NUMERICAL SIMULATION OF FOOD CONVECTION HEATING PROCESS

Lappeenranta–Lahti University of Technology LUT

Bachelor's thesis

2024

Yifan Zhao

Examiners: D.Sc.(Tech.) Liyao Xie

D.Sc.(Tech.) Markku Nikku

ABSTRACT

Lappeenranta–Lahti University of Technology LUT

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In co-operation with partner university: Hebei University of Technology(Hebut)

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In some cities or regions with a faster pace of life, prepared foods have become a choice for many office workers and students. Such foods usually only need to be heated in a microwave or oven after purchase before they are ready to eat. The heating method for this type of food is usually air convection heating. However, temperature control is very important for cooking. If the temperature is too low, the cooking time will be prolonged or the food will not be cooked. If the temperature is too high, the surface of the food will be burnt. In addition, there is a difference in the rate at which the inside and outside of the food heat up during the cooking process, and this difference has a significant impact on the quality and taste of the food. In order to solve related problems, this thesis takes cylindrical chicken patties as an example and uses the COMSOL software numerical simulation method to simulate the transient temperature and moisture concentration distribution of cylindrical chicken patties at different temperatures during the convection heating process of an air fryer. This study found that changing different heating temperatures does affect the efficiency of convective heat transfer and the diffusion of moisture, and restricts the heating process to a certain extent. Therefore, in actual production, repeated trials and continuous optimization are required to find the best heating method.

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Four years have passed by. LUT and HEBUT have accompanied me through my four-year bachelor's degree career, and I have learned the professional knowledge imparted by the teachers. Graduation is not only the end of one stage, but also the beginning of another. I am proud of LUT and HEBUT. In the future of my life, I will cherish and be grateful for the time I spent in school, live up to the professional knowledge taught by teachers, apply what I have learned, and create value for society with my own practical actions.

SYMBOLS AND ABBREVIATIONS

Roman characters

M	molecular weight	kg/mol
C	specific volume water	m^3/kg
T	temperature	ºC, K
D	diffusion coefficient	m^2/s
H	moore's latent heat	J/mol
Q	heat	J
J	the molar flux density	$mol/(m^2 \cdot s)$
q	density of heat flow rate	W/m^2
k	hygroscopicity	$kg/(m \cdot s)$
h	heat transfer coefficient	$W/(m^2 \cdot K)$
c	moisture concentration	mol/m^3

Greek characters

ρ	density	kg/m^3

Constants

g	gravitational acceleration	9.81 m/s

Subscripts

0	initial
a	substance a
p	chicken patty
air	air condition
vap	evaporation
ted	total heat flux

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1 Introduction

Due to the faster pace of life, more and more people are choosing prepared foods that can be cooked simply by heating them in the oven or microwave. However, even if the cooking method is relatively simple and quick, undercooking or burning the food will affect people's appetite, taste and health. This is usually due to a problem with the cooking temperature settings. Taking eggs as an example, the method of making hot spring eggs is to put the eggs in hot water at a constant 80°C. The yolks of the eggs will be cooked, but the egg whites will still be raw. And if eggs are cooked quickly in overheated boiling water, the egg white will be cooked but the yolk will not be cooked, which is called a runny egg. From this we can see that the cooking results will vary greatly depending on the baking temperature. Research on food convection heating will optimize the heating function of cooking appliances such as ovens, which will have certain advantages for the development of food cooking in the future.(Hong Yuan, 2017)

1.1 Research background and meaning

In the modern food industry and home cooking, convection heating technology is widely used to heat food quickly and efficiently. In food preparation, convection heating is valued for its ability to provide even and rapid heating. As consumers have higher and higher requirements for food quality and cooking efficiency, the study of food heating processes has become particularly important. Especially when cooking food in an air fryer, how to achieve efficient heating while ensuring the taste and nutrition of the food has become a topic worth discussing. In addition, the heat and mass transfer mechanism during the heating process of the air fryer, the temperature distribution inside the food, and the diffusion and evaporation of water have a decisive impact on the heating effect of the food. Therefore, using simulation methods to study the food convection heating process can not only reveal the intrinsic mechanisms of these complex phenomena, but also provide theoretical support for the optimization of the food heating process.(Haochao Lin, 2016)

This thesis will discuss the heating principle of the air fryer, the calculation process of convective heating, and the concept of numerical simulation in the convective heating process of the air fryer, and will list the process and results of the numerical simulation.

1.2 Research content of this thesis.

This thesis aims to explore the heating process of meat patties in a convection oven through numerical simulation design with COMSOL software. This model takes into account factors such as the power consumption of chicken patties, and uses numerical simulation to find the optimal solution to improve the quality of the patties.

Temperature and moisture concentration are extremely critical factors in the process of heating meat patties. Therefore, this model uses the coupling of two transient interfaces to describe the changes of these two variables. In this way, we can more accurately simulate the heating process of meat patties and further explore the changes in temperature and moisture concentration during the heating process.The main research contents include:

In the study of the taste of chicken patties, the model coupled the two physical fields of dilute matter transfer and solid heat transfer, established a system of moisture concentration and temperature of cylindrical chicken patties, and analyzed the distribution of temperature and moisture concentration in convection cooking.

2 Theory related to air fryer convection heating

In this section, we describe in detail several rationale aspects of this study. This includes air fryer heating principles and convection cooking principles.

2.1 The working principle of air fryer

The air fryer is an innovative small kitchen appliance that uses hot air as the cooking medium instead of traditional hot oil. Unlike regular convection ovens, air fryers don’t require oil to produce deep-fried results.The prototype of the equipment originated from the commercial model launched by the American company QNC in the 1990s, while the home version started with the Actifry low-fat fryer launched by the French company Tefal in 2007. In 2010, Philips proposed the concept of air fryer development and introduced it to the global market. Since then, Chinese companies such as Joyoung and Midea have also begun to enter this market, making air fryers receive widespread attention in China.(Yan Jiu, 2022)

Unlike traditional ovens that rely on heating elements to directly heat the oven space, air fryers use advanced rapid air circulation technology. Inside, it combines a heating element and a powerful fan. After the heating element heats up, the fan quickly pushes the air to flow, forming a continuous cycle. This process ensures that hot air flows evenly across the food and heater surfaces, quickly heating up and effectively removing moisture from the food. This efficient airflow inside the air fryer not only delivers heat evenly to every corner of the food, but the radiant energy from its heater penetrates the food deep into its interior. This unique heating method achieves extremely high heat transfer efficiency and can simulate a cooking effect similar to frying.(Qingxin Xue,2022)

The working principle of an air fryer relies on the high-speed rotation of hot air in a closed container to evenly heat food (As shown in Figure 1). Typically, the fan speed of an air fryer is between 200 and 400 rpm. Its design focuses on the combination of efficient air circulation system and heating system. The high-speed airflow generated by the fan circulates inside the fryer to ensure that the food is evenly heated in all directions. This cooking method not only ensures cooking efficiency, but also provides healthier cooking options. (Huafang Chen, 2022)

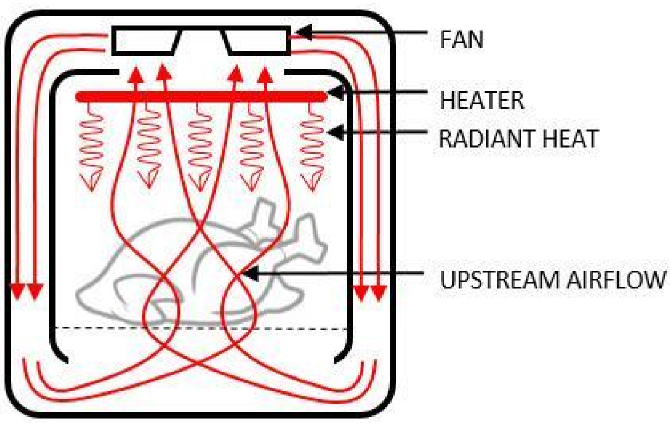

Figure 1. Air fryer heating principle.(Mr.Z, 2023)

The main advantages of air fryers are that they are healthy and affordable. It heats food by circulating hot air at high speed, which not only reduces the use of grease but also makes cleaning easier. Compared with traditional ovens, air fryers use more advanced aerodynamic technology, which can quickly heat and lock the moisture of food, improving the taste of food. In addition, the larger capacity and wider application scenarios make air fryers and their advanced versions, air ovens, gradually favored by consumers. As technology continues to advance, it is expected that air fryers will gradually replace traditional ovens. (Yan Jiu, 2022)

However, when we analyze the heating principle of the air fryer, we can actually analyze it as an oven. We can divide the heating process of the air fryer into three processes.

The first process is the preheating process. When the oven is started, the resistance wire inside it starts to work driven by current, generating heat. This heat heats the air inside the oven through heat exchange between gas and solid. Heat then diffuses inside the oven through the thermal movement of air molecules until the air temperature stabilizes at a set constant temperature T. During this process, when the food is quickly placed in the oven, the energy loss of the system is negligible.

Then is the heating process. When food is placed in the air fryer, the heat in the air is continuously transferred to the periphery of the food through conduction. At the same time, the heat source in the air fryer continues to operate to ensure that the air temperature remains at the set constant temperature T. During this process, various parts of the food are continuously heated, but due to the different shapes of the food, the extent to which it conducts heat will also be different. Taking the corners of rectangular food and polygonal food as examples, the rectangular food shown in Figure 2 and the polygonal corner shown in Figure 3 both show that the edge part of the food is heated faster than the central part. Especially corners heat up faster due to the concentration of heat. The corners have less mass compared to the center portion of the food and are more exposed to the hot air circulating in the air fryer. Therefore, they heat up faster, the same amount of thermal energy is distributed over a smaller area, resulting in more concentrated heat, and direct exposure allows them to absorb heat faster. Additionally, the shape of the corners often results in a higher curvature, which results in more intense heat transfer compared to a flat surface. This increased curvature allows for better contact with hot air, promoting faster heating.These faster heating parts will first reach the required baking temperature and then move on to the next heating stage.(Jing Yao, 2014)

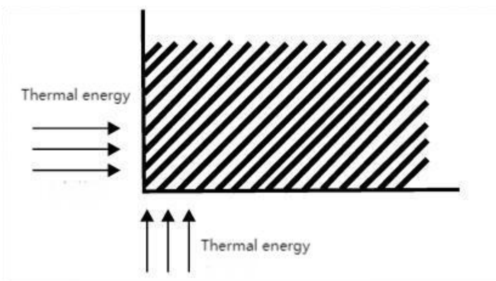

Figure 2. Rectangular food

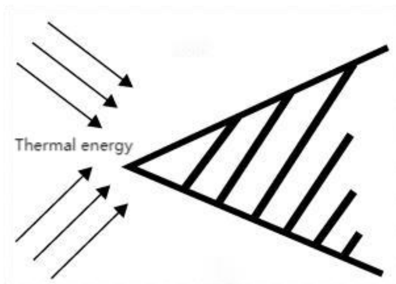

Figure 3. Polygonal food corner

This thesis is about cylindrical pies. The thesis will focus on cylindrical chicken patties, considering they are more common, as shown in Figure 4.

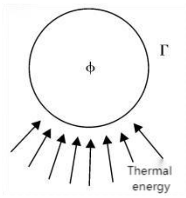

Figure 4. Circular food cross section

Last one is the baking process. When the temperature of every part of the food reaches the set temperature and is equal to the temperature of the air inside the air fryer, the heating process will continue for a period of time. At this stage, although the overall temperature of the food remains stable, the heat absorbed will be mainly used to promote chemical reactions in the food ingredients, thereby enhancing the flavor of the food. This stable heating state will continue until the end of the entire baking process.(Jing Yao, 2014)

2.2 Convection cooking principle

This short chapter will introduce the principles of convection cooking. Among them, it includes an introduction to convective heating and the numerical simulation.

Inside the air fryer, heat transfer occurs mainly through convection and radiation. These two heat transfer mechanisms not only work at the same time, but also the intensity of their action changes at different points in time, resulting in different dominant heat transfer modes. Convection heat transfer mainly involves the heat exchange between the oven wall and the air, and between the air and the food; while radiation heat transfer includes the heat transfer between the wall and the food, and between the heating tube and the food. During the baking process, since the diameter of the heating tube is thin and its surface area is smaller than that of the wall, this part of the radiant heat is usually ignored in calculations. In addition, given that air is mainly composed of oxygen and nitrogen, the radiation and absorption capabilities of these two gases are weak, the air can be regarded as a transparent body, and the radiation heat exchange between it and the wall is not considered.(Jing Wang, 2015)

In the context of air fryer cooking processes, the theories of heat and mass transfer are critical to understanding the drying (desiccation) that is often mentioned in such contexts. The air fryer utilizes the principles of heat transfer primarily through convection, where heated air is circulated around the food, allowing for a uniform cooking environment. This method effectively mimics the effects of deep-frying by cooking the exterior of the food to a crispy texture while keeping the interior moist. (Haochao Lin, 2016)

Mass transfer, particularly moisture removal, is also significant in air fryer cooking. The circulating hot air helps to evaporate moisture from the food's surface, contributing to the crispiness of the food. This evaporation process is a key aspect of drying mentioned in relation to air fryers, as it affects both texture and cooking speed.(Zhidao Du, 2020)

During the heating process of the air fryer, on the one hand, the heating element above the food releases radiant heat; on the other hand, the strong upward airflow through the bottom opening of the cooking chamber generates convective heat. The heat from both heat sources is focused directly on the food. During each stage of the cooking cycle, no excess air flows around the food and all air is directed towards the food, ensuring even distribution of heated air across the base of the food.(Cebeci, 2002)

2.3 Numerical simulation

Numerical simulation, also known as computer simulation, is the process of using computer programs to solve approximate solutions to mathematical models. The application of this technology is especially seen in the calculation of the solidification temperature field, and its development has benefited from the significant progress in computer technology since the 1960s. By using computer simulation technology, researchers can not only successfully solve and visually display the dynamic changes of the temperature field, but also provide a solid theoretical foundation and calculation method for other quality issues in related thermal processes.(Reddy, 2005)

This thesis uses COMSOL software to establish mathematical and physical models and conduct numerical simulations of food heating scenarios.

3 Methodology

This section introduce the numerical simulation tools used in this study. This includes the simulation software the study used as well as an introduction to the physical models and boundary conditions.

3.1 COMSOL numerical simulation

COMSOL Multiphysics is simulation software designed for engineers and researchers to simulate a variety of physical scenarios. The software supports independent simulation of a single physical field, and can also flexibly couple multiple physical fields to conduct various complex simulation analyses. COMSOL provides a comprehensive model builder that allows users to create geometries, define material properties and physical configurations, and perform solutions and analysis of results. The software is widely used for in-depth analysis of engineering problems, processes, and equipment.(COMSOL, 2024)

COMSOL Multiphysics includes an Application Builder that allows users to customize and develop easy-to-use simulation applications based on existing simulation models and easily share them with team members. The software is also equipped with a powerful model manager that supports version control and data storage of simulation projects, helping to improve the efficiency and convenience of data management.(COMSOL, 2024)

COMSOL also provides a rich module resource library that can be seamlessly integrated into COMSOL Multiphysics, allowing users to obtain customized professional solutions for different engineering needs under the same interface.(COMSOL, 2024)

In this study, I mainly used the solid heat transfer module to numerically simulate the process of heating cylindrical chicken patties in an air fryer, and obtained the temperature curve, temperature transient distribution and moisture transient distribution diagram. These data closely simulate the process of cooking food with convection heating in an air fryer.

3.2 Physical model and boundary conditions

This section will introduce the physical model and boundary conditions for simulating a cylindrical chicken patty.

3.2.1 Model dimensions and materials

The chicken patty the study designed is cylindrical, with a bottom radius of 21mm and a thickness of 12mm. Since the model drawing uses the method of symmetrical rotation of the rectangular axis for modeling, we get the upper part of the cylindrical chicken patty model. Therefore, we establish a spatial rectangular coordinate system with the center of the cross-section where the cylinder thickness is 6 as the origin, and a more intuitive model display can be obtained as shown in Figure 5.

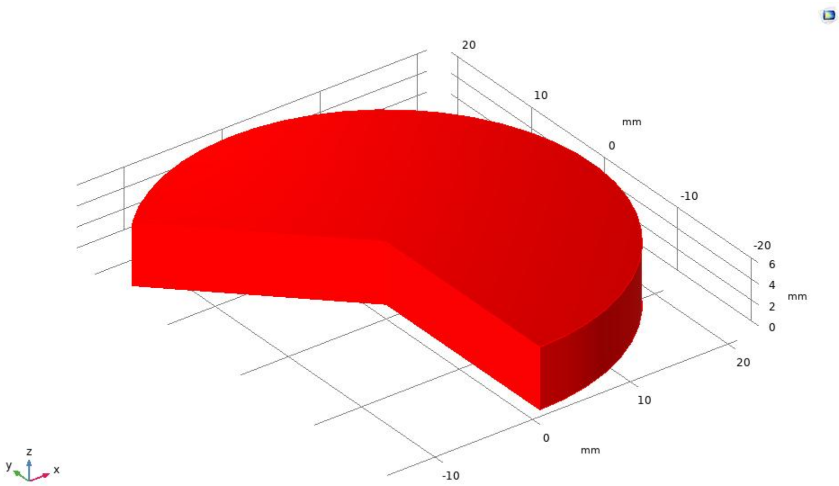

Figure 5. Cylindrical chicken patty model.

The initial physical properties of the cylindrical chicken patty and the initial physical properties of the oven air in the cooking doneness model are shown in Table 1.

Table 1. Initial parameters

Symbol	Expression	Value	Unit	Description
T_{air}	453.15	453.15	K	Air fryer air temperature
T_0	278.15	278.15	K	Initial chicken patty temperature
ρ_p	1100	1100	kg/m^3	Chicken patty density
h_T	25	25	$W/(m^2 \cdot K)$	Heat transfer coefficient
M_{H2O}	0.018	0.018	kg/mol	Water molecular weight
c_0	$0.78 \cdot \rho_p/M_{H2O}$	47667	mol/m^3	Initial moisture concentration
c_b	$0.02 \cdot \rho_p/M_{H2O}$	1222.2	mol/m^3	Air moisture concentration
C_m	0.003	0.003	m^3/kg	Specific volume water
k_m	$1.29 \cdot 10^{-9}$	$1.29 \cdot 10^{-9}$	$kg/(m \cdot s)$	Hygroscopicity
h_m	$1.67 \cdot 10^{-6}$	$1.67 \cdot 10^{-6}$	$kg/(m^2 \cdot s)$	Mass transfer coefficient, expressed in mass units
D	$k_m/(\rho_p \cdot C_m)$	$3.9091 \cdot 10^{-10}$	m^2/s	Diffusion coefficient
k_c	$h_m/(\rho_p \cdot C_m)$	$5.0606 \cdot 10^{-7}$	m/s	Mass transfer coefficient
ΔH_{vap}	$2.3 \cdot 10^6 \cdot M_{H2O}$	41400	J/mol	Molar latent heat of vaporization

Combining the parameters in the table above, the cylindrical chicken patty model in the study combines two transient interfaces, representing temperature and moisture content. The model does not simulate the flow velocity field outside the chicken patty because the convective heat transfer and moisture transfer coefficients of the surrounding air are already set.

The model takes into account the fact that as the chicken patty cooks, heat is transferred from the surface to the interior, causing changes in temperature and moisture concentration. The process of diffusion is used to describe the movement of heat and moisture within a patty. The specific heat capacity of a chicken patty increases with temperature, which affects the amount of heat required to raise the temperature of the patty. In addition, the model also takes into account the effect of water concentration on the thermal conductivity of patties. As the water concentration increases, the thermal conductivity also increases. The model also takes into account the heat flux generated by the evaporation of water from the surface of the patty.

And inside the chicken patty, the diffusion process can be described as heat and moisture transfer.

3.2.2 Setting of boundary conditions

As mentioned in the description of the cylindrical chicken patty physical model above, the cylindrical model is obtained by establishing a two-dimensional rectangle for axial symmetry and rotation. In other words, our model establishment actually only needs to establish a rectangle with the base radius as the length and half the thickness as the width, and the initial simplified model can be obtained as shown in Figure 6.

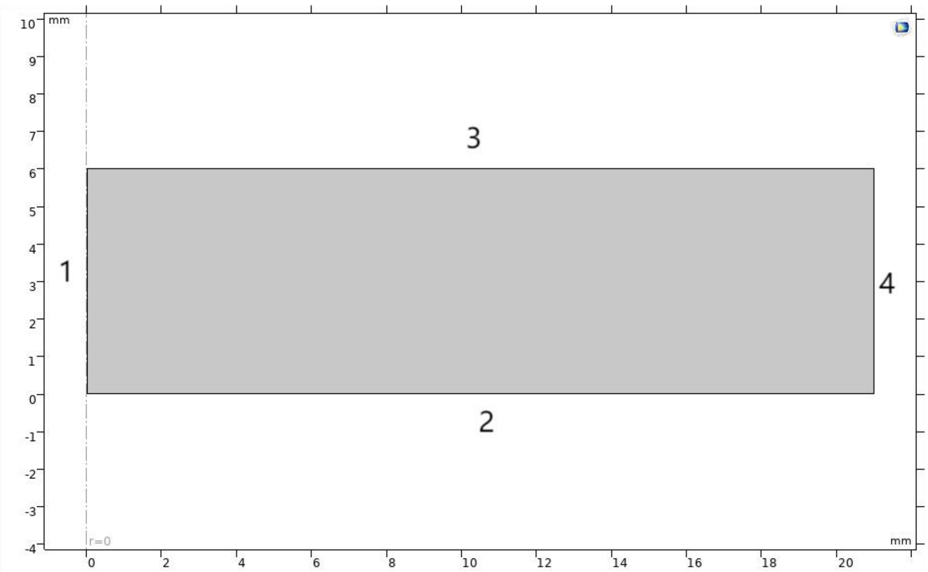

Figure 6: Model domain and boundary numbers.

According to Figure 6, we obtained the four boundaries of the model 1~4.

In order to describe the diffusion of water, here I have prepared a method combined with the heat equation to describe the diffusion equation of water more accurately.During the heating process, the moisture on the outer boundary of the chicken patties evaporates due to heating, thereby generating a heat flux.

In practical models, we usually use the following equation to describe the transient heat transfer equation of a single temperature field.(Haiqing Chen, 1999)

$$\rho \times C_p \times \frac{\partial T}{\partial t} + \rho \times C_p \times u \times \nabla T + \nabla \cdot q = Q_{ted} + Q \quad (1)$$

$$q = -k \times \nabla T \quad (2)$$

Among them, ρ represents density, T represents temperature, t represents time, q represents density of heat flow rate, Q represents the heat generated by the heat source, and Q_{ted} represents the total heat flux.

The specific heat capacity expression of this model is as follows.(Haiqing Chen, 1999)

$$C_p = 3017.2 + 2.05 \times \Delta T + 0.24 \times \Delta T^2 + 0.002 \times \Delta T^3 \quad (3)$$

From the above equation, we can get the ΔT (ΔT = T - 0°C) jointly determine the specific heat capacity C_p, that is to say, the specific heat capacity C_p increases with the increase of temperature.

The relevant expression of thermal conductivity k is as follows.(Haiqing Chen, 1999)

$$k = 0.194 + 0.436 \left(\frac{cM_{H_2O}}{\rho} \right) \tag{4}$$

Among them, k is the thermal conductivity in W/(m·K), c is the concentration in mol/m^3, M_{H2O} is the molar mass of water in kg/mol, ρ is the density in kg/m^3 .

So, at the diffusion interface, the water concentration diffusion equation can be expressed by the following equation.

$$\frac{\partial C_a}{\partial t} + \nabla \cdot J_a = R_a \tag{5}$$

$$J_a = - D_a \times \nabla \cdot C_a \tag{6}$$

Among them, C_a represents the concentration of water in mol/m^3, t represents time in seconds, J_a represents the molar flux density of substance a in mol/(m^2·s), and R_a represents the production rate of substance a in unit it is mol/(m^3·s).(Jing Yao, 2014)

Since boundary 1 and boundary 2 in the chicken patty model in Figure 6 are inside the chicken patty, we can assume that the temperature fields on boundary 1 and boundary 2 are symmetrical. As the air fryer heats, air convection will increase the amount of heat passing through boundary 3 and boundary 4. Based on the symmetry of the temperature fields we assume at boundary 1 and boundary 2, we can add one more term on boundary 3 and boundary 4. This term represents the heat flux transferred to the outside of the chicken patty due to evaporation of water. Here, we use the $\lambda D \nabla c$ term. Among them, λ is the molar latent heat of evaporation, expressed in J/mol.

According to the above content, we can get the boundary conditions of the heat transfer interface as follows.

$$n \times (-k\nabla T) = 0 \qquad \text{boundary 1 and 2} \tag{7}$$

$$n \times (k\nabla T) = h_T \times (T_{air} - T) + \lambda n \times (D\nabla c) \qquad \text{boundary 3 and 4} \tag{8}$$

Among them, h_T is the heat transfer coefficient, the unit is $W/(m^2 \cdot K)$, Tair is the oven air temperature, the unit is K.

We can also obtain the boundary conditions for water diffusion as follows.

$$n \times (-D\nabla c) = 0 \qquad \text{boundary 1 and 2} \tag{9}$$

$$n \times (D\nabla c) = k_c \times (c_b - c) \qquad \text{boundary 3 and 4} \tag{10}$$

Where D is the diffusion coefficient of water in the substance. In this study, D is the moisture diffusion coefficient of chicken patties, and the unit is m^2/s. k_c is the mass transfer coefficient, the unit is m/s. c_b is the moisture concentration of a large amount of external air, in mol/m^3.

Here, the expression of the diffusion coefficient D is as follows. Among them, k_m is the moisture conductivity, and the unit is $kg/(m \cdot s)$. C_m is the specific volume of water, which is the ratio of the weight of water to the weight of the substance being studied. This is the ratio of water weight to chicken patty weight.(Haiqing Chen, 1999)

$$D = \frac{k_m}{\rho \times C_m} \tag{11}$$

The expression for the mass transfer coefficient is as follows. Among them, h_m is the mass transfer coefficient expressed in mass units, and the unit is kg/(m^2·s). C_m is the specific volume water content.(Haiqing Chen, 1999)

$$k_c = \frac{h_m}{\rho \times C_m} \tag{12}$$

Assuming the chicken patties taken out of the refrigerator are at 5°C and the moisture concentration in the air in contact with the chicken patties is 1222 mol/m^3, that is, the wet weight is 22 kg/m^3. This means that moisture is expressed as mass per unit volume of chicken when modeling treatments.

Assuming the ingredients are uniformly distributed chicken patties, the air temperature in the air fryer is evenly distributed.

The model's assumptions and equations allow for accurate simulation of heat and moisture transfer during chicken patty cooking. This can be used to optimize cooking times and temperatures.

Through numerical simulation with COMSOL software, the study can obtain the temperature and moisture concentration of chicken patties as they change over time.

4 Result analysis

In this section, the study will analyze the results of numerical simulation of the above model. The results include the transient distribution of chicken patty temperature, the transient distribution of chicken patty moisture concentration and the calculation of cooking doneness.

4.1 Chicken patty cooking doneness

The middle part of the chicken patty is the hardest to cook because it is not in contact with the air in the air fryer. According to the description above of the COMSOL software, we can judge the cooking doneness of the chicken patty by heating the middle part of the chicken patty to 70°C, the ratio of the final moisture mass of the chicken patty to the initial moisture mass.

After numerical simulation, we obtained the temperature change of the middle part of the chicken patty with time when the air temperature in the air fryer is 180°C, as shown in Figure 7. The abscissa represents time, and the unit is s. The ordinate represents temperature, and the unit is °C.

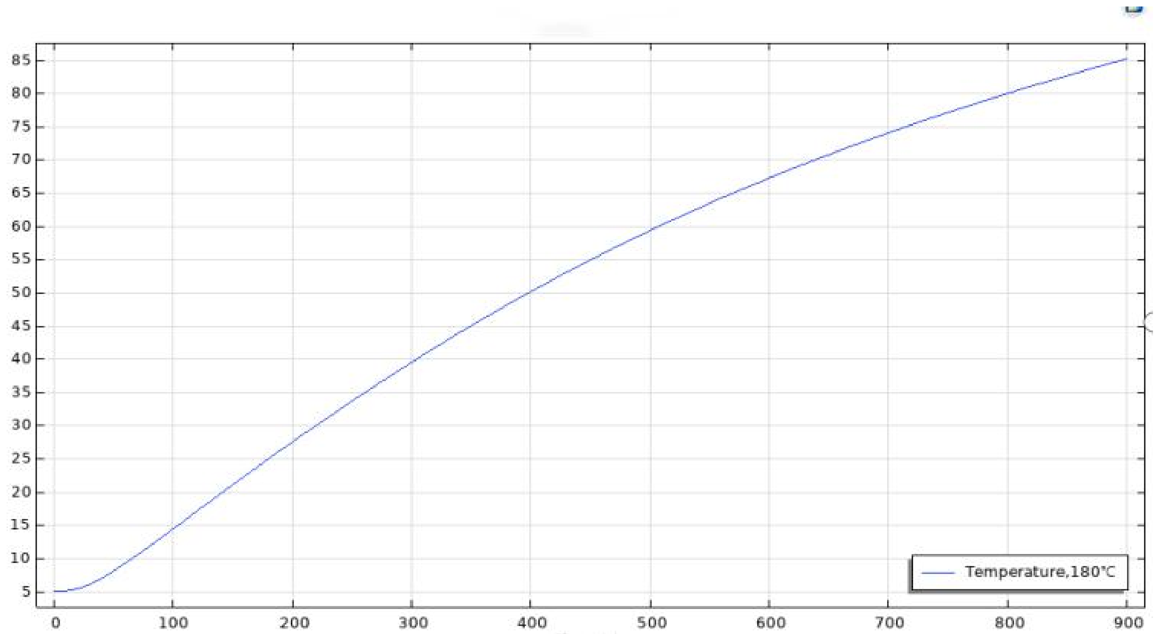

Figure 7. When the air temperature is 180°C, the temperature of the middle part of the chicken patties increases over time.

It can be seen from the figure that the middle part of the chicken patty reaches 70°C at about 640 seconds.So we can get the temperature field inside the chicken patty when the time is 640s as shown in Figure 8.

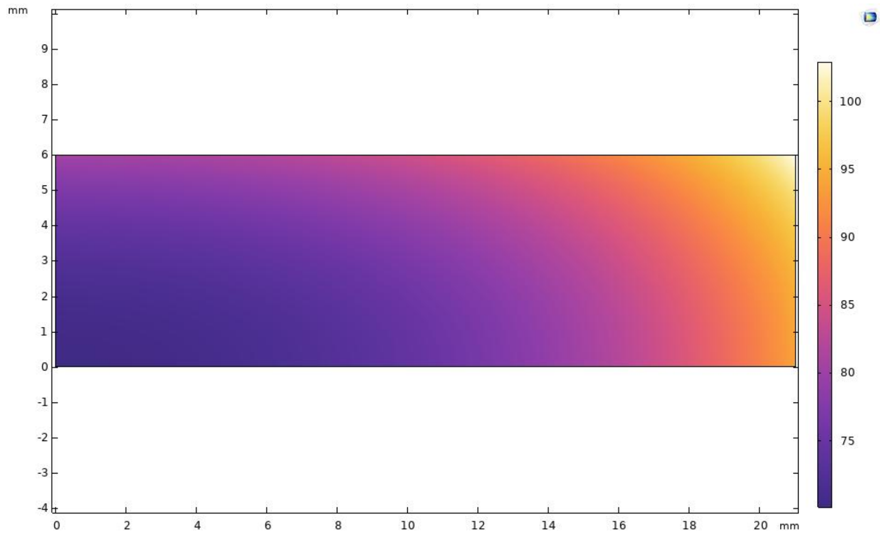

Figure 8. Temperature field after 640 s when the cooking temperature is 180°C.

When the air temperature in the air fryer is 180°C, the study divide the current moisture concentration in the middle part of the chicken patty by dividing the initial moisture concentration of the chicken patty to get the ratio, and get the cooking doneness of 0.93454, which is 93.45%.

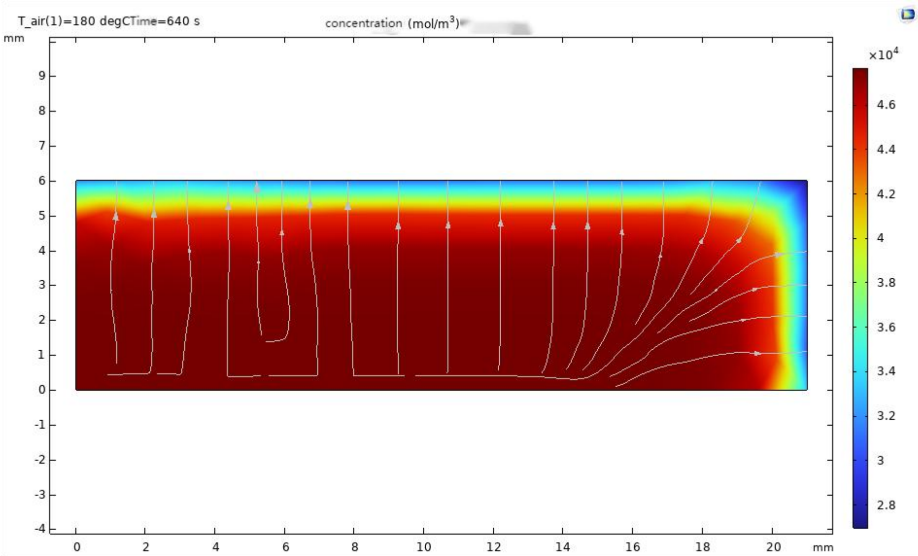

Figure 9. Moisture concentration after 640 s at a cooking temperature of 180°C.

Figure 9 shows the moisture concentration of chicken patties when cooking for 640 seconds under these conditions. The streamlines represent the total flux.

In order to explore the effect of rising air temperature in the air fryer on chicken patties, the study simulated the temperature field and moisture concentration distribution of chicken patties after the temperature increased, and calculated the maturity.

In order to explore a more suitable air temperature in the air fryer, the study used 50°C as a step to explore the situation of chicken patties when the air temperature was 230°C and 280°C.

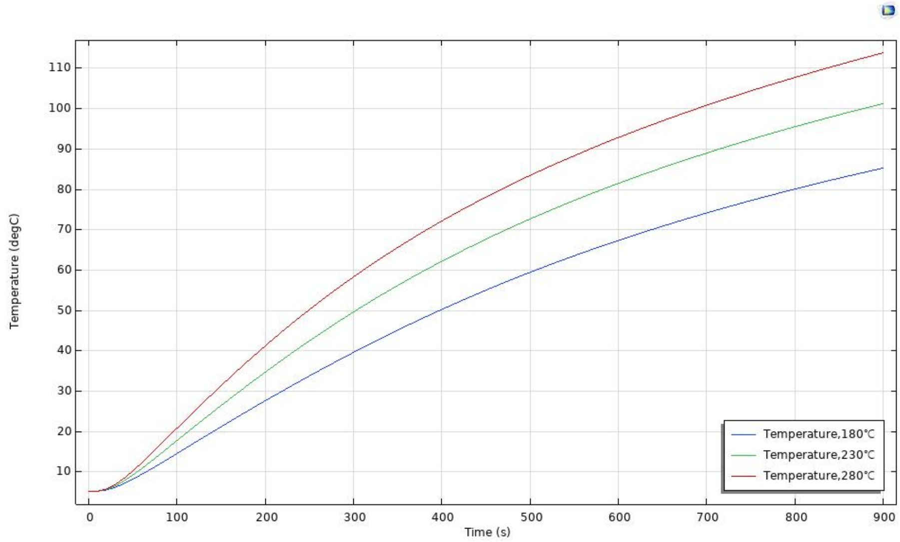

Figure 10. When the air temperature is 180°C, 230℃, 280℃, the temperature of the middle part of the chicken patties increases over time.

Figure 10 shows the curve of the temperature change of the middle part of the chicken patty with time at three air temperatures. Like the above method, the study still choose to heat the middle part of the chicken patty to 70°C as it is cooked. From this the result get that when the air temperature is 230°C, the middle part of the chicken patty reaches 70°C after about 480 seconds.

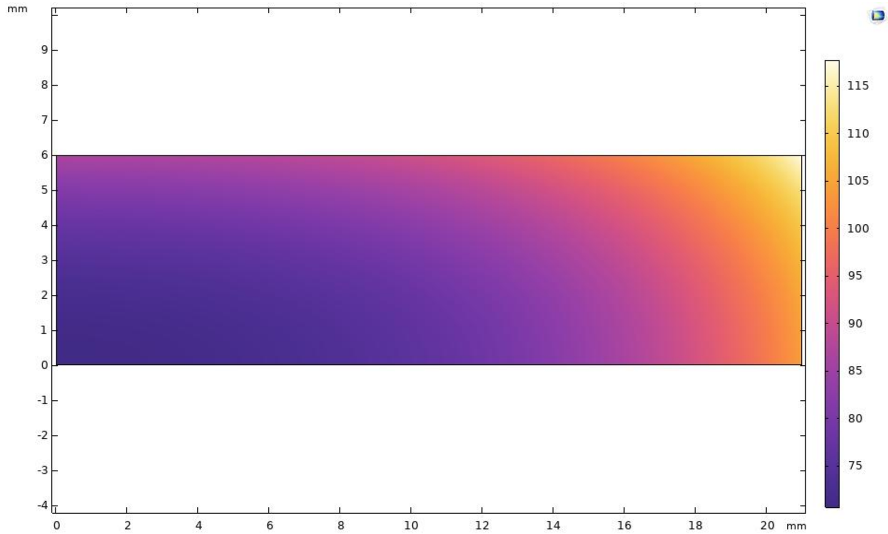

Figure 11. Temperature field after 480 s when the cooking temperature is 230°C.

Figure 11 shows the transient distribution of chicken patty temperature when the air temperature is 230°C and heated for 480 seconds.Using the same method, we calculated that the cooking doneness of the chicken patty at this time is 0.94815, which is about 95%. It can be seen that although the cooking time is shortened, the maturity of the chicken patties is increased.

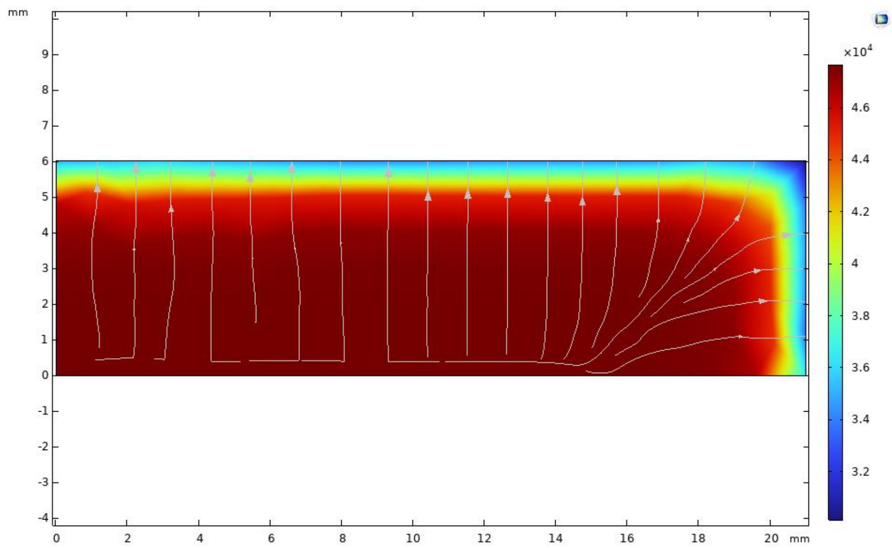

Figure 12. Moisture concentration after 480 s at a cooking temperature of 230°C.

Figure 12 shows the distribution of moisture concentration when chicken patties are cooked. Using the same method, when the air temperature in the air fryer is 280°C, we can see that the middle part of the chicken patty reaches 70°C after 390 seconds.

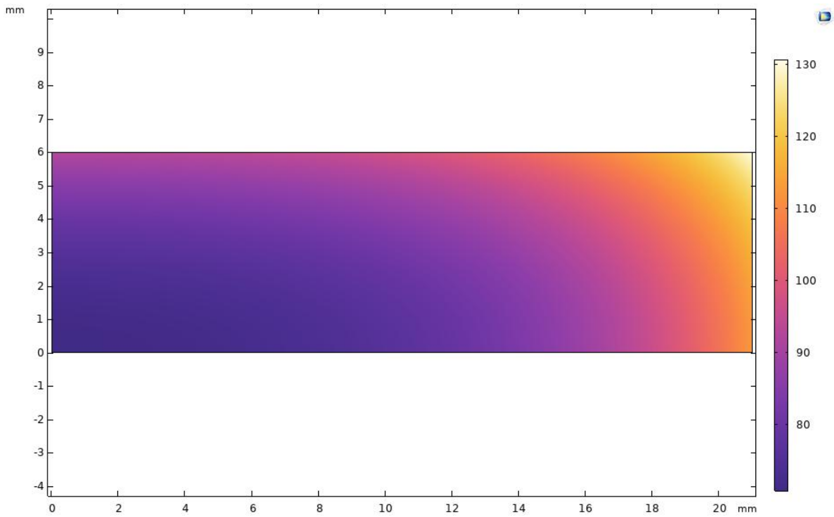

Figure 13. Temperature field after 390 s when the cooking temperature is 280°C.

Figure 13 shows the transient distribution of the temperature of the chicken patties when the middle temperature of the chicken patties reaches 70°C and the air temperature in the air fryer is 280°C for 390 seconds of cooking. Using the same method to calculate the cooking doneness, we get the doneness at this time to be 0.9567, which is about 96%.

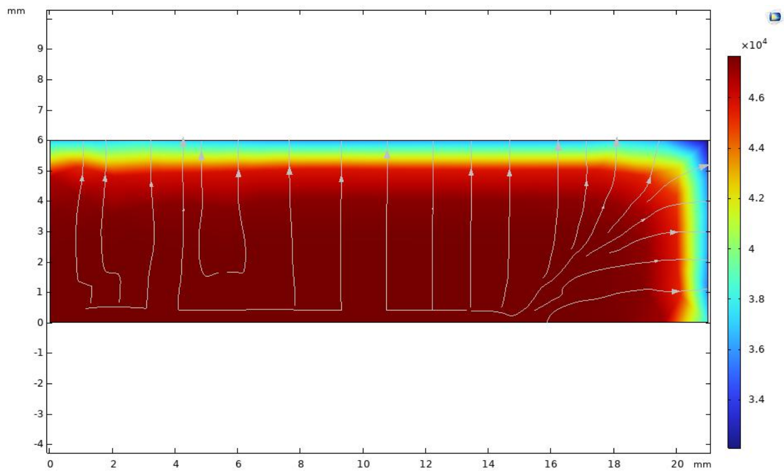

Figure 14. Moisture concentration after 390 s at a cooking temperature of 280°C.

Figure 14 shows the transient distribution of moisture concentration when the temperature of the middle part of the chicken patty is 70°C, the air temperature in the air fryer is 280°C, and the chicken is cooked for 390 seconds.

4.2 Comparative analysis

Through the data obtained above, we get the results as shown in Table 2:

Table 2. Result in three different air temperature.

Air temperature	Cooking time	Cooking doneness
180°C	640s	93.45%
230°C	480s	94.82%
280°C	390s	95.67%

From this can see that as the air temperature in the air fryer increases, the time required to cook the chicken patties to maturity decreases, while the cooking doneness of the chicken patties increases.

However, by comparing the three sets of temperature transient distribution diagrams, the study can also see that as the air temperature in the air fryer increases, the temperature of the outermost layer of the chicken patty also gradually increases. For example, when the air temperature in the air fryer shown in Figure 8 is 180°C, the outer skin temperature of the chicken patties is less than 110°C, but when the air temperature in the air fryer shown in Figure 11 is 230°C, the outer skin temperature of the chicken patties is greater than 115°C, as shown in Figure 13, when the air temperature in the air fryer is 280°C, the outer skin temperature of the chicken patty is greater than 130°C.

In addition, comparing the three groups of moisture concentration transient distribution diagrams, we can see that when the air temperature in the air fryer is 180°C, the outer skin moisture concentration is less than 2.8 mol/m^3 as shown in Figure 9. As shown in Figure 12, when the air temperature in the air fryer is 230°C, the moisture concentration of the outer skin is less than 3.2 mol/m^3. As shown in Figure 14, when the air temperature in the air fryer is 280°C, the moisture concentration of the outer skin is less than 3.4 mol/m^3.

From this the study can analyze that as the air temperature in the air fryer increases, when the middle part of the chicken patty is cooked to 70°C, the temperature of the outer skin of the chicken patty will also increase. Within a certain range of air temperature in the air fryer, the moisture concentration of the outer skin of the chicken patties increases slightly. Therefore, we can see that when the air temperature in the air fryer is 180°C, although the cooking time is long, the outer skin of the chicken patties is less likely to burn.

By comparing the three sets of data, the study can determine which setting is more suitable for the public's cooking taste by studying the final state of the chicken patties cooked by different air temperature settings in the air fryer. This has important implications for the preparation of ingredients for prepared dish suppliers.

4.3 Error analysis

Since it is a numerical simulation, the main errors in this study come from the structure of the food ingredients and the ambient temperature. We assume that the ingredients are uniformly distributed chicken patties, but in reality, the distribution of chicken patties cannot be even.

Secondly, the air temperature distribution in the air fryer is not always uniform. In this numerical simulation, we ignored the gradual increase in air temperature in the air fryer, which would be inconsistent with reality.

5 Conclusion

In this study, we utilize the numerical simulation capabilities of COMSOL software to study the transient temperature and moisture concentration distribution and cooking maturity of cylindrical chicken patties during convective heating. This research aims to improve the understanding and control of the heating process of prepared foods, which are becoming increasingly popular due to the fast-paced lifestyles of many urban residents. By studying the effects of varying air temperatures in an air fryer environment on convective heat transfer efficiency and moisture diffusion in chicken patties, this study provides valuable insights into optimizing cooking methods for prepared foods.

Research results show that adjusting the heating temperature will significantly affect the efficiency of heat transfer and moisture diffusion, thereby affecting the entire heating process. Our simulations show that as the temperature inside the air fryer increases, the time it takes for the chicken patties to reach cooked doneness decreases and the cooked doneness increases. However, higher air temperatures can also increase the temperature of the outer layer of chicken patties, which can lead to overcooking or burning at excessively high cooking temperatures.

Our comparative analysis at different air temperatures (180°C, 230°C and 280°C) shows that the best balance between cooking efficiency and food quality can be achieved by adjusting the heating conditions. While higher temperatures can shorten cooking times and increase doneness, they also create a greater risk of over-drying or burning the surface of the food. The study therefore highlights the importance of trial and error and continuous optimization in real food production to discover the most efficient heating methods that preserve both taste and nutritional value.

It is worth noting there will be potential differences due to the assumed uniformity of food ingredients and the stable air temperature within the air fryer, which will be somewhat different from actual cooking using an air fryer. I think future research could further refine these models by incorporating variable food composition and more complex air temperature dynamics to more closely simulate actual cooking scenarios.

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