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Analysis of physico-thermal characteristics of Gulabjamun balls during hypobaric frying

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Abstract
Gulabjamun is traditional dairy product of the Indian subcontinent. The physico-thermal properties of Gulabjamun during sub-baric (Hypobaric) frying were analyzed at varying temperatures. The Gulabjamun balls were fried at three temperatures 110,115 and 120 °C for 300s. The average sphericity values of Gulabjamun were derived from the dimensions measured along the three major axes as 0.969±0.002 to 0.989±0.002. The expansion ratio values varied from 1.338±0.10 to 1.410±0.06 after 300s of frying. The Apparent density values decreased with increase in the frying temperatures. The thermal conductivity of Gulabjamun decreased as frying time and temperature increased. It decreased from the initial value of 0.326±0.015, 0.339±0.014 and 0.343±0.012W/mK to 0.192±0.015, 0.195±0.014W/mK and 0.204±0.012W/mK at 120, 115 and 110 °C, respectively after 300 s of frying. The thermal diffusivity showed an increasing trend up to 150 s and then progressively decreased to 0.120, 0.111 and 0.108 mm^2/s, at 120, 115 and 110 °C, respectively. The volumetric specific heat value decreased with increase in the frying temperature.

Keywords: Gulabjamun, sphericity, expansion ratio, apparent density, thermal conductivity, thermal diffusivity, volumetric specific heat

Introduction
India is the leading milk producing country of the world, which accounts for more than 19% world's total milk production. The Indian dairy market has been growing steadily and the annual milk production is reported as 155.5 million tonnes in 2015-16 (NDDB, 2016) [8]. In spite of this increase in production, a gap between the demand and supply has become imminent in the dairy industry due to variety of factors such as changing consumption habits, increased purchasing power, dynamic demographic patterns and the rapid urbanization of rural India, necessitating an urgent need for faster rate of growth of the dairy sector to match the rapidly growing Indian economy (Chand *et al*., 2010) [1]. On the other hand, enhanced milk production leads to pressure on the Dairy Industry to convert the fluid milk into milk products with improved shelf life and added value.

Gulabjamun is a deep-fried and soaked dairy product prepared from khoa, widely popular all over India. The manufacture of Gulabjamun is largely in the handled by halwais who adopt small scale batch method and hence there are large variations in the sensory quality of Gulabjamun. In general, the product is characterized with brown colour, smooth and spherical shape, soft and slightly spongy body that is free from lumps, uniform granular texture and a pleasant cooked flavour (Kant and Broadwayb, 2017) [4]. The product should be fully succulent with sugar syrup with optimum sweetness.

Vacuum or sub-baric processing is a novel technique that is carried out well below atmospheric pressure level. Literature reports indicate that sub-baric frying compromises an alternative way to fry fruit and vegetables to yield fried products of enhanced quality attributes. Sub-baric frying has several advantages including, significantly lowered final oil content in comparison to atmospheric fried vegetables and slower development of rancidity of the oil. Most of the benefits of sub-baric frying are attributed to the low temperatures used and the minimal exposure to oxygen, which reduces the adverse effects on the oil quality, preserves the natural colour and flavour and nutritional value of the fried product (Yamsaengsung *et al*. 2011) [15]

Measurements of thermal properties are very important in the determination of heart transfer parameters.

It is reported that heat transfer during food processing operations are very important engineering considerations; these transport phenomena are simultaneous and complex due to the temperature gradients developed in the product. The changes in product characteristics and properties during unit operations such as frying provide an interesting engineering problem to analyse and quantify in order to understand the dynamics of heat and mass transfer. Analysis of heat and mass transfer during processing of various food products is reported in literature (Ni and Datta 1999, Yamsaengsung *et al*., 2008, Farkas *et al*., 1996) [10, 16, 2]. However, reports on its analysis during sub-baric processing are sparse and analysis of these transport phenomena during sub-baric processing of indigenous dairy products such as Gulabjamun is yet to be reported.

Materials and Methods

Preparation of Gulabjamun balls

Milk was procured from the experimental dairy plant of ICAR-National Dairy Research Institute, Bengaluru, India. The milk was standardized to 4.0% fat and 8.5% solids-not-fat (SNF). The other ingredients for the preparation of Gulabjamun such as Maida (refined wheat flour) and refined sunflower oil (Brand: Fortune Sunlite) were obtained from the local supermarket. The standardized milk was converted to khoa by evaporation in an open steam-jacketed kettle (steam pressure: 196.13 kPa) with continuous stirring and scraping until a semisolid dough was obtained. Dough was prepared by blending a mixture in the proportion of khoa (100 g) and refined wheat flour (maida) (30 g) kneaded in an orbital mixer (Make: M/s Lalith Industries, Bangalore, India) for 5 min. The required amount of water to correct the moisture content of khoa to 65% (d.b) was computed and potable water of that volume was added to the dough during the kneading process for uniform and homogenous distribution in the dough.

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Sub-baric frying of Gulabjamun

From the kneaded dough the portioned Gulabjamun balls prepared (without the baking powder) were processed in a sub-baric thermal processor (SBTP). The SBTP consists of a parallel vacuum frying chamber and a vacuum soaking chamber. The Gulabjamun balls were loaded into the trays and loading basket was lowered in to the heated oil bath by running the automated hoist system of the unit. For the experiments three levels of frying temperature were chosen based on preliminary studies i.e., 110, 115 and 120ºC and the balls fried at the chosen temperature up to a duration of 5min and samples were drawn every 30 s for necessary analysis. After the elapse of the frying time, the trays were hoisted above the oil bath and suspended in full vacuum of 680mmHg for 10 min. Thereafter, the vacuum of the unit was broken, the hatch door of the unit was opened and the trays were retrieved to collect the fried Gulabjamun balls.

Determination of weight and dimensional changes

The weight and dimensional changes of Gulabjamun during frying were measured using a weighing balance (Model: CP323S, Sartorius Mechatronics India Pvt. Ltd.) and digital caliper (Model: CD-6"CSX, Mitutoyo Corp. Kawasaki, Japan), respectively. The dimensions of fried Gulabjamun were measured as 'a', 'b' and 'c' in 'x', 'y' and 'z' directions of the geometry, respectively. From the 'a', 'b' and 'c' values obtained, sphericity, apparent density and expansion ratio were calculated.

Sphericity (φ)

The geometry of fried foods is essential to model the heat and mass transport phenomena in the product. Gulabjamun at every 30 s of frying were evaluated for their ability to retain the shape at all the three temperatures. Sphericity of Gulabjamun was calculated using Eq (1) (Mohsenin, 1980) [6].

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

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

Expansion ratio (ε)

The expansion ratio of a product can be defined as the ratio of final cross sectional area to initial cross sectional area. It was determined using Eq.

$$\varepsilon = \frac{A_t}{A_0} \tag{2}$$

Where A_t is the cross sectional area of Gulabjamun at time't' and A_o is the initial cross sectional area of Gulabjamun (at time = 0s)

Apparent density (ρ_{app})

The apparent density (ρ_{app}) of the fried Gulabjamun was calculated as mass per unit volume from the Eq.

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

Where *'w'* is the weight of Gulabjamun and 'R' is the radius of Gulabjamun.

Measurement of core temperature

The core temperature of the Gulabjamun balls during frying was documented using a thermocouple (K type) probe of the data logger thermometer (Model: CENTERR 309, Ankom International, Bengaluru, India). The geometric centre of Gulabjamun (dough ball) was pierced using the thermocouple before immersing the ball in oil for frying. The core temperature of the sample was recorded every 10 s during the entire period of frying for each replication of the experiment.

Measurement of thermal properties

The thermal properties of Gulabjamun such as thermal conductivity, thermal diffusivity and volumetric specific heat were monitored and recorded using KD2 Pro thermal properties analyzer (Decagon Devices, Pullman, WA) with SH-1, dual needle type probes (30 mm). Gulabjamun balls were withdrawn from the fryer at 30s interval and cooled before determination of the thermal properties at 30s intervals. The properties were measured after cooling the samples to ambient temperature. The probe was inserted into the geometric centre of the product and kept undisturbed when the measurement was taken.

Results and Discussions

The physico-thermal properties of Gulabjamun as it transitioned at various times during sub-baric frying were determined and the results are discussed below.

Dimensional changes in Gulabjamun during sub-baric frying

Sphericity

The average sphericity values of Gulabjamun fried at 110, 115 and 120 °C were derived from the dimensions measured along the three major axes as 0.969 ± 0.002, 0.977 ± 0.002 and 0.989 ± 0.002, respectively. Since the sphericity values were near unity, the product was considered as a sphere for the modelling of heat and mass transfer phenomena. The sphericity of Gulabjamun was observed to be marginally lower at lower frying temperatures, probably since the product sampled at intermediate stages of frying had a soft crust, which could not retain its shape.

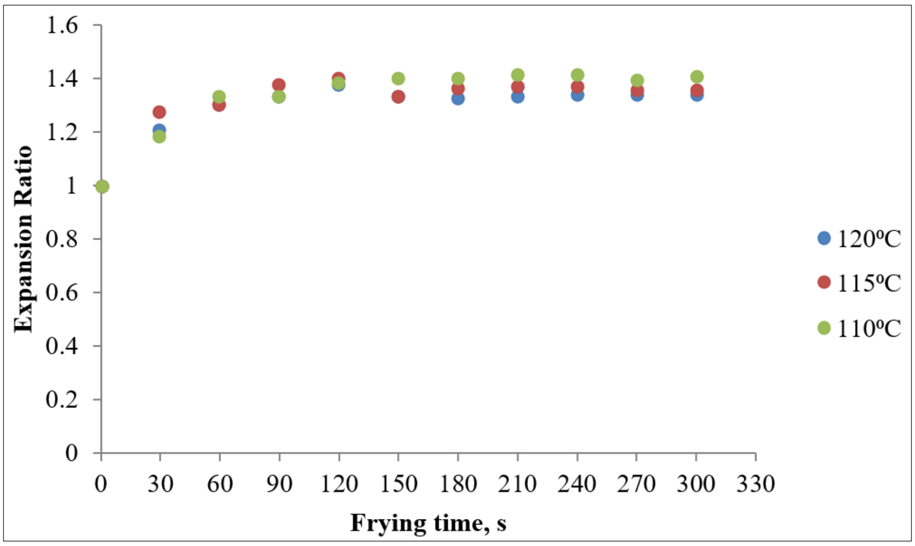

Fig 1: Expansion Ratio of Gulabjamun during sub-baric frying

Expansion ratio

Changes in expansion ratio of Gulabjamun with respect to frying time and temperature are depicted in Fig. 1. The maximum expansion ratios of 1.338 ± 0.10, 1.357 ± 0.11 and 1.410 ± 0.06 were attained after 300s of frying at 110, 115 and 120 ºC, respectively. The product expansion was attributed to the formation of void spaces in the product, formed by flash evaporation of moisture.

The rate of expansion of Gulabjamun increased with increase in frying temperature and is in accordance with the observations made during conventional frying of *pantoa* (Neethu *et al*., 2014) [9]

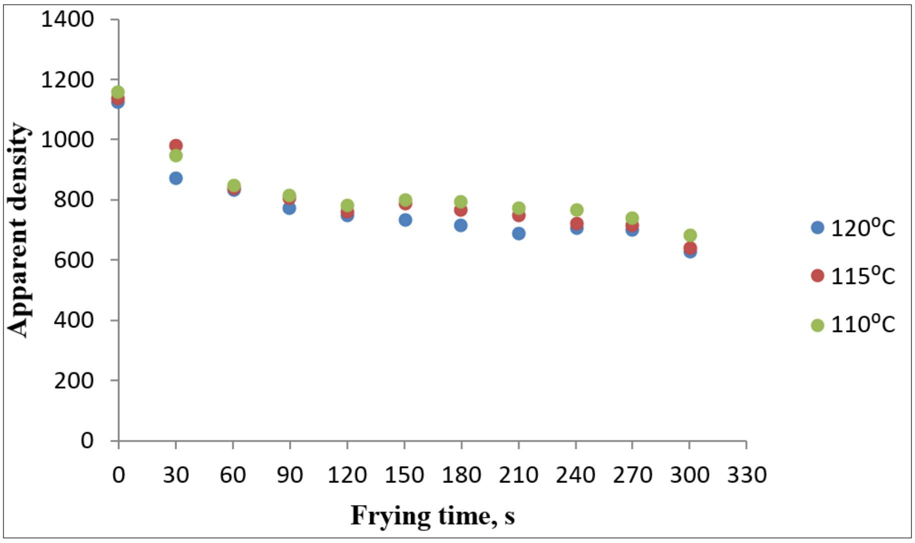

Fig 2: Apparent density vs. frying time

Apparent density

The apparent density of Gulabjamun during sub-baric frying was computed as mass per unit volume and observed to decrease with frying time and temperature (Fig. 2). The initial value of 1158.35 ± 90.17, 1134.81 ± 93.63 and 1125.50 ± 89.98 kg/m^3 decreased to 681.27 ± 90.17, 638.61 ± 93.63 and 626.11 ± 89.98 kg/m^3 for frying at 110, 115 and 120 °C, respectively.

The mean apparent density of conventionally fried Gulabjamun was reported to be 827.42, 808.81 and 775kg/m^3

when fried at 125, 135 and 145 °C, respectively (Franklin *et al*., 2013) [3], indicating that sub-baric frying resulted in lower density of the fried product which could be due to increased expansion as a result of the puffing of the product.

The highest decrease in density of the product at 120 °C could be due to the increased moisture loss in the product during frying at this temperature. The apparent density was reported to be highly influenced by moisture loss and oil uptake during frying (Krokida *et al*., 2000) [5]. The changes in apparent density was observed after 30-60 s of frying (initial lag period), i.e., when most of the moisture start to evaporate from the product. A similar trend for apparent density as a function of frying time and temperature during frying of donuts (Vélez-Ruiz and Sosa-Morales, 2003a) [12], potato chips (Moreira *et al*., 2009; Yagua and Moreira, 2011) [7, 14] was reported.

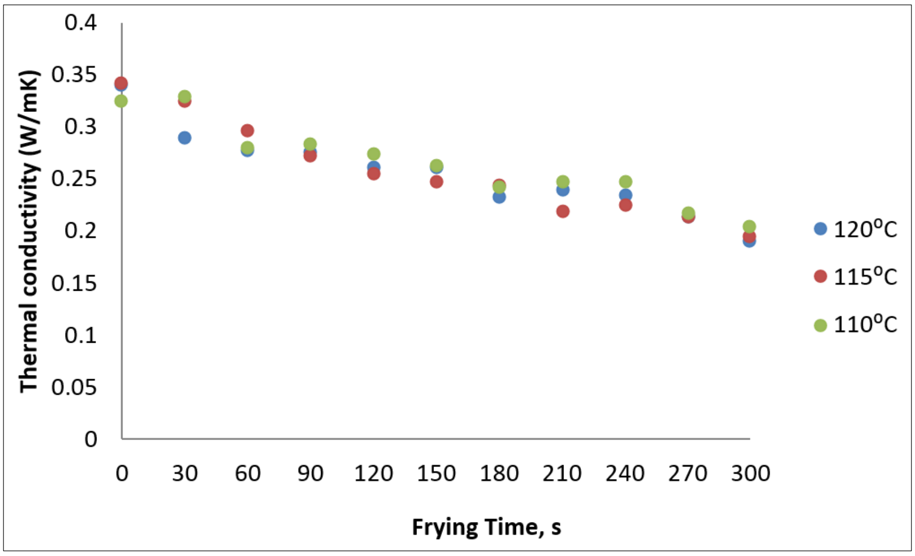

Fig 3: Thermal conductivity of Gulabjamun during sub-baric frying

Thermal conductivity

The thermal conductivity of Gulabjamun samples measured at different time - temperature combinations is shown in Fig. 3. The thermal conductivity of Gulabjamun decreased as frying time and temperature increased. It decreased from the initial value of 0.326±0.015, 0.339±0.014 and 0.343±0.012W/mK to 0.192±0.015, 0.195±0.014W/mK and 0.204±0.012W/mK at 120, 115 and 110 °C, respectively after 300 s of frying. The decrease in 'k' values with time could be attributed to reduced moisture content and increased fat uptake in the product during frying. Initially, there was more moisture in the product, and it contributed to higher thermal conductivity. Fat acts as insulation and reduce the heat conduction, thereby lowering the 'k' values (Radhakrishnan, 1997) [11]. The results are also consistent with the findings of (Neethu *et al*., 2014) [9]. They reported that the 'k' values of Pantoa decreased from 0.23 to 1.99W/mK when fried in cooking oil at 125 to 145 °C at normal atmospheric pressure.

Table 1: Thermal diffusivity at different frying temperatures

Frying time	110 °C	115 °C	120 °C
0	0.101±0.013	0.102±0.011	0.103±0.008
30	0.102±0.030	0.103±0.002	0.106±0.010
60	0.101±0.001	0.105±0.006	0.115±0.003
90	0.103±0.003	0.106±0.008	0.116±0.008
120	0.103±0.001	0.111±0.004	0.118±0.009
150	0.132±0.001	0.156±0.009	0.129±0.006
180	0.122±0.031	0.121±0.018	0.127±0.010
210	0.120±0.009	0.120±0.008	0.125±0.012
240	0.111±0.010	0.113±0.008	0.123±0.020
270	0.110±0.005	0.112±0.070	0.121±0.027
300	0.108±0.020	0.111±0.009	0.120±0.022
Average	0.110±0.003	0.114±0.009	0.118±0.019

Thermal diffusivity

The thermal diffusivity of Gulabjamun measured at different time-temperature combinations of sub-baric frying is tabulated in Table 1; it was observed to increase as a function of frying temperature. The thermal diffusivity showed an increasing trend up to 150 s and then progressively decreased to 0.120, 0.111 and 0.108 mm^2/s, at 120, 115 and 110 °C, respectively. These results are consistent with frying of similar indigenous dairy products (Neethu *et al*., 2014) [9] and may be attributed to the effect of crust formation and its effect on thermal diffusivity.

Table 2: Volumetric specific heat values at different frying temperatures

Frying time	110 °C	115 °C	120 °C
0	1.099±0.147	1.213±0.082	1.179±0.173
30	1.249±0.397	1.091±0.280	1.241±0.270
60	1.110±0.141	1.112±0.208	1.151±0.217
90	1.169±0.210	1.125±0.379	1.111±0.293
120	1.158±0.204	1.034±0.102	1.064±0.222
150	1.072±0.169	1.100±0.033	0.983±0.036
180	0.893±0.326	0.868±0.084	1.842±0.050
210	0.937±0.261	0.987±0.064	1.816±0.255
240	0.835±0.306	0.941±0.299	0.697±0.268
270	0.877±0.385	0.714±0.139	0.770±0.529
300	0.555±0.085	0.640±0.141	0.733±0.254
Average	0.996±0.075	0.984±0.026	0.963±0.184

Volumetric specific heat (Cp)

The volumetric specific heat of Gulabjamun samples measured at different frying times and temperatures is presented in Table 2. The Cp value decreased from the initial value of 1.099±0.147MJ/m^3.K to 0.996±0.075, 1.213±0.082 to 0.984±0.026 and 1.179±0.173 to 0.963±0.184MJ/m^3.K while frying at 110, 115 and 120 ºC, respectively. The volumetric specific heat decreased with frying temperature which is in accordance to the observation reported by Vélez-Ruiz and Sosa-Morales (2003b) [13] for donuts. In general, Cp showed a trend similar to that of thermal conductivity and the decrease in Cp value with time could be attributed to the decrease in moisture content of the product.

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Conclusion
The study evaluated the physico-thermal properties of Gulabjamun during sub-baric frying. Sphericity of Gulabjamun was nearer to unity and the expansion ratio of sub-baric fried Gulabjamun was comparatively more than the conventional one. The decrease in thermal conductivity values with increase in frying time could be attributed to reduced moisture content and increased fat uptake in the product during frying. The variation of thermal diffusivity values may be attributed to the effect of crust formation and its effect on thermal diffusivity. The decrease in Cp value with increase in frying time could be attributed to the decrease in moisture content of the product

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