.03.058.

[7] Akbari K.R., Heat and mass transfer in industrial biscuit baking oven and effect of temperature on baking time, *Journal of Heat and Mass Transfer Research*, Vol.2, No.2, 2015, pp. 79–90. https://doi.org/10.22075/jhmtr.2015.343.

[8] Chakraborty S., Dash K.K., A comprehensive review on heat and mass transfer simulation and measurement module during the baking process, *Applied Food Research*, Vol.3, No.1, 2023, 100270. https://doi.org/10.1016/j.afres.2023.100270.

[9] Narayansing C., Anishaparvin A., Indrani D., Ksms R., Anandharamakrishnan C., Computational fluid dynamics (CFD) modeling of an electrical heating oven for bread-baking process, *Journal of Food Engineering*, Vol.100, No.3, 2010, pp. 452-460, https://doi.org/10.1016/j.jfoodeng.2010.04.030.

[10] Salish K., Pushpadass H.A., Magdaline E.E.F., Hrishikesh M., Sivaram M., Bikash C.G., Three-dimensional computational fluid dynamics modeling of baking of *chhana podo* (milk cake), *Journal of Food Process Engineering*, Vol.44, No.1, 2020, e13587, https://doi.org/10.1111/jfpe.13587.

[11] Lintermann A., Computational meshing for cfd simulations. In: Inthavong, K., Sing, N., Wong, E., Tu, J. (eds) Clinical and biomedical engineering in the human nose, *Biological and Medical Physics, Biomedical Engineering*, Springer, Singapore, 2020, pp. 85-115, https://dx.doi.org/10.1007/978-981-15-6716-26.

[12] Tank A, Chhanwal N., Indrani D., Anandharamakrishnan C., Computational fluid dynamics modeling of bun baking process under different oven load conditions, *Journal of Food Science and Technology*, Vol.51, No.9, 2014, pp. 2030–2037, https://doi.org/10.1007/s13197-012-0736-6.

[13] Sharma, A., *Introduction to computational fluid dynamics: development, application and analysis*, Springer Nature, 2021.

[14] Cevoli, C., Panarese V., Catalogne C., Fabbri A., Estimation of the effective moisture diffusivity in cake baking by the inversion of a finite element model, *Journal of Food Engineering*, Vol.270, 2020, 109769. https://doi.org/10.1016/j.jfoodeng.2019.109769.

[15] Bideau P.L., Cutte R., Glouannec P., Page J.F., *Numerical model for predicting heat and mass transfer phenomena during cake baking*, Engineering Materials Science, 2016

[16] Al-Nasser M.H., Fayssal I., Moukalled F., Numerical simulation of bread baking in a convection oven, *Applied Thermal Engineering*, Vol.184, No.1, 2020, 116252. http://dx.doi.org/10.1016/j.applthermaleng.2020.116252.

Contribution of Individual Authors to the Creation of a Scientific Article (Ghostwriting Policy)

- Diana Nekesa is the first author and carried out the simulation and the optimization.
- Rebecca Muhumuza Nalule is the Senior author.
- Annet Kyomuhangi organized and executed Section 4 and contributed to the build-up of the manuscript.
- Asaph Keikara Muhumuza was responsible for compiling the article.
- Anselm Oyem is the corresponding author and formatted the manuscript to the required standard.

Sources of Funding for Research Presented in a Scientific Article or Scientific Article Itself
No funding was received for conducting this study.

Conflict of Interest

The authors have no conflicts of interest to declare.