SIMULATION MODEL TO PERFORM THERMAL ANALYSIS OF VARIOUS PAN MATERIALS DURING REPETITIVE OIL FRYING OPERATIONS

Tarek FOUDA, Nourhan KASSAB

Tanta University, Faculty of Agriculture, Agriculture Engineering Department, Egypt.
E-mails: tfouda628@gmail.com, nourkassab2308@gmail.com,

Corresponding author: tfouda628@gmail.com

Abstract

Thermal analysis during frying operations depends on the types of materials, the pans, and the quality of the oil used. Continuous exposure to changing temperatures changes the specifications. The experiment was planned to study the thermal analyse with various pan materials properties and repeated oil frying. The pan was tested and oil frying under steady-state heating conditions. The infrared images extracted with MATLAB, and testo software also Solid Works software were used to determine the material's convection coefficient, and specific heat,. The temperature rise at each point through surface and volume parameters from 0 to 8 minutes at three frying stage of oil and each skillet. The results showing as the frying temperature begins to rise, it rises with heat transfer rate (convective) reached 1,435.32 J/Kg·K during the third stage at 8 minutes. The specific heat capacity peaked at 1,191.37 J/Kg·K during the first stage at 6 minutes. Conversely, the minimum values for these indices were 522.90°C, 1,322.35 J/Kg·K, and 1,006.89 J/Kg·K, observed during the second stage at the beginning, specifically for the wok skillet.

Key words: i*nfrared, pan materials, heating, oil frying*

INTRODUCTION

Solanum tuberosum L., or potatoes, are the first essential non-cereal crop and the fourth most important crop overall. One important source of carbs, which are the main source of energy for a person's daily diet, is potatoes. Not only is it a multinutritional component source of iron, potassium, phosphorus, calcium, and magnesium, but it also contains important antioxidants and phenols. Furthermore, the resistant starch found in potatoes may guard against colon cancer, prevent fat accumulation, and have hypoglycemic and prebiotic effects [4].

One significant non-cereal crop is the potato. It offers carbs, one of the main dietary sources of energy for humans. In order to preserve vegetables and fresh fruits need be blanched before processing them. Pretreating various food materials with high-humidity hot-air impingement blanching (HHAIB) is a potential new method. In order to preserve the nutritional and physical qualities of potatoes while inhibiting the production of browning enzymes, this study sought to determine the ideal hot-water blanching (HHAIB) settings [11].

In the US, more than 17.4 billion pounds of French fries are produced each year, making up almost 44% of the total amount of processed potatoes produced. A French fry consists of two parts: (1) a crispy, oily, and dehydrated outside and (2) a cooked, moist, and oil-free within. The outside crust has a structure that is quite similar to that of a fried potato slice or potato chip. Raw potato strips need to be blanched in hot water and then dried in hot air until they have a moisture level of around 60% (total basis). This is the preparation process for French fry processing. The dried potato strips are cooked in hot oil (160–190C), cooled, then frozen and packaged. To finish the preparation, fry or bake the frozen par-fried potatoes one more time. The ultimate oil and moisture content of French fries are between 15 and 38%, respectively [15].

Cooking is an essential component of daily life for many apparent reasons, such as improving flavor, texture, palatability, digestibility, and shelf life in both domestic and commercial settings, as well as lowering the risk of food-borne infections. Estimates from the FAO indicate that the energy requirement associated with food is 15% for food processing and transportation, 10% for primary production, and 75% for cooking and food preparation [3].

A skillet is a physical delivery device that transfers heat to food's surface by the use of natural gas, induction, or an electrical coil. Food cooks according to the conduction of thermal energy across the food contact surface. Heat travels through the skillet's components and from the cooktop, the heat source, to the skillet's base by a process called conduction of heat. The way that thermal energy is transported from the Skillet to the meal is mainly determined by the materials that were utilized in its construction [9].

Immersion frying is another popular name for deep-fat frying. It is thought to be a food dehydration process, or more precisely, a method of extracting water through convection while undergoing a state shift. During this process, the food is periodically exposed to air and heated to a high temperature (180 C) in an environment of oil. The combined heat and mass transfer between the food and the frying media makes frying a highly complex process. A number of physical and chemical factors, including temperature, warm-up time, kind of oil, food, oil rotation, manipulation, and equipment, affect the amounts. However, when food is fried, a number of chemical processes and changes occur, including the starch gelatinization process, the Maillard reaction, the denaturation of protein, and the reduction of moisture.These alterations result in the food's surface becoming dehydrated, the formation of a crust, and the passage of heat from steam through the product [13].

The homogeneity and quick cooking of the food make frying a desirable method when compared to other methods. Vacuum frying and atmospheric frying are the two types of deep-fat frying methods. In oil mass called convection and within the food named conduction work together to transfer heat during deep-fat frying [10].

The meal has the same heat treatment applied to every surface, giving it a consistent flavor. A fine oil film forms on a product when it cooks in the fryer. The product's internal steam pressure lowers as its temperature naturally convects due to external factors (such as weather) and when it is removed from the fryer. This compels the oil to move within the product's surface. During frying, the product's thermophysical characteristics gradually alter. Both the food's pores and the density of the stuff diminish. When porosity increases, the specific heat falls, humidity content reduces, and oil content increases during frying. The thermal conductivity also decreases when these factors increase [2].

Four stages can be distinguished in immersion frying: (1) preliminary heating; (2) surfaces boiling; (3) dropping rate; and (4) bubble end point. In the initial phase, food immersed in oil has its surface heated to a temperature equal to that of water at its boiling point; heat is transferred between the food and oil through natural convection, with no water evaporating from the food's surface. By evaporating water in the second stage from the surface of the food, forced convection rather than natural convection is the method of heat transfer. This is due to the turbulence in the surrounding oil. At this point, the food's surface starts to take on the appearance of a crust. The food's internal humidity causes the temperature of that portion to gradually rise to boiling point in the third stage. A few physicochemical processes may occur during this time, including the denaturation of proteins and gelation of starches, as well as an decrease in the surface steam transfer rate and increase in the thickness of the superficial crust. The pace at which the humidity is eliminated decreases in the final stage, and the food's surface is free of bubbles. It is possible to classify these four frying states as either boiling phases (stages 2 and 3) or non-boiling phases (stages 1 and 4) [14].

The distinct flavors and crispy textures of potato chips make them very appealing. But because they contain between 35 and 45 percent oil by weight, people have a bad impression of them. Additionally, potato chips seem to contain the highest amounts of acrylamide of all the foods that have been examined up to this point. Demand for premium, health-conscious meals have increased recently as a result of growing consumer knowledge of the connection between nutrition and wellbeing. Therefore, researchers have been very interested in producing potato chips with minimal oil and acrylamide concentration and good sensory quality [8].

One of the most crucial markers of the final product's quality is the distinctive crispy texture of potato chips, which arises from modifications made to the potato tissue's initial structure during heating. The rate at which heat transfers has a direct impact on the development of this crispy texture. This quality can be imparted through deep fat frying since hot frying oil has a high heat transfer rate. The crispy and stretched texture of potato slices is caused by the rapid release of water due to high heat transfer rates during frying [12].

The elevated heat transfer rates that occur during deep-fat frying are primarily responsible for the development of the desired sensory attributes and important structural components of fried potatoes, including density, porosity, and volume. Heat and mass transmission during frying are affected by the shape of the meal, the temperature and pressure of the oil, as well as the thermal and physical-chemical properties of the food and oil. During the frying process, most of the oil does not penetrate the fine structure of the food, so a large part of the oil sticks to the surface of the food after it was on the surface after frying. This occurs in the cooling or post-frying stage [6].

Cooking with fat, often known as oil frying, is a popular technique for food production and preparation. The fat is a crucial component of the fried food and acts as a medium for heat transfer. It is used frequently or constantly at high temperatures, causing a variety of chemical reactions, including oxidation, fission, polymerization, and hydrolysis. This leads to the build-up of breakdown products, which are highly harmful to human health and have an adverse effect on the quality of fried dishes, especially when frying fat or oil is misused [7].

Deep frying is one of the oldest methods of food preparation that basically involves immersing food ingredients in hot oil. The water evaporates because to the high temperature, moving through the surrounding oil and away from the food. Food absorbs oil, which helps to replenish some of the lost water. Immersion frying can also be thought of as a dehydration method since it involves submerging a food product in edible oil or fat that has been heated above the boiling point of water. Too-high drying velocities are a hallmark of frying in hot oil at temperatures between 160 and 180 degrees Celsius.

Improving the final product's mechanical and structural qualities depends on this quick drying. High heat transfer rates, quick cooking, browning, texture development, and taste development are the results of these conditions.

The Maillard reaction, which is influenced by the temperature, frying time, asparagine content, and superficial reducing sugar, produces the color of fried potatoes [1].

An age-old and widely used technique for preparing food, deep-frying is used both in industrial and residential settings.

From a chemical perspective, it suggests a dehydration process marked by a brief cooking period because of the hot transfer, food that is internally heated to less than 100ºC, and the absorption of fat from the frying medium. In order to achieve a quick and even heating, the meal is immersed in very hot fat or oil (160–180ºC) that serves as a heat transmitter. Heat transmission during cooking occurs significantly more quickly when the temperature differential between the meal and the heating medium rises.

Mass is moved from the food to the frying medium and vice versa simultaneously with the transfer of heat [5].

The aim of this study is to perform a thermal analysis with solidworks flow simulation of various pan materials during repetitive oil frying operations.

MATERIALS AND METHODS

Three materials of skillets were used in thermal analysis (Wock, which is made from stainless steel material), (Tefal, which is made from stainless steel +Polytetrafluoroethylene (PTEF)), and (Ramlay which is made from sheet metal (steel material)) as shown in Photo 1, and Table 1 showed the properties of these materials. Also, an infrared camera was used to take pictures of these skillets in the study during 3 stages, for 8 minutes for each one and analysed pictures with Testo, MATLAB software version 2016, then perform the thermal analysis on the SolidWorks software version 2023. Simulation model to determine the thermal indices in surface and volume parameter as shown in Figure 1.

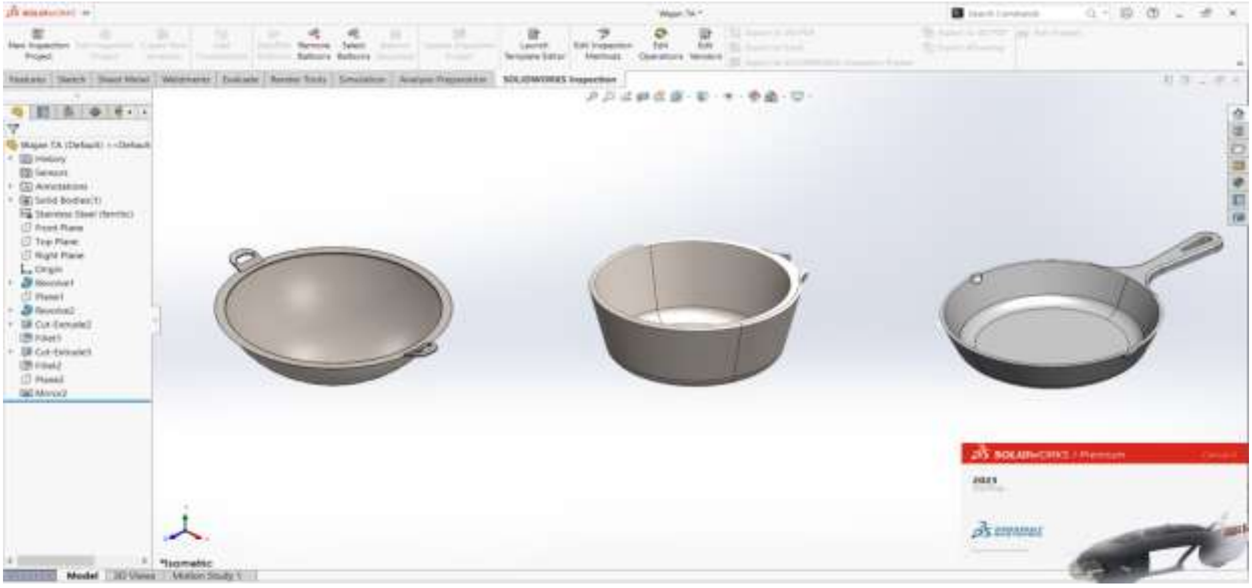

Photo 1. Skellies and their materials
Source: Authors' determination.

Table 1. Skillets materials properies

Stainless steel			Tefal (Stainless steel + PTFE (polytetrafluoroethylene))		Sheet metal (steel)	
Property	Value	Unit	Value	Unit	Value	Unit
Elastic Modulus	2e+11	N/m^2	400	N/m^2	190 to 210	GPa
Poisson's Ratio	0.28	N/A	0.4 to 0.5.	N/A	0.27 to 0.30.	N/A
Shear Modulus	7.7e+10	N/m^2	300 to 500	N/m^2	77 to 82	GPa
Mass Density	7,800	kg/m^3	2,320	kg/m^3	7,750 to 8,050	kg/m^3
Thermal conductivity	18	W/mK	0.25 to 0.35	W/mK	15 to 60	W/mK
Hardness	95	Rockwell	50 to 65	Rockwell	120 to 200	Rockwell
Thermal Expansion Coefficient	1.1e-05	(µm/(m·K))	80 to 135 x 10-6	(µm/(m·K))	10 to 13 x 10-6	(µm/(m·K))
Specific Heat	460	J/(kg·K)	0.5 to 0.55	J/ (Kg. K)	0.46 to 0.51	J/ (Kg. K)

Source: Own results.

Steps of the experiment

-The infrared images extracted for three pans, analyze images using Testo 2016, andMATLAB 2016, adtion to Perform thermal analysis on SolidWorks 2023. To determine thermal indicesduring three frying periods, for 8 minutes each. Calculate internal and external temperatures of pans and air and oil temperatures using Testo. Display thermal images in 2D, 3D format and clarify higher temperatures from Testo.

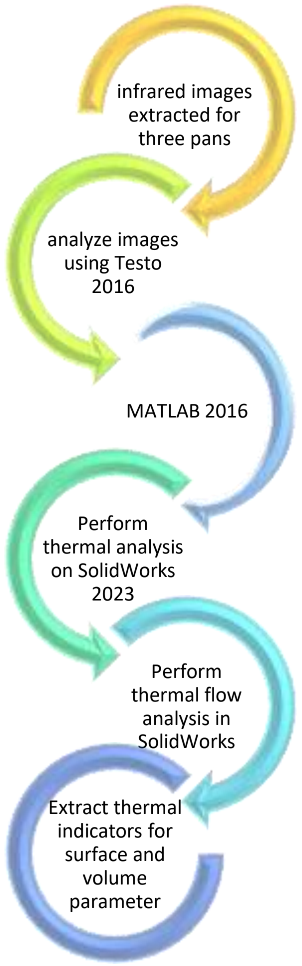

Fig. 1. The steps of the experiment
Source: Authors' drawing.

Surface parameters are focused on the material's exterior and involve properties and reactions occurring at or near the surface, and the importance of this type is surface reactions, corrosion resistance, adhesion properties, and catalytic activity.

Volume parameters encompass the entire material and involve bulk properties and behaviours, and the importance of this type is structural integrity, mechanical strength, thermal expansion, and bulk thermal conductivity.

Thermal indices

According to Zhang et al. (2010) [16]

Thethermal indices were founded as follows:

1- Heat Transfer Rate (Convective), J/Kg. K

$q=\frac{h\cdot A\cdot (Ts-T\infty)}{m}$ ……………………………..…(1)

where:

q is the heat transfer rate (W, or J/s),

h is the convective heat transfer coefficient (W/m²·K),

A is the surface area through which heat is being transferred (m²),

$T_s$the surface temperature (K or °C),

T_∞ is the temperature of the surrounding fluid (K or °C).

m is the mass of the material (kg)

2- Specific Heat, J/kg. K

$C=\frac{q}{m\Delta T}$…………………………………..(2)

where:

c is the specific heat capacity (J/kg·K),

q is the amount of heat absorbed or released (Joules),

mis the mass of the substance (kg),

ΔT is the change in temperature (K or °C).

3-Surface Heat Flux (Convective), W/m^2

$q^n=h\cdot(T_s-T_\infty)$……………………………(3)

q+ is the convective heat flux (W/m²),

h is the convective heat transfer coefficient (W/m²·K),

T_s is the surface temperature (K or °C),

T∞ is the temperature of the surrounding fluid (K or °C).

4-Heat Transfer Coefficient (Adiabatic Temperature) (W/m^2/K)

$q=h\cdot A\cdot(T_{aw}-T\infty)$………………………(4)

where:

T_{aw} represents the adiabatic wall temperature,(K or °C).

5-Solid Thermal Conductivity, (W/m·K)

q=-K.

$A.\frac{\Delta T}{\Delta X}$…………………………………..…(5)

where:

q is the heat transfer rate (W),

k is the thermal conductivity of the material (W/m·K),

A is the cross-sectional area through which heat is being conducted (m²),

$\frac{\Delta T}{\Delta X}$is the temperature gradient in the direction of heat flow (K/m). Also, represents the rate of change of temperature with respect to distance within the material.

6-Absolute Total Enthalpy (J/kg)

Absolute total enthalpy, referred to as total enthalpy, is a thermodynamic quantity representing the total energy of a system per unit mass. It includes internal energy, pressure-volume work, and kinetic and potential energy.

h_t=h+$\frac{v^2}{2}$+gz……………………………….(6)
where:
h_t is the total enthalpy per unit mass (J/kg),
$\frac{v^2}{2}$ is the specific kinetic energy (J/kg), with v being the flow velocity (m/s),
h is the static enthalpy per unit mass (J/kg), defined as h=u+pv
where:
u is the internal energy per unit mass (J/kg),
p is the pressure (Pa), and
v is the specific volume (m^3/kg),
gz is the specific potential energy (J/kg),
where:
g is the acceleration due to gravity (m/s^2), and
z is the height above a reference level (m).

7-Stanton number

is a dimensionless number used in fluid dynamics and heat transfer. It measures the ratio of heat transferred to the fluid to the heat capacity of the fluid. It is a key parameter in convective heat transfer, particularly in boundary layer flows.

St=$\frac{h}{\rho c_p u}$…………………………………….(7)
where:
h is the convective heat transfer coefficient ($W/m^2 \cdot K$),
ρ is the density of the fluid (kg/m^3),
c_p is the specific heat capacity of the fluid at constant pressure (J/kg·K),
u is the flow velocity (m/s).

8. Energy balance, (W)

Q_{in} -Q_{out} +Rate of energy generation = Rate of energy accumulation…………………………...(8)
Where:
Q_{in}= q_x is rate of energy in, W
Q_{out}= q_x+ Δx is rate of energy out, W
rate of energy accumulation= $\rho\ c_p \Delta x\ \frac{dt}{dx}$
final energy balance formula:
q_x- q_x+ Δx=$\rho\ c_p \Delta x\ \frac{dt}{dx}$……………………..(8.1)
*Using Fourier's law of heat conductivity:
-KA$\frac{dt}{dx}$ + KA$\frac{dt}{dx}$ = $\rho\ c_p \Delta x\ \frac{dt}{dx}$………..……(8.2)

RESULTS AND DISCUSSIONS

Maintaining a constant level, the temperature gradient at each point through surface and volume parameters for 8 minutes at each stage provides significant insights into the overall performance of each skillet. As shown in Fig.2 to Fig 4, in wock skillet the maximum Adiabatic Fluid Temperature was 482.25°C, temperature of the solid was 432.15°C, and the highest heat transfer rate (convective) reached 853.27 W during the third stage at 8 minutes. While Teffal skillet the maximum Adiabatic Fluid Temperature was 479.35°C, temperature of the solid was 387.83°C, and the highest heat transfer rate reached 860.65 W during the third stage. As for Ramlay skillet the Maximum value for the same indicators was 471.25°C, 471.35°C, and 880.26 W during the third stage at 8 minutes, respectively.

Fig. 5 to Fig.7 illustrate the convergence between the values of Heat Transfer Coefficient, and Heat Transfer Coefficient (Adiabatic Temperature) for the wock skillet. The minimum values recorded were 18.06 and 18.11 $W/m^2 \cdot K$, while the maximum values were 23.54, and 23.45 $W/m^2 \cdot K$, corresponding to the The three stages respectively. for The Teffal skillet the minimum values recorded were 22.84 and 25 $W/m^2 \cdot K$, while the maximum values were 25.01, and 29.88 $W/m^2 \cdot K$. The same minimum and maximum values for the same parameters for Ramlayskillet were equal for the three stages 17.93, 18.48, 19.18, 19.90 $W/m^2 \cdot K$. The highest values reached by the Surface Heat Flux were 10.86KW/$m^2$for wock skillet and 12.04 KW/$m^2$for Teffal skillet and 13.73 KW/$m^2$for Ramlay skillet in the last stage for the three skillets respectively.

Fig. 9 to Fig. 11 show that the maximum and minimum values of the thermal indices were recorded as follows: For the wock skillet, The Specific Heat (Cp) ranged from 1,100.94to 1,238.26 J/Kg.K, the Absolute Total Enthalpy varied between 803.9 and 891.13 KJ/kg, These values were observed during the first and third stages, from the beginning to 8 minutes, respectively. For the Teffal skillet, The Specific Heat (Cp) ranged from 1,173.67to 1,423.13 J/Kg.K, the Absolute Total Enthalpy varied between 882.81 and 912.81 KJ/kg, during the first and third stages, respectively.

As the Ramlay skillet, the specific heat (Cp) increases from 1,304.55 to 1,550.21 J/Kg.K, and Absolute Total Enthalpy increases from 909.96 (J/kg*K) to 951.84 KJ/kg, respectively.

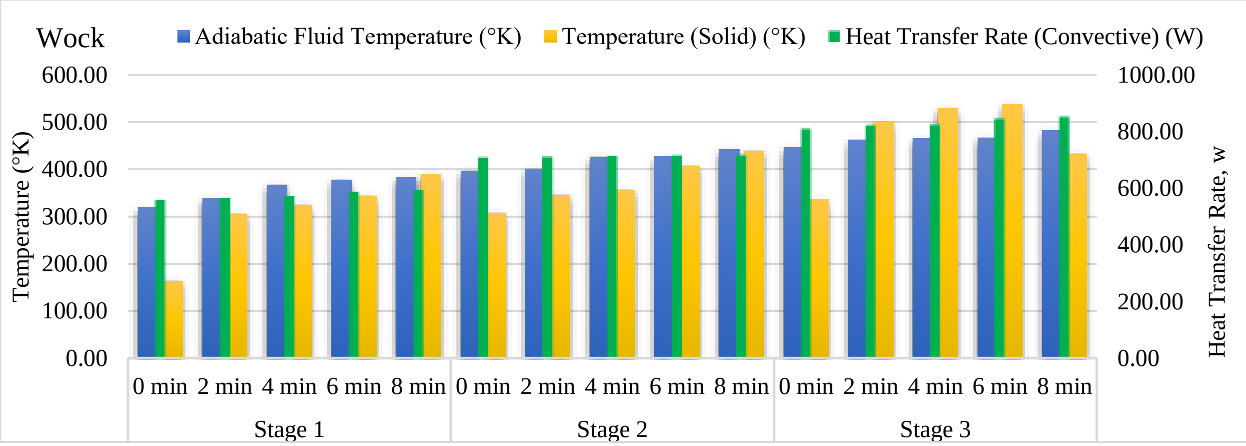

Fig. 2. Changing intemperature, adiabatic fluid temperature and heat transfer rate during frying stages of Wock skillet
Source: Author's determination.

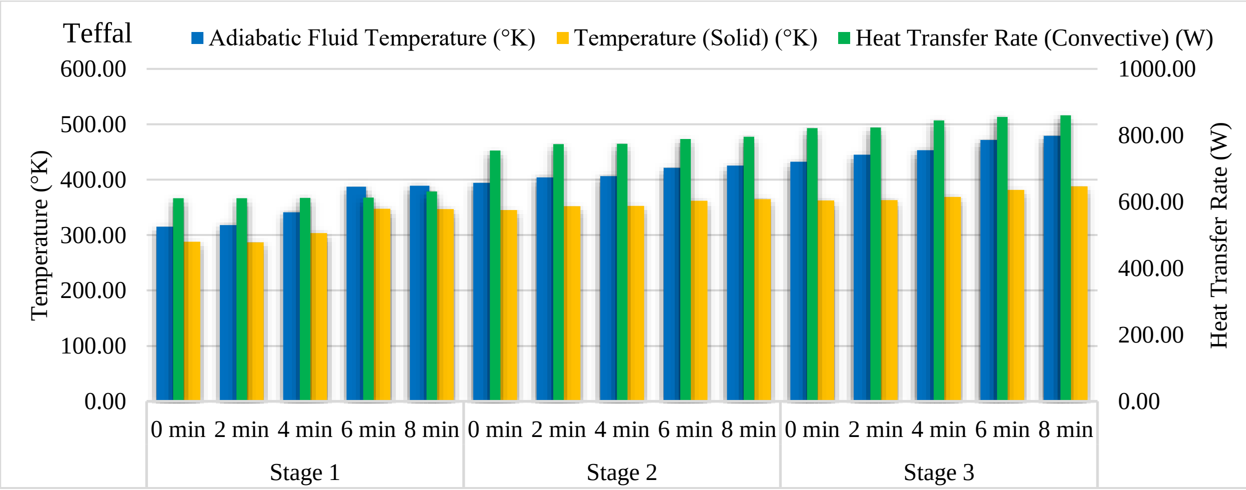

Fig. 3. Changing in temperature, adiabatic fluid temperature and heat transfer rate during frying stages of Teffalskillet
Source: Author's determination.

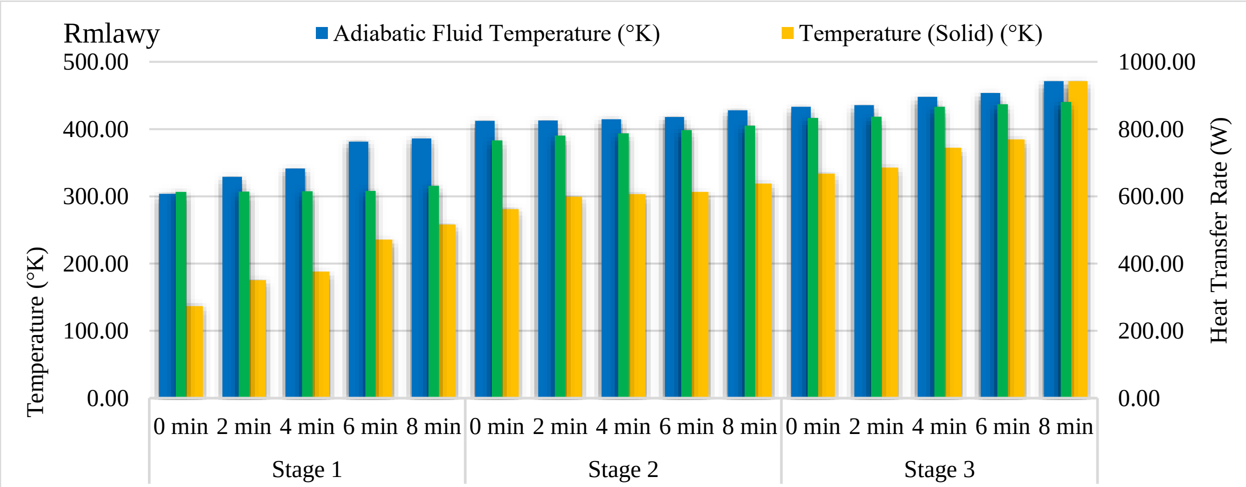

Fig. 4. Changing in temperature, adiabatic fluid temperature and heat transfer rate during frying stages of Rmlawy skillet
Source: Author's determination.

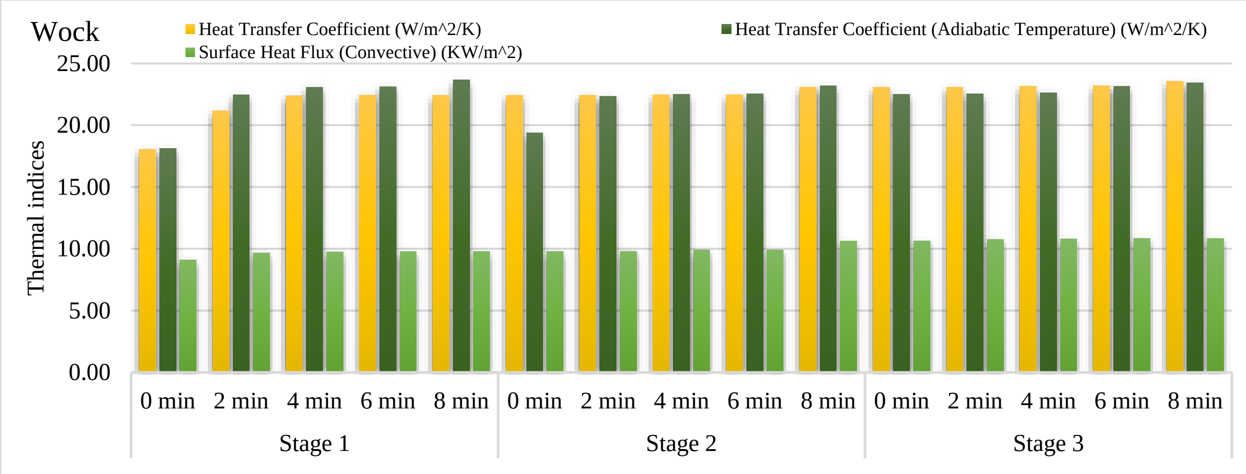

Fig. 5. Changing in heat transfer coefficient, heat transfer coefficient and surface heat flux during frying stages of Wock skillet
Source: Author's determination.

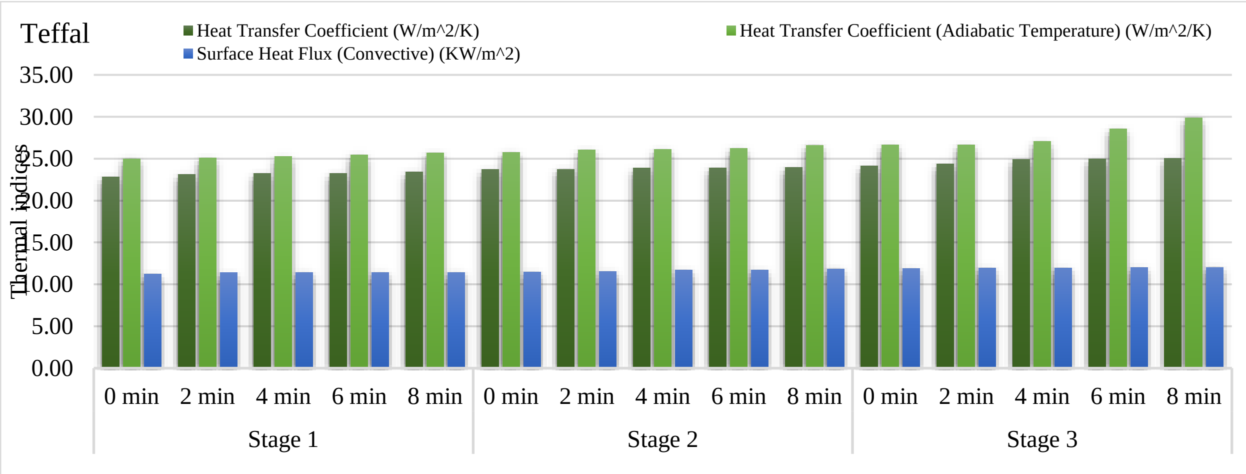

Fig. 6. Changing in Heat Transfer Coefficient, Heat Transfer Coefficient and Surface Heat Flux during frying stages of Teffal skillet
Source: Author's determination.

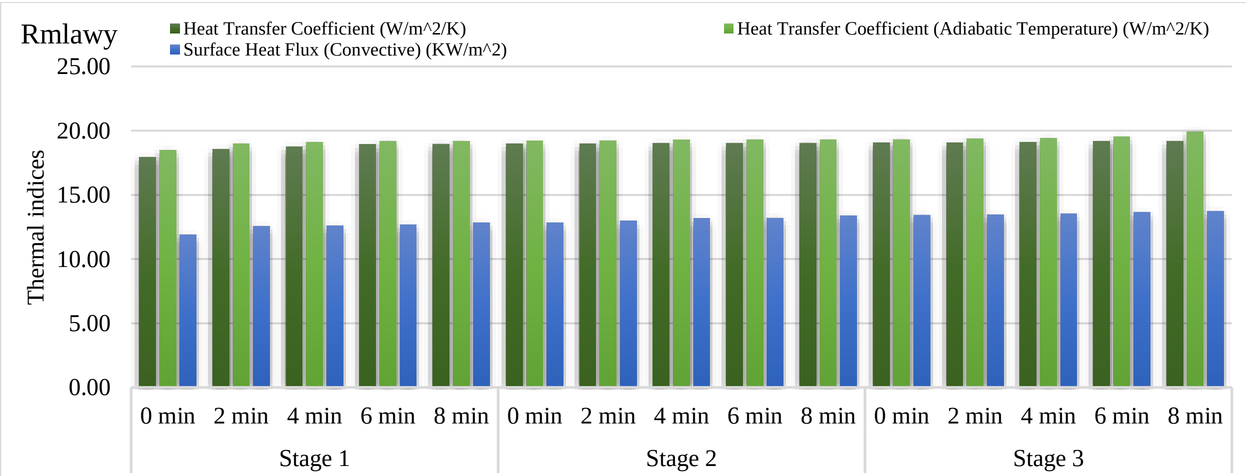

Fig. 7. Changing in heat transfer coefficient, heat transfer coefficient and surface heat flux during frying stages of Rmlawy skillet
Source: Author's determination.

Scientific Papers Series Management, Economic Engineering in Agriculture and Rural Development
Vol. 24, Issue 4, 2024
PRINT ISSN 2284-7995, E-ISSN 2285-3952

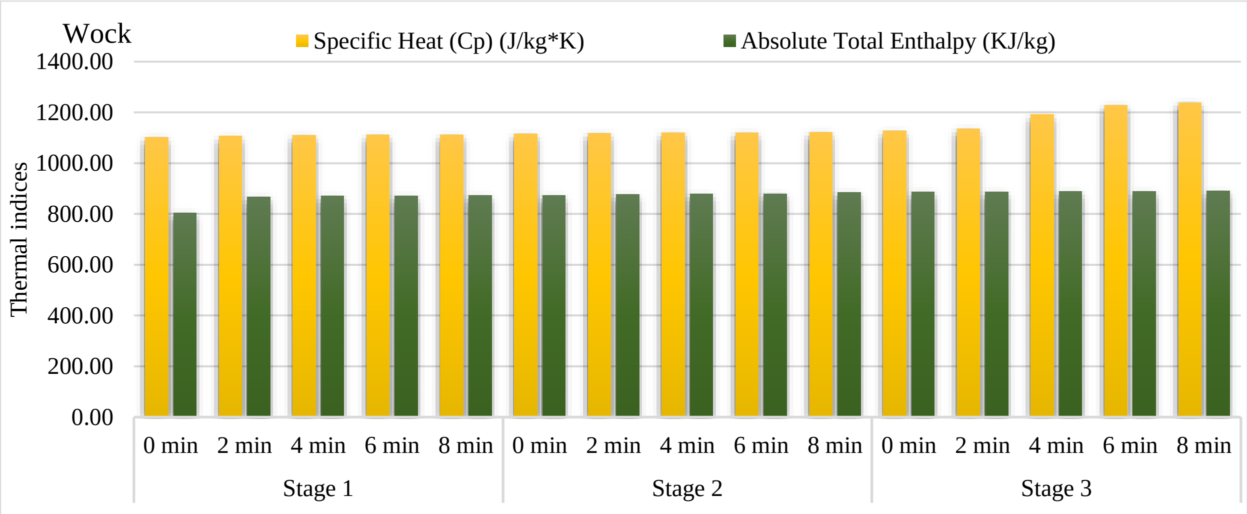

Fig. 8. Changing in Specific Heat and Absolute Total Enthalpy during frying stages of Wock skillet
Source: Author's determination.

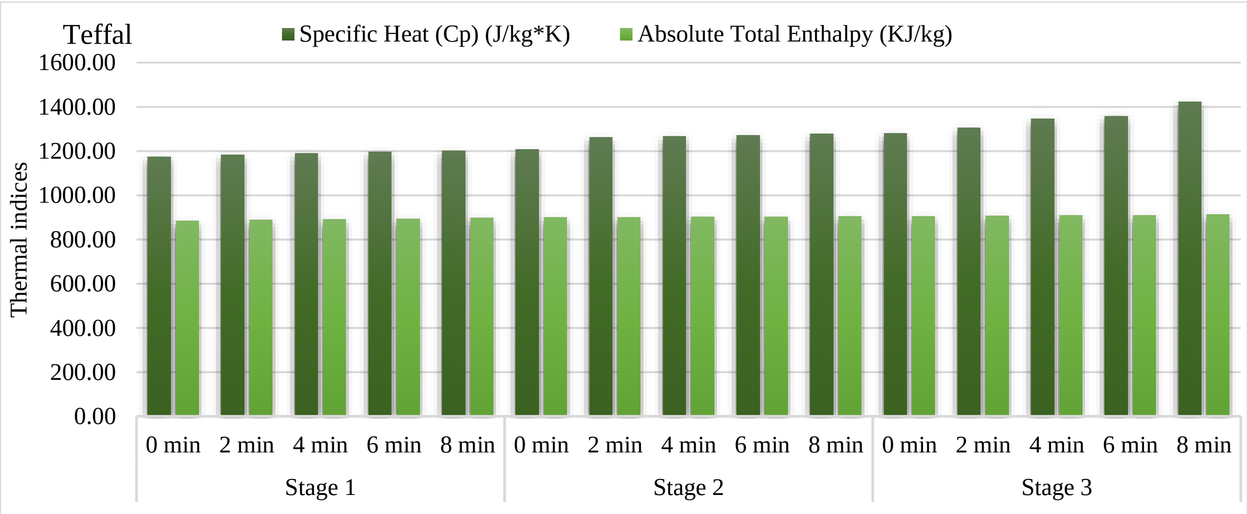

Fig. 9. Changing in specific heat and absolute total enthalpy during frying stages of Teffal skillet
Source: Author's determination.

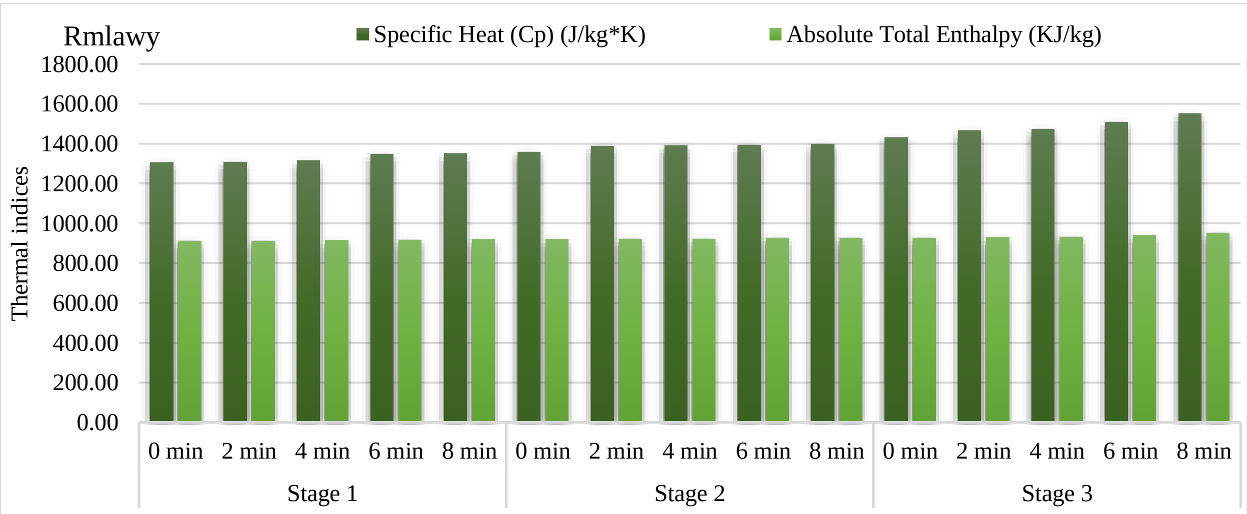

Fig. 10. Changing in specific heat and absolute total enthalpy during frying stages of Rmlawy skillet
Source: Author's determination.

CONCLUSIONS

In a study examining the impact of three types of frying skillets—wok, Tefal, and Rmlawy—on a constant heating process, researchers analysed the physical characteristics of the materials used in each skillet. The findings highlighted significant differences in thermal distribution and energy balance among the skillets. The wok skillet emerged as the most efficient, achieving the best thermal distribution and energy balance, making it an ideal choice for cooking. This efficiency is attributed to the material's superior heat conduction properties, which ensure even heating and optimal energy use. Consequently, the wok skillet's material composition is considered perfect for culinary applications requiring consistent and controlled heating.

REFERENCES

[1]Asokapandian, S., Swamy, G. J., Hajjul, H., 2020, Deep fat frying of foods: A critical review on process and product parameters. Critical Reviews in Food Science and Nutrition, 60(20), 3400-3413. Accessed on July 7, 2024.
[2]Bouchon, P., 2009, Understanding oil absorption during deep-fat frying. Advances in food and nutrition research, 57, 209-234. Accessed on July 7, 2024.
[3]Bulut, M., Boğa,M., 2021, Effects of climate change on agriculture and food security. Sustainable agriculture and livestock for food security under the changing climate, 339. Accessed on July 7, 2024.
[4]Buzera, A., Gikundi, E., Orina, I., Sila, D., 2022, Effect of pretreatments and drying methods on physical and microstructural properties of potato flour. Foods, 11(4), 507. https://doi.org/10.3390/foods11040507. Accessed on July 7, 2024.
[5]Cabreriso, M. S., Chain, P., Gatti, M. B., Ciappini, M. C., 2017, Cambioquímicos y sensoriales producido en aceite de girasol y de oliva extra virgen en el proceso de fritura doméstica. (Chemical and sensory changes produced in sunflower and extra virgin olive in the domestic frying process). In Spanish. Diaeta, 34, 22–28. Accessed on July 7, 2024.
[6]Dura´n, M., Pedreschi, F., Moyano, P.,Troncoso, E., 2007, Oil partition in pre-treated potato slices during frying and cooling. Journal of Food Engineering 2007, 81, 257–265. Accessed on July 7, 2024.
[7]Grebenteuch, S., Kroh, L. W., Drusch, S., Rohn, S., 2021, Formation of secondary and tertiary volatile compounds resulting from the lipid oxidation of rapeseed oil. Foods, 10(10), 2417. Accessed on July 7, 2024.
[8]Health Canada, 2012, Health Canada's Revised Exposure Assesment of Acrylamide in Food. www.hc-sc.gc.ca/fn-an/securit/chem-chim/foodaliment/acrylamide/rev-eval-exposure-expositioneng.php. Accessed on July 7, 2024.
[9]Karunanithy, C., Shafer, K., 2016, Heat transfer characteristics and cooking efficiency of different sauce pans on various cooktops. Applied Thermal Engineering, 93, 1202-1215. Accessed on July 7, 2024.
[10]Liberty, J. T., Dehghannya, J., Ngadi, M. O., 2019, Effective strategies for reduction of oil content in deep-fat fried foods: A review. Trends in Food Science & Technology, 92, 172-183. Accessed on July 7, 2024.
[11]Mowafy, S., Liu, Y., 2024, High-humidity hot-air impingement blanching conditions for the inhibition of potato-browning enzymes and for quality retention. Journal of the Science of Food and Agriculture, 104(5), 2679–2691. https://doi.org/10.1002/ jsfa.13153. Accessed on July 7, 2024.
[12]Pandey, A., Moreira, R.G., 2012, Batch vacuum frying system analysis for potato chips. J Food Process Eng 35(6), 863-873. Accessed on July 7, 2024.
[13]Parkash, S., Gertz, C., 2004, New theoretical and practical aspects of the frying Process. European Journal of Lipid Science and Technology, 106(11), 722–727. Accessed on July 7, 2024.
[14]Pathare, P. B., Roskilly, A. P., 2016, Quality and energy evaluation in meat cooking. Food Engineering Reviews, 8, 435-447. Accessed on July 7, 2024.
[15]Saguy, I., Dana, D., 2003, Integrated approach to deep fat frying: Engineering, nutrition, health and consumer aspects. Journal of Food Engineering 2003, 56, 143–152. Accessed on July 7, 2024.
[16]Zhang, Y., Faghri, A., Howell, J. R., 2010, Advanced heat and mass transfer. Global Digital Press. Accessed on July 7, 2024.