HEAT AND MASS TRANSPORT MODELLING DURING MEAT BALL COOKING

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Summary: The meat-ball (4.7 cm diameter) cooking processes (baking, broiling, deep-oil frying, and boiling) were modelled by using Fourier and Fick's laws for unsteady state. These were solved using appropriate initial and boundary conditions, finite difference, and continuous system modelling program (CSMP). The process models were validated with temperature profiles at different locations and mass loss during cooking. The average normalized standard errors between the observed and predicted temperature profiles were 3.53, 5.12, 3.83, and 3.04, respectively for baking, broiling, deep-oil frying and boiling. The average standard error between predicted and calculated meatball masses were estimated to be 0.04, 0.19 and 0.13 for baking, broiling, and deep-oil frying, respectively. These models are appropriate for developing process conditions and to predict time and cooking moisture loss.

Introduction: The objective of this study was to study the coupled heat and moisture transfer phenomena within a meatball during different cooking processes. This was achieved by modelling and predicting the temperature distribution and mass loss in meatballs during baking (forced convective oven cooking), broiling, deep-oil frying and boiling. The cooking is defined as a thermal process that leads to either positive or negative changes in a food product. All cooking processes are dependent on heat and moisture transport within and around the food product. Baking is typically performed on foods in ovens with induced air circulation. Broiling is realized primarily by radiative heat transfer from the oven walls. The radiative energy is transported by electromagnetic waves, and the rate of radiation is dependent on the temperature and spatial relationships of food material involved. Deep-oil frying is a cooking process typically conducted for its characteristic sensory properties, such as crisp crust, attractive aroma and colour. Boiling is performed at temperatures below or around 100°C, in either water or soups (Skjoldebrand, 1984). Holtz and Skjoldebrand (1986) developed a heat and mass transfer model to simulate the temperature profiles in meat loafs during baking. Burfoot and James (1984) modelled the roasting of a meat joint by Fourier heat transfer equation. Mittal and Blaisdell (1982) developed heat and mass transfer models for frankfurters cooking based on the Fick's and Fourier equations. Burfoot and Self (1988) developed a numerical model to predict the boiling time of beef cubes (20 and 30 mm^3) to within 1°C of water temperatures (65, 75, 85, and 95°C). Burfoot et al. (1990) compared the heating/cooling times and mass losses of meat joints by convective, immersion, and pressure/vacuum processes.

Materials and Methods: Cooking experiments were conducted to obtain temperature profiles and mass histories during baking, broiling, deep oil frying and boiling. Effective surface heat transfer coefficients for these cooking processes were also determined. Beef portions from shoulder and neck were grounded through 1 cm dia. orifices. A commercial minced meat recipe, required 12.3 kg of coarsely grounded beef, 1.575 kg of added water, and 1.125 kg of the hamburger binder/spice mix for every 15 kg of minced meat batch. These ingredients were mixed and grounded through 0.5 cm diameter orifices. Composition of this minced meat consisted of 64.50% water, 15.86% protein, 13.34% fat, 3.94% carbohydrate and 2.36% ash. Frozen minced beef packages were thawed at 2°C for 72 h prior to meatball preparation. A pair of commercial meatball shapers (4.7 cm inner dia.) were utilized to form meatballs weighing 60 ± 0.05 g each. A data acquisition and control system, consisted of a data-logger, a CPU module and serial interface (Labmate, CPU module Model 901; Sciemetric Instruments Inc., Nepean, Ontario), and a portable computer (Tandy 200, Radio Shack Inc.) were used. A BASIC control algorithm was implemented on the computer to interface with the data acquisition system. Temperature and mass data were retrieved and stored at set intervals (every 10 s during the first minute, and every 30 s there after) until the completion of each experiment.

For meatball temperature measurements, thermocouples were placed in the centre, 1.175 cm from the centre, and at the meatball surface. An additional thermocouple to monitor the heating medium temperature was located in the proximity of the meatballs. A meatball was considered cooked when its centre reached 70°C. Continuous mass measurements during baking and broiling were achieved by two cantilever load cells, which were constructed in full-bridge configurations to compensate for the temperature effect. Since high buoyancy forces in an agitated media restrict the usage of the mass measurement set up during deep-oil frying and boiling, manual weighing of meatballs at predetermined intervals were performed.

A commercial kitchen size multi-mode oven (400x380x600 cm) was used for all baking and broiling experiments (Deacor "Convection Plus" Self Cleaning Wall Oven, Model W305C, Pasalena, CA). The built-in convection heating mode (mode 5), which was a combination of top and bottom heating elements, with induced air circulation of 0.5 to 0.9 m/s (240 cm in front of the fan), was utilized for baking. Meatball broiling procedures were identical to that of baking. The oven, however, was set to the broiling mode (mode 2, heated top element only). A thermostatically controlled bath circulator (Circulator E8, Haake Mess-Technik GmbHu. Co., Germany) was used in all frying experiments. This circulator has a heating capacity of 1500 W, circulation rate of 15/min, and fluid temperature control within ± 0.02°C. The bath vessel, measured 310 x 290 x 130 cm, had a capacity of 12 L. Procedures for meatball boiling were identical to that of deep-oil frying. Water temperature of 90°C was used.

Model Development: During these cooking processes, heat energy is transferred by convection from the heating media to the meatball surface, followed by conduction towards the geometric centre. Meanwhile, molecular moisture diffuse outward to the meatball surface, which in turn is vaporized and lost to the surrounding through convection. An one dimensional spherical finite difference framework, consisted of ten concentric shells of equivalent thickness, was developed to solve the heat and moisture transfer models. Eleven nodes in total, one at the centre of each shell element, and the eleventh one on the outer surface were assigned.

The model assumed that: (i) the meatballs were homogeneous, isotropic, porous and spherical in geometry; (ii) initial temperature and moisture distributions in meatballs were uniform; (iii) capillary flow of water was mobilized by concentration gradient in liquid state through out the meatballs; (iv) vaporization of water was restricted to the meatball surface only; (v) negligible meatball shrinkage, and negligible effect of crust formation on physical properties; and (vi) fat transport was neglected. Based on above assumptions, mathematical models for these processes are as follows:

Heat Transfer: $$\frac{\partial T}{\partial t}=\frac{1}{r^2}\frac{\partial}{\partial r}(\alpha r^2\frac{\partial T}{\partial r}) \quad (1)$$

Moisture transfer $$\frac{\partial m}{\partial t} = \frac{1}{r^2}\frac{\partial}{\partial r}(D_m r^2\frac{\partial m}{\partial r}) \quad (2)$$

Initial conditions $$T(r,0) = T_0, \qquad m(r,0) = m_0 \quad (3)$$

Boundary conditions

$$\left.\frac{\partial T}{\partial r}\right|_{r=0} = 0, \qquad \left.\frac{\partial m}{\partial r}\right|_{r=0} = 0, \qquad \left.\frac{\partial m}{\partial r}\right|_{r=R} = m_e \quad (4)$$

$$k\left.\frac{\partial T}{\partial r}\right|_{r=R} = h(T_a-T_s) + D_m \cdot \rho_{dm} \cdot L_v\left.\frac{\partial m}{\partial r}\right|_{r=R} \quad (5)$$

where T_a = processing temperature, T_o = initial meatball temperature, r = radial position, α = thermal diffusivity, t = time, m_e =

equilibrium moisture concentration, m_o = initial moisture concentration, D_m = moisture diffusivity, L_v = latent heat of vaporization, R = meat ball radius, T_s = meat ball surface temperature, T = meat ball temperature, m = meat ball moisture content, k = thermal conductivity, h = heat transfer coefficient and ρ_{dm} = density of dry matter. Expending Eqn. 1 and 2 with constant α and D_m:

$$\frac{\partial T}{\partial t} = \alpha\left(\frac{2}{r}\frac{\partial T}{\partial r} + \frac{\partial^2 T}{\partial r^2}\right) \qquad \frac{\partial m}{\partial t} = D_m\left(\frac{2}{r}\frac{\partial m}{\partial r} + \frac{\partial^2 m}{\partial r^2}\right) \tag{6}$$

To simplify the numerical calculations, temperature (θ), moisture content (C) and radial length (ψ) in non-dimensional forms are defined as follows:

$$\theta = \frac{T - T_o}{T_a - T_o} \qquad \partial C = \frac{m - m_e}{m_o - m_e} \qquad \psi = \frac{r}{R} \tag{7}$$

subsequently, the model (Eqn. 1 to 6) in non-dimensional form becomes:

$$\frac{\partial \theta}{\partial t} = \frac{\alpha}{R^2}\left(\frac{2}{\psi}\frac{\partial \theta}{\partial \psi} + \frac{\partial^2 \theta}{\partial \psi^2}\right) \qquad \frac{\partial C}{\partial t} = \frac{D_m}{R^2}\left(\frac{2}{\psi}\frac{\partial C}{\partial \psi} + \frac{\partial^2 C}{\partial \psi^2}\right), \qquad \theta\ (\psi,\ 0) = 0, \quad C\ (\psi,\ 0) = 1 \tag{8}$$

$$\frac{k\,\partial \theta_s (T_a - T_o)}{R\,\partial \psi} = h(T_a - T_s) + \frac{D_m\,\rho_{dm}\,L_v}{R}\frac{\partial C}{\partial \psi}(m_o - m_e), \qquad \frac{\partial C_s}{\partial \psi} = C_e \tag{9}$$

Results and Discussion: Effective heat transfer coefficients for meatballs during baking, broiling, frying and boiling are summarized in Table 1. Experimental meatball moisture diffusivities for meatball baking, broiling and deep-oil frying were determined from one set of observed data. No significant moisture loss was observed during meatball boiling in water. The experimental minced meat equilibrium moisture contents reported by Hallstrom (1990) were used.

Baking: Observed and predicted meatball temperature profiles are shown in Fig. 1. The rates of temperature change were initially sluggish due to heat transfer lags, but gradually increased as the experiment progressed. An average baking time of 1600 s was required to raise the meatball centre to 70°C. The simulated temperature profiles agreed well with the experimental data. The normalized standard errors varied between 1.28 to 4.79 for four experimental runs. The observed and predicted meatball mass histories are given in Fig. 2. The observed mass history reflected the combined moisture and fat losses during the baking process. The average observed final meatball mass was 53.2 g. The standard error between the observed and calculated mass histories was determined to be about 0.04.

Broiling: Fig. 3 exhibits the observed and predicted temperature profiles during meatball broiling. The average broiling time required for meatball centre to reach 70°C was 2600 s. The oscillatory oven temperature, which fluctuated in excess of 15°C (10.7%) around the 140°C set point, was attributed as a major source of high overall temperature standard errors, which ranged from 3.95 to 6.37 between the observed and predicted temperature profiles. Compared to baking at the same oven temperature of 140°C, broiling required 980 s, or approximately 60% longer in cooking time (Table 1). The observed mass profile (Fig. 4) indicates that the mass of meatball increased for a short time period immediately after the initiation of the baking. An average final meatball mass of 53.24 g was observed. The simulated mass history had successfully predicted with standard errors between 0.17 and 0.2.

Deep-Oil Frying: The observed and predicted deep-oil meatball frying results are shown in Fig. 5 and 6. The average deep-oil frying time of meatball was recorded at 670 s, achieved by a combination of high heat transfer coefficient and thermal conductivity of the frying oil. The simulated temperature profiles at the two experimental nodes closely predicted the experimental data, with normalized standard errors ranged between 2.42 and 4.84. An average final meatball mass of 57.9 g was calculated from four frying experiment runs. The predicted mass history, which was simulated based on a constant moisture diffusivity value independent of moisture content and temperature, has a standard error of 0.13.

Boiling: An average meatball boiling time was 770 s. Normalized standard error ranged from 2.73 to 3.59 between the observed and predicted temperature profiles.

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Table 1. Summary of effective surface heat transfer coefficients at specific processing conditions during meatball baking, broiling, deep-oil frying and boiling

Process	Processing conditions			h_{eff} W/(m^2.K)	h_{calc} W/(m^2.K)	α m^2/s	D_m m^2/s	Cooking time, s	Final mass, g	Std. error (T)	Std. error (mass)
	Temperature °C	R.H. %	Velocity m/s								
Baking	140 ± 10	0.5	0.7 ± 0.2	23.0	18.8	1.8E-7	0.39E-9	1620	57.4	1.3 to 4.8	0.03 to 0.05
Broiling	140 ± 15	0.5	~ 0	9.0	11.5	1.9E-7	0.25E-9	2600	57.4	3.9 to 6.4	0.17 to 0.2
Frying	115 ± 0.4	0	1*	284.6	558	1.6E-7	0.80E-9	672	57.9	2.4 to 4.8	0.13
Boiling	90 ± 0.4	100	1*	4518	4134	1.6E-7	N/D	766	60.5	2.7 to 3.6	N/A

* value estimated based on circulator manufacturer specification; R.H.= relative humidity; h_{eff} = effective heat transfer coefficient, experimental h_{calc} = heat transfer coefficient calculated from empirical equations; D_m = moisture diffusivity; α = thermal diffusivity; N/D = not determined

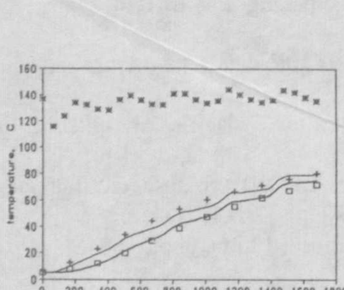

Fig. 1 Observed and predicted meatball temperature profiles during baking. * oven temperature; □ centre observed; – centre predicted; + midpoint observed; - midpoint predicted

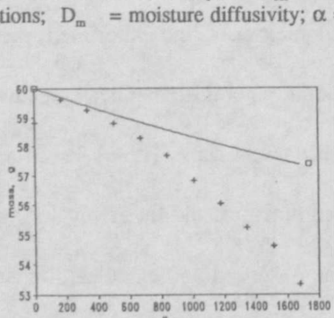

Fig. 2 Observed and predicted meatball mass histories during baking. □ observed (moisture lost only); + observed (moisture and fat lost); - predicted (moisture lost only)

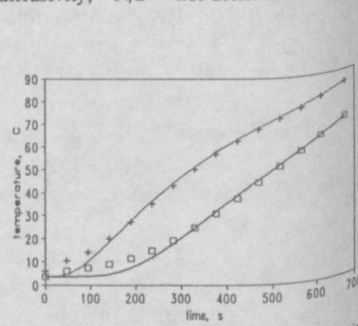

Fig. 5. Observed and predicted meatball temperature profiles during deep-oil frying at 115°C. □ centre observed; – centre predicted; + midpoint observed; - midpoint predicted

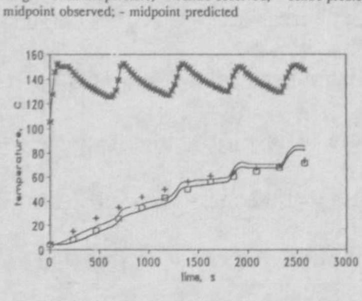

Fig. 3 Observed and predicted temperature profiles during meatball broiling. * oven temperature; □ centre observed; – centre predicted; + midpoint observed; - midpoint predicted

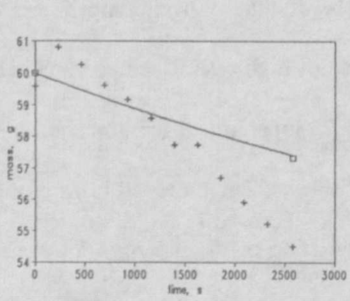

Fig. 4. Observed and predicted mass histories during meatball broiling. □ observed (moisture lost only); + observed (moisture and fat lost); - predicted (moisture lost only)

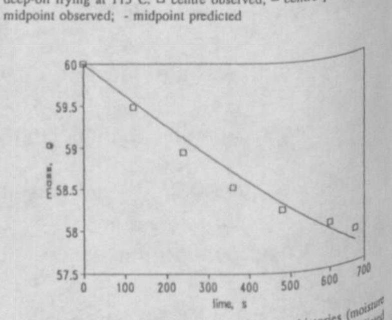

Fig. 6. Observed and predicted meatball mass histories (moisture lost only) during meatball deep-oil frying. □ observed; - predicted

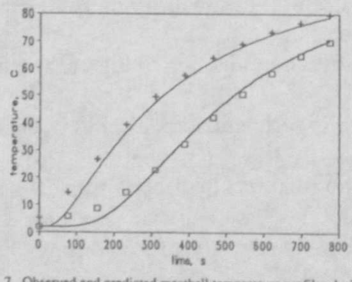

Fig. 7. Observed and predicted meatball temperature profiles during boiling at 90°C. □ centre observed; – centre predicted; + midpoint observed; - midpoint predicted