Exploring Thermal Dynamics of Gulabjamun Balls under Hypobaric Conditions

ABSTRACT

The physico-thermal characteristics of Gulabjamun, a traditional dairy product from the Indian subcontinent, were analyzed during hypobaric frying at different temperatures. The study involved frying Gulabjamun balls at 110°C, 115°C, and 120°C for 300 seconds. The sphericity of Gulabjamun was measured by assessing its dimensions along three major axes, resulting in values ranging from 0.969 ± 0.002 to 0.989 ± 0.002. After 300 seconds of frying, the expansion ratio of Gulabjamun ranged from 1.338 ± 0.10 to 1.410 ± 0.06. The apparent density of Gulabjamun decreased as the frying temperature increased. The thermal conductivity of Gulabjamun decreased with longer frying time and higher frying temperature. The thermal diffusivity initially increased up to 150 seconds and then decreased. The volumetric specific heat decreased with higher frying temperature. These findings enrich our comprehension of the intricate physical and thermal processes occurring during the low-pressure frying of Gulabjamun, providing significant implications for both research endeavors and practical applications in the industry.

Keywords:Hypobaric, Frying, Thermal,Analysis, Gulabjamun

1. INTRODUCTION

India, renowned as the world's leading milk-producing country, contributes over 19% of the global milk production. Despite this, the Indian dairy market faces challenges such as a burgeoning demand-supply gap attributed to shifting consumption patterns, rising affluence, evolving demographics, and rapid urbanization in rural areas. To keep pace with India's fast-growing economy, there's a pressing need for accelerated growth in the dairy sector. This growth, however, strains the dairy industry to convert fluid milk into value-added products with extended shelf life[1].

Gulabjamun, a popular deep-fried dairy confection made from khoa, enjoys widespread popularity throughout India. Its production, predominantly handled by halwais using small-scale batch methods, results in significant sensory variations. Ideally, Gulabjamun should exhibit a brown color, smooth spherical shape, soft and slightly spongy texture free from lumps, uniform granular consistency, and a pleasing cooked flavor, fully saturated with sugar syrup at optimal sweetness levels[2].

Sub-baric processing, a novel technique conducted well below atmospheric pressure, presents a promising alternative for frying fruits and vegetables, yielding fried products with enhanced quality. Sub-baric frying offers advantages such as reduced final oil content compared to atmospheric frying, slower oil rancidity development, and preservation of natural color, flavor, and nutritional value due to low temperatures and minimal oxygen exposure[3].

Measurement of thermal properties plays a crucial role in determining heat transfer parameters, especially during food processing operations where temperature gradients are prevalent. Understanding heat and mass transfer dynamics during unit operations like frying is essential. While literature extensively covers such analyses in various food processing scenarios, research on sub-baric processing, especially concerning indigenous dairy products like Gulabjamun, remains scarce. Therefore, an investigation into the heat and mass transfer phenomena during sub-baric processing of Gulabjamun presents an intriguing engineering challenge yet to be explored [4-6].

2. MATERIAL AND METHODS

2.1 Preparation of Gulabjamun balls

To prepare the Gulabjamun balls, milk from the NDRI in Bengaluru, India, was standardized to have 4.0% fat and 8.5% SN. Other constituents such as refined wheat flour and refined sunflower oil were purchased from a local supermarket. The milk was evaporated in an open steam-jacketed kettle under a steam pressure of 196.13 kPa, while stirring continuously, until it reached a semi-solid consistency known as khoa. A dough was then made by mixing 100g of khoa and 30g of refined wheat flour in an orbital mixer, Bangalore, India, for 5 minutes. To achieve a moisture content of 65% (d.b) in the khoa, the required amount of potable water was calculated and added to the dough during the kneading process to ensure even distribution.

.2.2 Sub-baric frying of Gulabjamun

The prepared dough was used to shape balls without the addition of baking powder. These balls were then uploaded in a sub-baric thermal processor (SBTP), consisting of a vacuum frying chamber and a vacuum soaking chamber. The balls were placed in trays, and the trays were lowered into a heated oil bath using the automated hoist system of the processor. Three frying temperatures were chosen based on preliminary studies: 110, 115, and 120ºC. The balls were fried at the selected temperature for a maximum of 5 minutes, with samples taken every 30 seconds for analysis. After the frying, the trays were lifted above the bath of oil and held under complete vacuum (680mmHg) for 10 minutes. Then, the vacuum was released and fired balls were taken from the trays by opening hatch door.

2.3 Estimation of dimension and weight changes

During the frying process, the changes in weight and dimensions of the Gulabjamun were evaluated. A weighing balance was used to measure the weight, while a digital caliper was used to measure the dimensions. The dimensions of the fried Gulabjamun were assessed in terms of 'a', 'b', and 'c' in the 'x', 'y', and 'z' directions of the geometry. Using these values, various parameters such as sphericity, apparent density, and expansion ratio were calculated.

2.4 Sphericity (φ)

Having a good understanding of the geometry and shape of fried foods is essential for studying the transfer of heat and mass within the product. In this study, the balls were examined every 30 seconds while frying to observe its capability to maintain shape at the 3 chosen temperatures. The sphericity of the Gulabjamun was computed using Equation (1) [7].

$$\phi = \frac{\text{Geometric mean diameter}}{\text{Major diameter}} = \frac{(abc)^{1/3}}{a} \quad (1)$$

Where ‘a’, ‘b’ and ‘c’ are the dimensions of Gulabjamun.

2.5 Expansion ratio (ε)

It can be determined by comparing the final cross-sectional area with the initial cross-sectional area. This calculation was performed using the given equation.

$$\varepsilon = \frac{A_t}{A_0} \quad (2)$$

Where A_t is the cross-sectional area at time ‘t’ and A_o is the initial cross sectional area (at time = 0s)

2.6 Apparent density (ρ_{app})

It was determined by dividing the mass of the product by its volume, as stated in Eq 3.

$$\rho_{app} = \frac{\text{Weight of gulabjamun ball}}{\text{Volume of gulabjamun ball}} = \frac{w}{\frac{4}{3}\pi R^3} \quad (3)$$

Where ‘w’ is the weight of Gulabjamun, and ‘R’ is the radius of Gulabjamun.

2.7 Determination of core temperature

Throughout the frying process, the core temperature of the balls was measured using a K-type thermocouple probe connected to a data logger thermometer. Prior to being placed in the frying oil, the thermocouple was inserted into the geometric center of each Gulabjamun dough ball. In each replication of the experiment, the core temperature of the sample was recorded every 10 seconds throughout the frying period.

2.8 Determination of thermal properties

The heat properties of Gulabjamun, including its ability to conduct heat, its rate of heat diffusion, and its specific heat volume, were observed and documented using a KD2 Pro thermal properties analyzer fitted with SH-1 dual needle type probes measuring 30 mm. After removing the Gulabjamun balls from the fryer at 30-second intervals, they were allowed to cool before assessing their thermal properties, also at 30-second intervals. The measurements were taken once the samples had reached the ambient temperature. The probe was inserted into the center of the product and was not disturbed during the measurement process.

3. RESULTS AND DISCUSSION

3.1 Dimensional changes in Gulabjamun during sub-baric frying

3.1.1 Sphericity

Regarding dimensional changes, the average sphericity values of balls fried at 110°C, 115°C, and 120°C were 0.969 ± 0.002, 0.977 ± 0.002, and 0.989 ± 0.002, respectively. These values were close to 1, indicating a nearly spherical shape of the product during frying. However, at lower frying temperatures, slight deviations in sphericity were observed, likely due to the soft crust formed at intermediate frying stages, affecting the product's shape retention

3.1.2 Expansion ratio

In terms of expansion ratio, the maximum values were 1.338 ± 0.10, 1.357 ± 0.11, and 1.410 ± 0.06 after 300 seconds of frying at 110°C, 115°C, and 120°C, respectively as shown in Fig 1. This increase in size was linked to the formation of empty spaces within the product, which occurred due to the quick evaporation of moisture. The rate of expansion increased with higher frying temperatures, consistent with observations from conventional frying studies on pantoa [8].

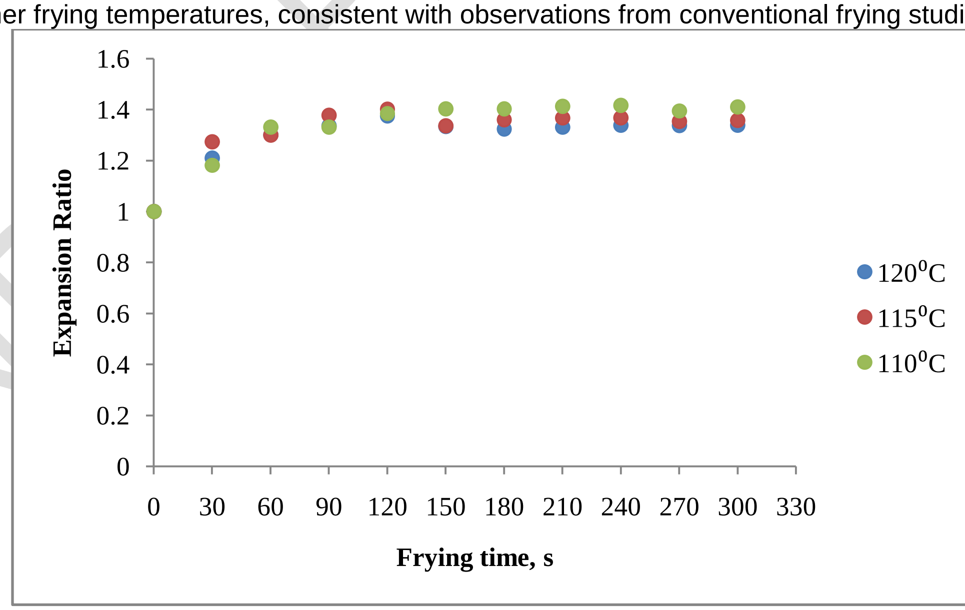

Fig. 1. Expansion Ratio of *Gulabjamun* during sub-baric frying [16]

3.1.3 Apparent density

The apparent density of Gulabjamun during low-pressure frying, calculated as the mass per unit volume, exhibited a decreasing trend with both frying time and temperature. Initially, the density values were measured as 1158.35 ± 90.17 kg/m^3, 1134.81 ± 93.63 kg/m^3, and 1125.50 ± 89.98 kg/m^3 for frying temperatures of 110°C, 115°C, and 120°C, respectively as shown in Fig 2. Subsequently, these values decreased to 681.27 ± 90.17 kg/m^3, 638.61 ± 93.63 kg/m^3, and 626.11 ± 89.98 kg/m^3 for the respective temperatures after the frying process.

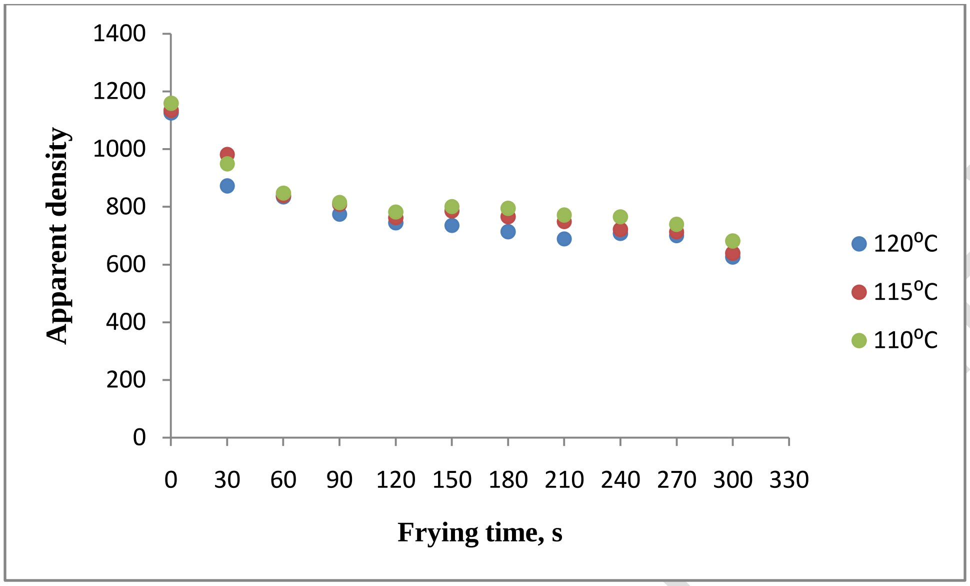

Fig. 2. Apparent density vs. Frying time [16]

Comparison with conventionally fried Gulabjamun, as reported by [9], revealed apparent density values of 827.42 kg/m^3, 808.81 kg/m^3, and 775 kg/m^3 when fried at 125°C, 135°C, and 145°C, respectively. This indicates that hypobaric frying led to a reduced density of the fried product, likely due to rose expansion resulting from product puffing.

The most significant decrease in density occurred at 120°C, possibly due to heightened moisture loss during frying at this temperature. Apparent density was found to be heavily influenced by moisture loss and oil uptake during frying, consistent with previous research [10]. Changes in apparent density were observed within the initial lag period of 30-60 seconds, coinciding with the onset of moisture evaporation from the product. Similar trends in apparent density concerning frying time and temperature have been reported in studies on donuts [11], potato chips [12,13].

3.1.4 Thermal conductivity

It was assessed across various time-temperature combinations, exhibited a decreasing trend. Initially, the thermal conductivity values were recorded as 0.326 ± 0.015 W/mK, 0.339 ± 0.014 W/mK, and 0.343 ± 0.012 W/mK at 120°C, 115°C, and 110°C, respectively as shown in Fig 3. Following 300 seconds of frying, these values declined to 0.192 ± 0.015 W/mK, 0.195 ± 0.014 W/mK, and 0.204 ± 0.012 W/mK for the respective temperatures.

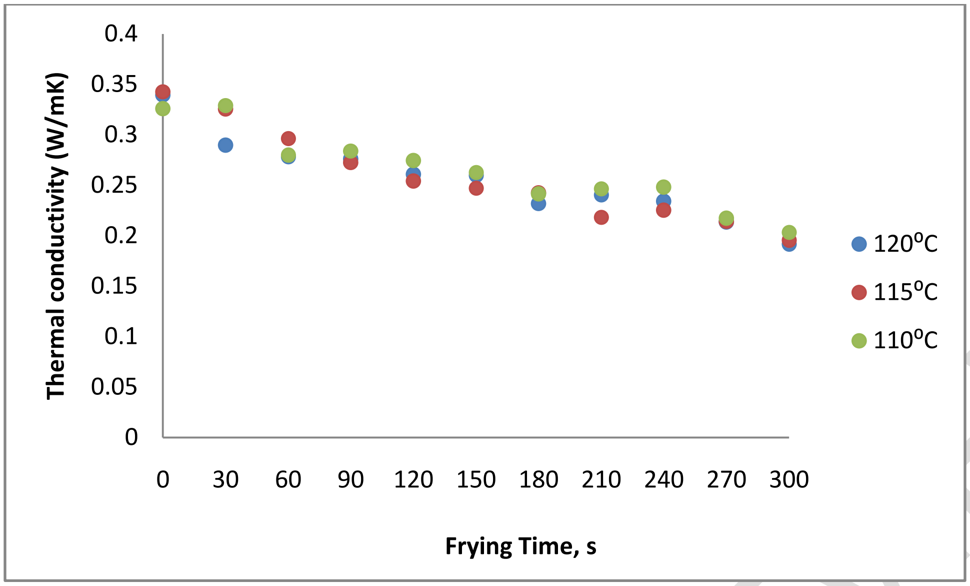

Fig. 3. Thermal conductivity of *Gulabjamun* during hypobaric frying [16]

This reduction over time can be attributed to decreased moisture content and increased fat uptake within the product during frying. Initially, higher moisture levels contributed to elevated thermal conductivity, while the presence of fat acted as insulation, impeding heat conduction, and subsequently lowering thermal conductivity values [14]. These findings align with similar observations reported by [8], who documented a decline in thermal conductivity values of Pantoa from 0.23 to 1.99 W/mK when fried in cooking oil at temperatures ranging from 125°C to 145°C under normal atmospheric pressure.

3.1.5 Thermal diffusivity

The thermal diffusivity of Gulabjamun, measured at various time-temperature combinations during sub-baric frying. It was noted that the thermal diffusivity increased with frying temperature. Specifically, the thermal diffusivity exhibited an ascending trend up to 150 seconds, after which it progressively declined. At the conclusion of the frying process, the thermal diffusivity values were determined to be 0.120 mm^2/s, 0.111 mm^2/s, and 0.108 mm^2/s at 120°C, 115°C, and 110°C, respectively. These findings are consistent with observations made during the frying of similar indigenous dairy products [8]. The fluctuation in thermal diffusivity trends could be attributed to the formation of a crust and its impact on the thermal diffusivity properties.

3.1.6 Volumetric specific heat (Cp)

It was observed that the Cp value decreased from the initial value of 1.099 ± 0.147 MJ/m^3·K to 0.996 ± 0.075 MJ/m^3·K, 1.213 ± 0.082 MJ/m^3·K to 0.984 ± 0.026 MJ/m^3·K, and 1.179 ± 0.173 MJ/m^3·K to 0.963 ± 0.184 MJ/m^3·K while frying at 110°C, 115°C, and 120°C, respectively.This decrease in volumetric specific heat with increasing frying temperature aligns with findings reported by [15] for donuts. Generally, the trend observed was similar to that of thermal conductivity. The reduction in Cp value over time can be attributed to the diminishing moisture content of the product during the frying process.

4 CONCLUSION

This research delved into the physical and thermal characteristics of Gulabjamun during low-pressure frying, uncovering several noteworthy insights. The near-perfect sphericity observed in Gulabjamun suggests a nearly spherical shape. Moreover, the expansion ratio during sub-baric frying surpassed that of traditional frying techniques. The decline in thermal conductivity values throughout the frying process was linked to decreased moisture levels and higher fat absorption within the product.Furthermore, variations in thermal diffusivity values were linked to crust formation during frying. Lastly, the decline in volumetric specific heat (Cp) values with prolonged frying time was associated with decreasing moisture content in the product. These insights enhance our understanding of the complex physico-thermal dynamics involved in the sub-baric frying process of Gulabjamun, offering valuable implications for both research and industry applications

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