Fuzzy Logic Control of Food Frying Process: A Conception of Frying Process Control

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ABSTRACT

Food frying process control using fuzzy logic is concerned with physiochemical changes occurring in food due to the effect of heating. The consumers as well as producers are particular about the nutritive, taste, unique flavor-texture combination, aesthetic values of food and the efficiency of the food frying process. To meet these requirements, a conception of frying process control was developed and analyzed.
Frying process productivity depends on the obtained oil temperature to form a basis for the controller programming. It was found that there is a possibility of increasing frying process efficiency while maintaining required food quality features. To achieve these goals, modifications of both frying equipment and product formulation have been explored and the continuous fryer for food frying process control was developed.

A unique fuzzy logic controller structure with an efficient realization and small base rule that can be easily implemented in existing industrial controllers was proposed and simulated. The FLC also exhibits robustness in performance for plant with significant variation in dynamics, which is an advantage over PID.

(Keywords: frying of food, frying oil, process control, fuzzy logic, measured and manipulated variable)

INTRODUCTION

Food frying is defined as a process of cooking and drying through contact with hot oil and involves simultaneous heat and mass transfer. The quality of the products from frying depends not only on the frying conditions but also on the type of oils and foods used during the process. Oils play a dual role in the preparation of fried foods because they serve as a heat transfer medium between the food and the fryer, and they also contribute to the food's texture and flavor characteristics.

In frying of foods, the temperature of the heated oil, the frying time, and the fryer type (batch or continuous) are factors that affect the process.

The speed and efficiency of the frying process depend on the temperature and quality of the frying oil. The temperature of the oil is usually between 160 C and 205 C. It is important to understand what happens to the temperature, moisture content, and oil content of the product during the frying process to determine safe temperatures and turnover times of the frying oil for a given fryer type.

In many control applications we know how we want a system to behave but find it difficult to express the desired behavior in an analytic formula. Fuzzy logic is a powerful tool for expressing human preferences and making the control system behavior accurately reflect these preferences.

This study was conducted to reveal the nutritive, taste, and aesthetic values of food, most especially the efficiency and optimization of the frying process, which is very important to both consumers and producers.

In this case the main problem is proper system of fryer operation control to achieve the desired efficiency and at the same time maintain the necessary nutrient values of the fried products. When developing the rules for control system, the main streams of supplied and consumed thermal energy must be considered.

The work on fuzzy logic control of food frying process is divided into five parts for detailed study (Figure 1).

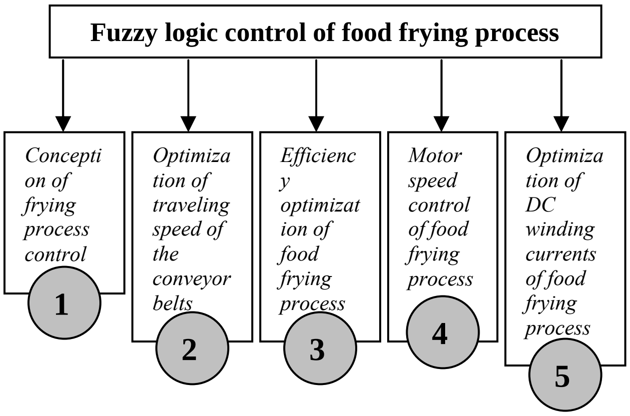

Figure 1: Division of work on Fuzzy Logic Control of Food Frying Process [In Print Papers - Osofisan, et al. 2008 a-e, PJST 8(2)]

HEAT TRANSFER

There are two basic modes of heat transfer involved in the process of frying, and those are convection (all sides contact, additional medium - liquid and gas required) and conduction (direct contact, no additional medium required). The oil serves as the heating medium. Heat is transferred from the oil to the surface of the product by way of convection. It is then transferred from the surface to the center by conduction. Thermal properties of the food material such as specific heat, thermal conductivity and density affect the rate at which heat is conducted. The magnitudes of these properties change throughout the frying process.

Water is an important factor in convective heat transfer, water migrates from the central portion of the food material radially outward to the walls and edges to replace that which is lost by dehydration at the surface. As the phase change from liquid water to steam occurs, thermal energy from the frying oil is carried off, which prevents burning caused by excessive dehydration. Due to the ability of the water to remove thermal energy from the oil, the temperature of the food material only reaches approximately 100 C even though the oil temperature may be around 180 C. As water escapes from the inner portion of the product and comes into contact with the hot oil, bubbles form and move vigorously throughout the oil, therefore causing turbulence. In general, turbulent conditions promote more rapid heat transfer. The amount of water vapor bubbles decrease with increased frying time due to the decreased amount of remaining moisture within the product.

THERMAL ENERGY TRANSFER

The proper system design of fryer operation control is very important to achieve the desired efficiency and at the same time to maintain the necessary nutrient values of the fried products. When developing the rules and the control system, the main stream of supplied and consumed thermal energy must be considered (Figure 2)[6].

The streams are as follows:

Q1-thermal power necessary for heating and evaporation of water contained in the raw products,

Q2-thermal power necessary for raw products heating,

Q3-thermal power necessary for heating supplementary fat placed in the fryer,

Q4-thermal power transmitted to the environment through the fryer casing,

Q5-thermal power transmitted by the fryer ventilation system to the environment,

Q6-thermal powers radiated into the environment.

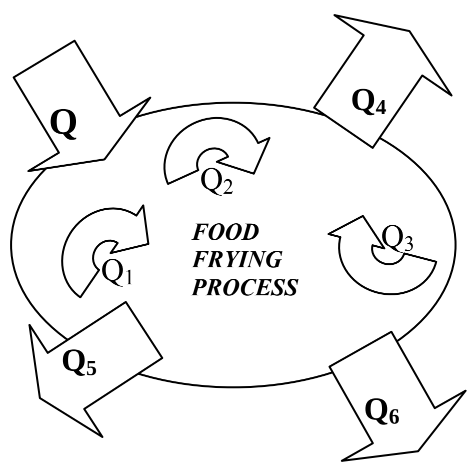

Figure 2: Division of Supplied Thermal Energy (Q) into Streams of Thermal Energy ($Q_1 - Q_6$) During Food Frying (Rywotycki, R., 2003) [6]

FRYING PROCESS CONTROL

Mathematical Modeling

It is important that the complexities of the frying process are fully understood so that mathematical models and simulations of the process can be developed.

The initial equation for developing the mathematical model of thermal energy consumption during frying food was the equation of thermal balance. In order to simplify the model it was assumed that the fryer works in a steady state. In a steady state, the heat input equals the output [6].

The heat power balance is illustrated by the following equation;

$$Q = Q_1 + Q_2 + Q_3 + Q_4 + Q_5 + Q_6 \text{ (kJ/s)} \qquad \textbf{(1)}$$

Where; Q is the total thermal power, $Q_{1.....6}$

The important point in developing a mathematical model for energy consumption during 'frying food' was the amount of water supplied to the fryer with the raw material. The water weight is described by the following equation;

$$m = m_1 - (m_2 - m_3) + m_4 \text{ (kg/s)} \qquad \textbf{(2)}$$

m_1, m_2, m_3, m_4 are the mass of water weight, and the individual heats consisting its balance are as follows:

Thermal power necessary for heating and evaporating water contained in the raw product

$$Q_1 = [c_1(T_2\text{-}T_1) + r](m_1 - m_2 + m_3 + m_4) \text{ (kJ/s)} \qquad \textbf{(3)}$$

Themal power necessary for the raw product heating

$$Q_2 = c_2 (T_3 - T_1)(m_2\text{-}m_3) \text{ (kJ/s)} \qquad \textbf{(4)}$$

Themal power necessary for heating fat placed in the fryer

$$Q_3 = c_3 (T_3\text{-}T_4)m_3 \text{ (kJ/s)} \qquad \textbf{(5)}$$

Themal power transmitted through the fryer casing to the envrionment

$$Q_4 = V(T_6\text{-}T_5)A \text{ (kJ/s)} \qquad \textbf{(6)}$$

Themal power tansmitted by the fryer ventilation system to the environment

$$Q_5 = x_5 Q\text{(kJ/s)} \qquad \textbf{(7)}$$

Themal power evaporated to the environment

$$Q_6 = X_6 Q \text{ (kJ/s)} \qquad \textbf{(8)}$$

Coeffcient x_5 and x_6 describe the power loss in relation to total power (total themal power losses were further determined as Q_s).

It is difficult to express explicitly by mean of an equation either thermal power Q_5 transmitted to the environment by the fryer ventilation system or radiated thermal power Q_6. (Power losses may be estimated at several percent depending on the environment).

To simiplify further calculations it has been assumed that $Q_5 = Q_6 = 0$.

By substitution to the power balance equation (1) the equations of fragmentary power appearing during the process of frying, with the necessary mathematical rearranging, the equation below was obtained:

$$Q = (m_1 + m_4)[(c_1 (T_2 - T_1) + r] - (m_2\text{-}m_3) [_{C1} (T_2 - T_1) - _{C2} (T_3 - T_1) + r] + m_3 c_3 (T_3\text{-}T_4) + kA (T_6 - T_5) \qquad \textbf{(9)}$$

Specific heat $_{C1}$, $_{C2}$, $_{C3}$ present in Equation (9) and k = heat transmission coeffcient, do not have consant values but change slightly with temperature. Because the effect of temperature on those coefficient values is small, it was assumed that they are constant. The solution using the finite element technique is obtained predominantly by variation and weighted residual (Galerkin's) method. The variation approach has its foundations in variation calculus and requires the use of a functional, whereas the weighted residual approach uses the governing equations (Joseph, 2001) [5].

To illustrate the formulation of finite element method solution, consider a 2-D domain shown in Figure 3. The differential equation governing transient heat conduction in the domain can be expressed as [9]:

$$\rho\, C_p \frac{\partial T}{\partial t} = k_\chi \frac{\partial^2 T}{\partial \chi^2} + k_y \frac{\partial^2 T}{\partial y^2} + I \qquad \textbf{(10)}$$

Where *I* is the internal heat generation; ρ is the material density; c is the specific heat; k_x and k_y

are the thermal conductivities in the x and y directions, respectively.
With boundary conditions:

$$T = T\,(x, y, t)$$
$$\text{on } S_1,\ t > 0 \qquad \textbf{(11)}$$

$$k_x \frac{\partial T}{\partial x} n_x + k_y \frac{\partial T}{\partial y} n_y + q + h\,(T - T_\infty) = 0$$

$$\text{on } S_2,\ t > 0 \qquad \textbf{(12)}$$

$$T = T_0\,(x, y)$$

$$\text{in } \Omega,\ t = 0 \qquad \textbf{(13)}$$

Where T_0 is the initial temperature, $T\,(x, y, t)$ is a specified boundary temperature distribution at any time, n_x and n_y are the direction cosines of the outward normal vector $\hat{n}$ to the bounding curve S, q is the heat loss at the boundary due to conduction, and $h\,(T - T_\infty)$ is the heat loss at the boundary due to convection, ambient temperature T_∞ and convection heat transfer coefficient h.

Since the temperature distribution is a function of both space and time, it is possible to assume that the distribution of T within each element has the form:

$$T^{(e)}\,(x, y, t) = \sum_{i=1}^{r} N_i\,(x, y)\,T_i\,(t) \qquad \textbf{(14)}$$

where, the superscript (e) restricts the range to one element.

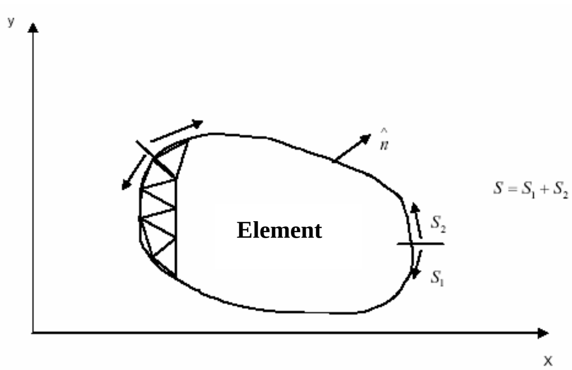

Figure 3: Two-Dimensional Domains for Heat Conduction (Yunfeng Wang, 2005) [9].

Applying the Galerkin's method as been used by Yunfeng Wang, 2005 [9].

$$\iint_{D^{(e)}} N_i\left[\frac{\partial}{\partial x}\left(k_x \frac{\partial T^{(e)}}{\partial x}\right) + \frac{\partial}{\partial t}\left(k_y \frac{\partial T^{(e)}}{\partial y}\right) + I - Pc_p \frac{\partial T}{\partial y}\right] dx\,dy = 0 \qquad \textbf{(15)}$$

After integrating by parts, the following matrix equation is obtained.

$$\int N_i \Delta c \frac{\partial T}{\partial x} dxdy = -\iint_{D^{(e)}} \left(k_x \frac{\partial T^{(e)}}{\partial x} \frac{\partial N_i}{\partial x} + k_y \frac{\partial T^{(e)}}{\partial y} \frac{\partial N_i}{\partial y}\right) dx\, D^{(e)}\, dy + \iint_{D^{(e)}} N_i I dx\, dy + \int_{S_2^{(e)}} \left(k_x \frac{\partial T^{(e)}}{\partial x} n_x + k_y \frac{\partial T^{(e)}}{\partial y} n_y\right) N_i d\Sigma^{(e)} \qquad \textbf{(16)}$$

When equation (14) is substituted, the resulting equation for the entire element can be written thus:

$$[K_{ci}]^{(e)}\{T\}^{(e)} + [C_{ij}]\left\{\frac{dT}{dt}\right\}^{(e)} = \{I_i\}^{(e)}\{q_i\}^{(e)} - [K_{hij}]^{(e)}\{T\}^{(e)} + \{q_{T\infty i}\}^{(e)} \qquad \textbf{(17)}$$

Where, K_{cij} is the conductivity matrix, C_{ij} is the mass matrix and the force martrix components are the right part of the Fourier's Law:

$$q = -k\, dT/dx, \qquad \textbf{(18)}$$

Where q is the rate flux (W), k is heat conductivity (W/mk), T is product temperature (k) and x is length (m), which is variable.

$$K_{cij} = \iint_{D^{(e)}} \left(k_x \frac{\partial N_i}{\partial x} \frac{\partial N_j}{\partial x} + k_y \frac{\partial N_i}{\partial y} \frac{\partial N_j}{\partial y}\right) dxdy \qquad \textbf{(19)}$$

$$C_{ij} = \int_{D^{(e)}} \Delta c\, N_i N_j\, dxdy \qquad \textbf{(20)}$$

$$I_i = \iint_{D^{(e)}} I N_i\, dxdy \qquad \textbf{(21)}$$

$$q_i = \int_{S_2^{(e)}} q N_i\, d\Sigma^{(e)} \qquad \textbf{(22)}$$

$$K_{hij} = \int_{S_2^{(e)}} h N_i N_j\, d\Sigma^{(e)} \qquad \textbf{(23)}$$

$$q_{T\infty i} = \int_{S_2^{(e)}} h T_\infty N_i\, d\Sigma^{(e)} \qquad \textbf{(24)}$$

Equation (17) is known as the governing FEM equation. It is solved at each element level and assembled for all elements in the domain to obtain problem solution. The FEMLAB heat transfer module solves problems involving any combination of conduction, convection and radiation in a way that makes it easy to get more realistic results from simulations. It comes with a CAD editor and high performance state of the solvers that addresses problems quickly and accurately. A particular strength of the package is its Partial Differential Equation (PDE) modeling capability, whereby it can link and solve coupled equations from arbitrary fields [1-3].

Controllability and Process Design

As is in the case of every process that must be controlled, the nature of the physicochemical phenomena involved and the design of the process greatly affect its controllability characteristics.

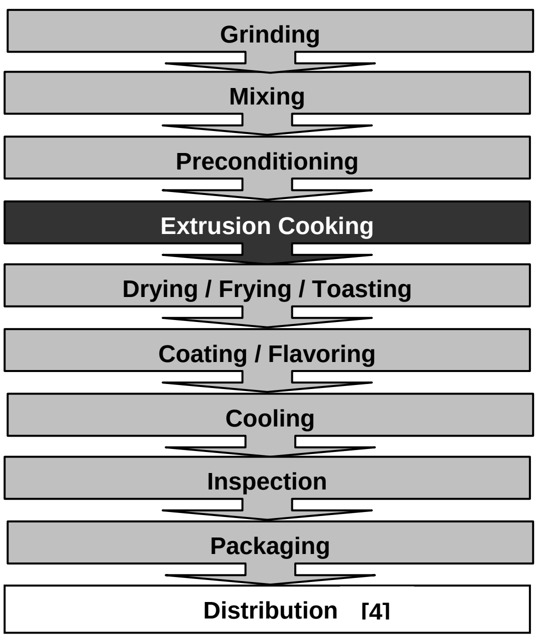

Figure 4: Components of a Potato-Chip Production Line. The Inspection Blocks Involve Visual Inspection of Peeled Raw Potatoes or Finished Chips.

Snack food manufacturing processes are generally serial (Figure 4 and 5),

Recirculation of heating or cooling media is common in snack food manufacturing (such as recirculation of cooking oil in continuous frying or cooling water in extrusion cooking) but is in large part decoupled from product throughput. On the other hand, there is very strong coupling between successive processing steps, owing to the fact that it is virtually impossible to have intermediate storage tanks for tolerance of throughput fluctuations. As a result, throughput control must be tight and reliability must be high, to avoid major process disruptions and product loss.

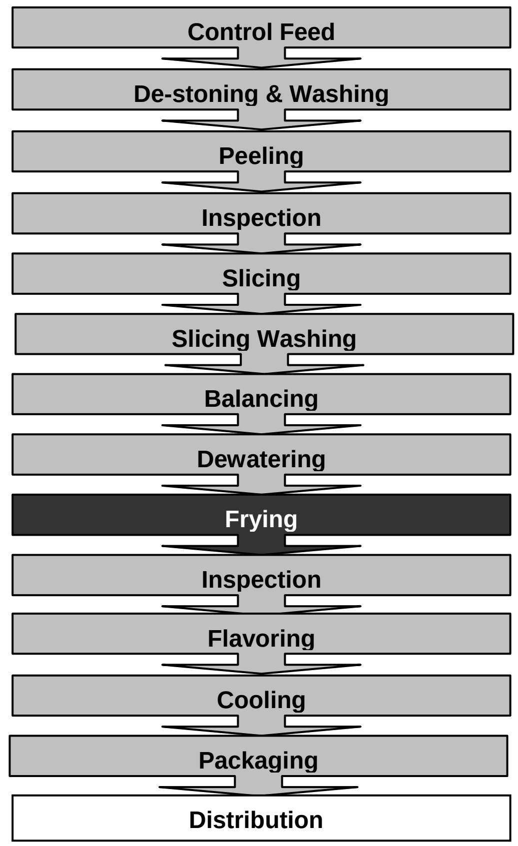

Figure 5: Components of an Extruded Snack Production Line. In both Lines, the Heart of the System is the "Reactor," that is the Fryer or Extrusion Cooker.

MODEL DEVELOPMENT

Chicken Nuggets (Figure 6) and snacks food products were simulated for the analysis and modeling of this work. (Some rational assumptions were made to avoid cumbersome and complexity of mathematical modeling and simulations).

To formulate the model, the following assumptions were made:

1) Chicken nugget sample was assumed to be rectangular in shape and no shrinkage during frying.

2) The thickness and width of the chicken nugget was small compared with the length so the heat and mass fluxes along the length direction was ignored.

3) Heat transfers were the same for the top and a bottom surface; the chicken nugget was symmetric with respect to the heat transfer direction.

4) Boundary conditions for moisture transfer assumed that surface moisture was zero.

5) A moving boundary was assumed.

6) The convective heat transfer coefficient was constant during the food frying process.

7) Thermal and mass transfer properties in the crust; coating and core were different but in each part were uniform.

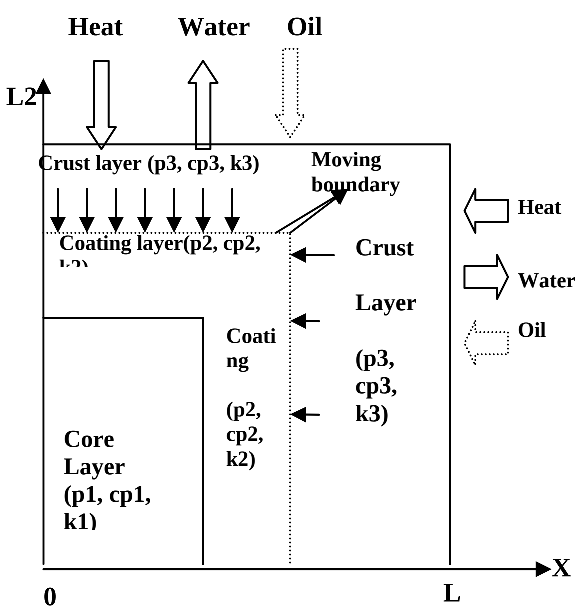

Figure 6: Schematic of the Proposed Heat and Mass Transfer Analysis (Yunfeng Wang, 2005)[9]

A quarter symmetric sample model was partitioned into 330 triangle elements with 187 nodes (Figure 7) using the automatic mesh generation of the FEMLAB® software [1,2] with the maximum element size of 1/15th of the maximum axis parallel distance in the sample geometry and the element growth rate as 1.3 (the maximum rate at which the element size can grow 30% from a region with small elements to a region with larger elements). The governing equation for rectangular shape (x direction) with phase change is given as:

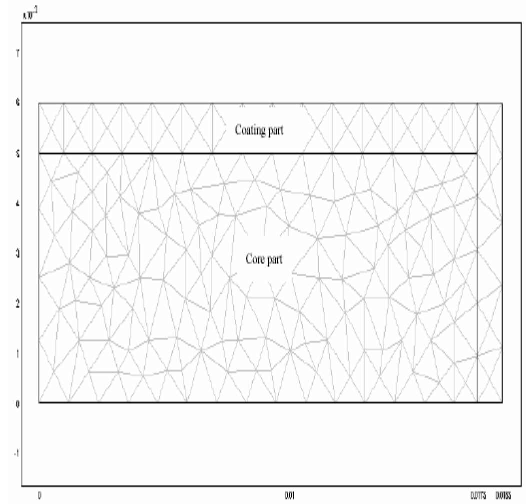

Figure 7: Schematic Diagram of Mesh Chicken Nugget Model (Dimensions are in Meters)

$$P c_p \frac{\partial T}{\partial t} = k_\chi \frac{\partial^2 T}{\partial \chi^2} + k_y \frac{\partial^2 T}{\partial y^2} + I \qquad \textbf{(25)}$$

where k_x and k_y are the thermal conductivities in the x and y directions, respectively. We assumed $k_x = k_y$ and I is the rate of internal evaporation heat.

$$I = \lambda p D_e \left(\frac{\partial^2 M}{\partial x^2} + \frac{\partial^2 M}{\partial y^2}\right) \qquad \textbf{(26)}$$

When λ is latent heat (J/kg) of water; D_e is effective diffusivity (m^2/s), and M is moisture content (kg/kg).

Boundary conditions:

$$k \nabla T = 0 \qquad x = 0 \text{ or } y = 0 \qquad \textbf{(27)}$$

$$h (T_f - T_s) = k \nabla T \qquad x = L1 \text{ or } y = L2 \qquad \textbf{(28)}$$

where k is thermal conductivity (W/mK); T_f is frying oil temperature (C) and T_s is surface temperature of nugget (C).

Initial condition:

$$T = T_I \qquad \textbf{(29)}$$

Where T_I is the initial temperature of nugget (^{0}C).

Since the temperature distribution is a function of both space and time, we shall assume that the distribution of T within each element has the form:

$$T^{(e)}(x, y, t) = \sum_{i=1}^{r} N_i(x, y,)T_i(t) \qquad \textbf{(30)}$$

Applying Galerkin's method [9],

$$\iint_{D^{(e)}} N_i\left[\frac{\partial}{\partial x}\left(kx\frac{\partial T^{(e)}}{\partial y}\right) + \frac{\partial}{\partial y}\left(k_y\frac{\partial T^{(e)}}{\partial y}\right) + I - pc_p\frac{\partial T}{\partial y}\right]dxdy\ \partial_x = 0 \qquad \textbf{(31)}$$

After integrating by parts, the matrix equation is obtained.

$$\int_{D^{(e)}} N_i \Delta c \frac{\partial T^{(e)}}{\partial x}\,dxdy = -\iint_{D^{(e)}}\left(k_x\frac{\partial T^{(e)}}{\partial x}\frac{\partial N_i}{\partial x} + k_y\frac{\partial T^{(e)}}{\partial y}\frac{\partial N_i}{\partial y}\right)dxdy + \iint_{D^{(e)}} N_i I dxdy + \int_{S^{(e)}}\left(k_x\frac{\partial T^{(e)}}{\partial x}n_x + k_y\frac{\partial T^{(e)}}{\partial y}n_y\right)N_i d\Sigma^{(e)} \qquad \textbf{(32)}$$

When equation (30) is substituted, we have the resulting equation for the entire element:

$$[K_{cij}]^{(e)}\{T\}^{(e)} + [C_{ij}]\left\{\frac{dT}{dt}\right\}^{(e)} = \{Ii\}^{(e)} - \{q_i\}^{(e)} - [K_{hij}]^{(e)}\{T\}^{(e)} + \{q_{T\,fi}\}^{(e)} \qquad \textbf{(33)}$$

Where, the superscript *(e)* restricts the range to one element.

$$K_{cij} = \iint_{D^{(e)}}\left(k_x\frac{\partial N_i}{\partial x}\frac{\partial N_j}{\partial x} + k_y\frac{\partial N_i}{\partial y}\frac{\partial N_j}{\partial y}\right)dxdy \qquad \textbf{(34)}$$

$$C_{ij} = \int_{D^{(e)}} \Delta c\, N_i N_i\, dxdy \qquad \textbf{(35)}$$

$$I_i = \iint_{D^{(e)}} I N_i\, dxdy \qquad \textbf{(36)}$$

$$q_i = \int_{s(e)} qN_i\, d\Sigma^{(e)} \qquad \textbf{(37)}$$

$$K_{hij} = \int_{S2^{(e)}} hN_i\, N_j\, d\Sigma^{(e)} \qquad \textbf{(38)}$$

$$q_{T\,fi} = \int_{S2^{(e)}} hT_f\, N_i\, d\Sigma^{(e)} \qquad \textbf{(39)}$$

Considering the moving boundary located between the coating layer and the crust layer (Figure 9), when the temperature at a location inside the coating layer attained boiling point, the water will change into vapor and evaporate at the surface, while this location will become crust.

The boundary will move from crust to inner layer, thus this location's parameters of the properties will change as:

$$p_2, k_2, c_{p2} \longrightarrow p_3, k_3, cp_3 \qquad \textbf{(40)}$$

If after long time, the moving boundary will enter the core part, so:

$$p_1, k_1, c_{p1} \longrightarrow p_3, k_3, cp_3 \qquad \textbf{(41)}$$

In numerical modeling, discontinuous parameters can lead to problems for the solver. Therefore, in FEMLAB ®, p, cp and k [2] were represented with a smooth function $Y = flc1hs\ (X, SCALE)$. The function $Y = flc1hs\ (X, SCALE)$ is a smoothed Heaviside function with a continuous first derivative (FEMLAB®, 3.0 Reference) [2] and Heaviside function is a discontinuous step function, usually defined as $h(x) = 0$ for $x < 0$, and as $h(x) = 1$ for $x < 0$.

$Y = flc1hs(X, SCALE)$ approximate the logical expression $Y = (X > 0)$ by smoothing the transition within the interval $-SCALE < X < SCALE$ (FEMLAB® Support Knowledge Base) [1]. With the help of the function $Y = flcihs\ (X, SCALE)$, p_2, k_2, and c_{p2} can be changed into p_3, k_3 and cp_3 smoothly. In this case, $flc1hs\ (T_{trans} - T, SCALE)$, T is the sample temperature; T_{trans} is the transition temperature of water from liquid to vapor and *SCALE* = 1^{o}C; (FEMLAB®, 3.0 Reference), that means when $-1^0C < T_{trans} - T < 1^0C$, p_2, k_2, cp_2 can be transferred to p_3, k_3, and c_{p3} smoothly.

MAJOR TRANSFERS

Moisture Transfer [8]

Fick's equation was used to model moisture diffusion in the chicken nugget samples:

$$\frac{\partial M}{\partial t} = D_m\left(\frac{\partial^2 M}{\partial x^2} + \frac{\partial^2 M}{\partial y^2}\right) \qquad \textbf{(42)}$$

Where D_m is moisture diffusivity (m^2/s), M is moisture content (kg/kg).

Boundary Conditions:

$M(L1, y, t) = M(x, L_2, t) = \text{constant} = 0$

Where M (L_1, y, t) and M (x, $L2$, t) are moisture content of sample surface at any frying time.

Initial Conditions:
$M(x, y, 0) = M_i$
Where $M(x, y, 0)$ is initial moisture content at any location of sample and M_i is initial moisture content.

Since during the actual frying operation, a lot of factors may affect the moisture diffusivity, such as pore developed during frying, effective moisture diffusivity, D_{em} was used in place of moisture diffusivity, D_m, and the Fick's equation becomes:

$$\frac{\partial M}{\partial t} = D_{em} \left(\frac{\partial^2 M}{\partial x^2} + \frac{\partial^2 M}{\partial y^2} \right) \quad \textbf{(43)}$$

Finite element equation for moisture transfer was obtained using the Galerkin method, similar to the heat conduction. Rice and Gamble (1989) [4] reported effective moisture diffusivity to be in the range 1.40E-09 to 1.55E-08 m^2/s for frying potatoes at 145 to 185 C. Furthermore, the effective moisture diffusivity in chicken drums was found to be between 1.32E-09 and 1.64E-08 m^2/s during DFF (Deep Fat Frying).

Average moisture content of a given region was computed by a mass averaged integration of moisture as shown in Equation (42):

$$\overline{M} = \frac{\int_S M dS}{\int_S \overline{Ds}} \quad \textbf{(44)}$$

Where $\overline{M}$ is average moisture content; M is moisture content and S *is area of the sample domain.*

Fat Transfer

Similar to moisture transfer, Fick's equation was also used to describe the process of fat transfer during DFF. Fick's model adapted to fat absorption as follows [9]:

$$\frac{\partial M_f}{\partial t} = D_{ef} \left(\frac{\partial^2 M_f}{\partial x^2} + \frac{\partial^2 M_f}{\partial y^2} \right) \quad \textbf{(45)}$$

where D_{ef} is effective oil diffusivity (m2/s), M_f is the oil content (kg/kg). Finite element equation for moisture transfer was obtained using the Galerkin method, similar to the heat conduction. The effective oil diffusivities for chicken breast meat as 9.12E-9, 1.65E-8 and 3.32E-8 m^2/s when frying was conducted in 170, 180 and 190 C oil, respectively. Average oil content could be computed by integration based on the above oil transfer model:

$$\overline{M} = \frac{\int_S M_f dS}{\int_S Ds} \quad \textbf{(46)}$$

Where M_f is average oil content (kg/kg); M_f is oil content (kg/kg) and s is area of the sample domain (m^2).

Equation (25), (43), and (45 along with their appropriate boundary conditions are the coupled 2-D equations that describe heat and mass transfer in breaded chicken nugget during deep fat frying.

The proposed heat and mass transfer models were solved numerically by the finite element method software (FEMLAB® 3.0, Comsol Company). They were used to simulate the center temperature and mass transfer characteristics of coated chicken nuggets.

DEVIATION ANALYSIS

The root-mean-squares of deviations (RMSD) is used for statistical analysis to check the deviation between predicted and observed values. RMSD values of temperature (σ_r), moisture content (σ_m) and oil uptake ($\sigma_{r,g}$) of the chicken nuggets at various times during frying were calculated by:

$$\sigma_r = \sqrt{\left[\sum_{i=1}^{N} (T_{expI} - T_{cal,i})^2 / N \right]} \quad \textbf{(48)}$$

$$\sigma_m = \sqrt{\left[\sum_{i=1}^{N} (M_{expI} - M_{cal,i})^2 / N \right]} \quad \textbf{(49)}$$

$$\sigma_f = \sqrt{\left[\sum_{i=1}^{N} (M_{fxpI} - M_{fcal,i})^2 / N \right]} \quad \textbf{(50)}$$

where, T_{expI} , M_{expI} , and M_{fxpI} are experimental data for temperature, moisture and oil content, respectively. $T_{cal,i}$, $M_{cal,}$ and $M_{fcal,}$ are calculated data for temperature, moisture and oil content, respectively. N is the total number of the experiment.

Table 1: Parameters used for Mathematical Modeling and Simulation (Singh, 2001 and Tangduangdee et al., 2003)

Type	Property	Source
Crust layer	p3 = 1010 kg/m3 Cp3 = 0.837 + 3.349M [a] Kcrust = 0.08 + 0.52M	Measured Siebel equation (Singh, 2001)[7] Sweat equation (Singh, 2001) [7]
Coating layer	Initial moisture content (db) = 1.2274 Initial oil content (db) = 0.0021 p2 = 980 kg/m^3, cp2 = 0.837+3.349M Kcoating = 0.08 + 0.52M	Measured Measured Measured Siebel equation (Singh, 2001) [7] Sweat equation (Singh, 2001) [7]
Core layer	Initial moisture content (db) = 2.4872 Initial oil content (db) = 0.1593 p1 = 1090 g/m^3, cp1 = 0.837+3.349M Kcore = 0.08 + 0.52M	Measured Measured Measured Siebel equation (Singh, 2001) [7] Sweat equation (Singh, 2001) [7]
Process Conditions	Oil temperature: 160. 170 and 180^{o}C Boiling temperature: 103^{0}C Average heat transfer coefficient h = 500 W/m^2K	Specified Measured (Tangduangdee et al. 2003) [8]

M is moisture content of product kg/kg, wet base

RESULTS

The suggested method of control was tested while frying French fries in the 414-453 K temperature range which is perfectly in agreement with Yunfeng Wang, 2005.

Within the recommended temperature range for various food items (in this case 414 – 453 for French fries) the final and ready for consumption product is obtained.

Owing to the application of suggested solution a several percent increase in frying efficiency was obtained by matching the French fries quality (more or less fried, color of outer layer and its features - more or less crisp) to individual consumer preferences.

The results obtained in the experiment encourage further attempts at improving frying of all plant and animal based raw or half products in order to develop a system of automatic control of frying parameters by setting desired properties of fried products according to individual client preferences.

Figure 10, 11 and 12 show the result of heat transfer in a quarter section of chicken nugget fried at 160 C for 100, 150, 200, 250 and 300 s.

The Figures 8, 9 and 10 show outlines of temperature distribution in the sample at different frying times. Temperature ranged from

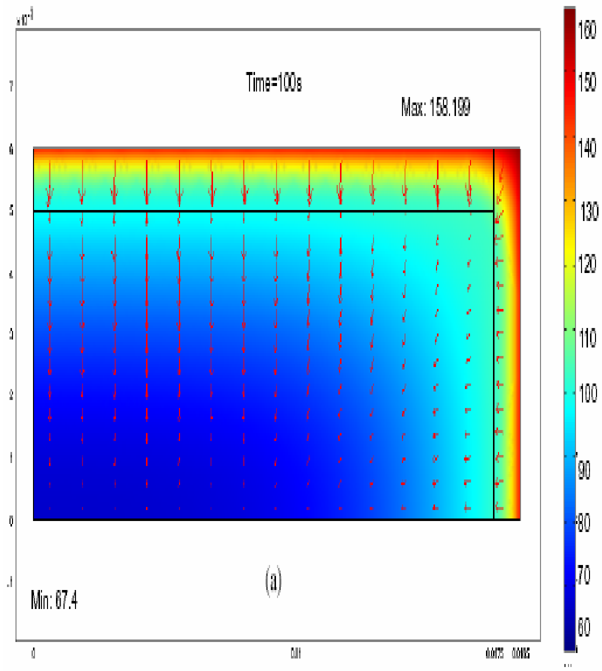

Figure 8: Simulated Temperature Distribution and Heat Transfer in Chicken Nugget Fried at 160 C for 100s.

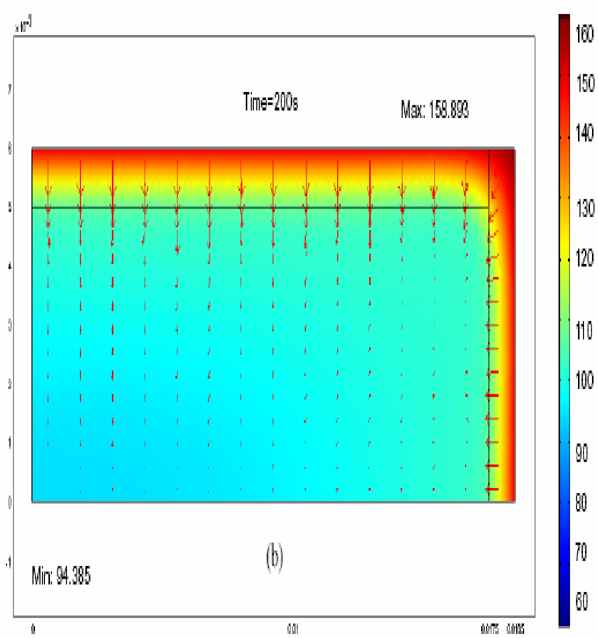

Figure 9: Simulated Temperature Distribution and Heat Transfer in Chicken Nugget Fried at 160 C for 200s.

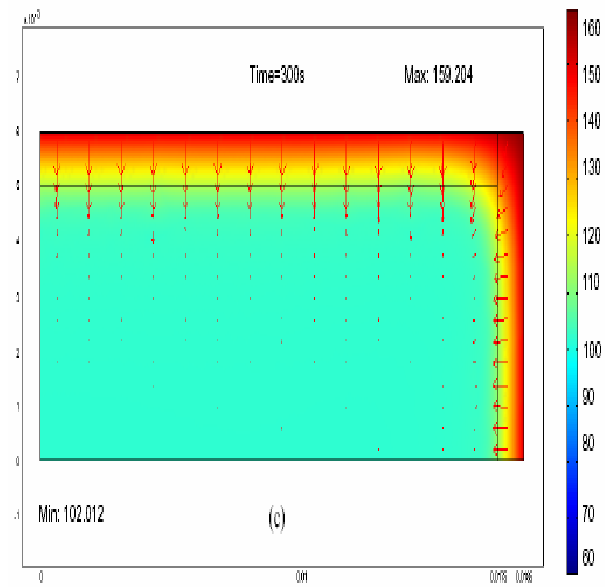

Figure 10: Simulated Temperature Distribution and Heat Transfer in Chicken Nugget fried at 160 C for 300s.

158.199, 158.893 and 159.204 C at the surface to 67.4, 94.385 and 102.012 C at the core layer center after the frying times of 100, 200 and 300 s, respectively. The moving boundary of crust moving from the coated surface and creeping into the core portion of the chicken nugget is evident. During the frying process, there was much turbulence and boiling as moisture was evaporated.

Figures 11, 12 and 13 show the simulated and observed moisture content of the coating and core portion of the breaded chicken nuggets during deep-frying at 160 C 170 C and 180 C there was perfect agreement in these results. It may be essential to evaluate, estimate and incorporate shrinkage in subsequence improvement to the above model. Figure 14 shows simulated and observed center temperatures of chicken nuggets during deep-frying at 160, 170 and 180 C.

The three temperature curves show similar temperature profiles. The temperature increased slowly during the first 20-30 s after immersing the product in the hot oil. After this period, the temperature increased dramatically during 30-200 s and then approached the boiling point of water (200-270 s) where it increased only slightly and finally tended to be a horizontal line due to the phase change of water at the boiling point

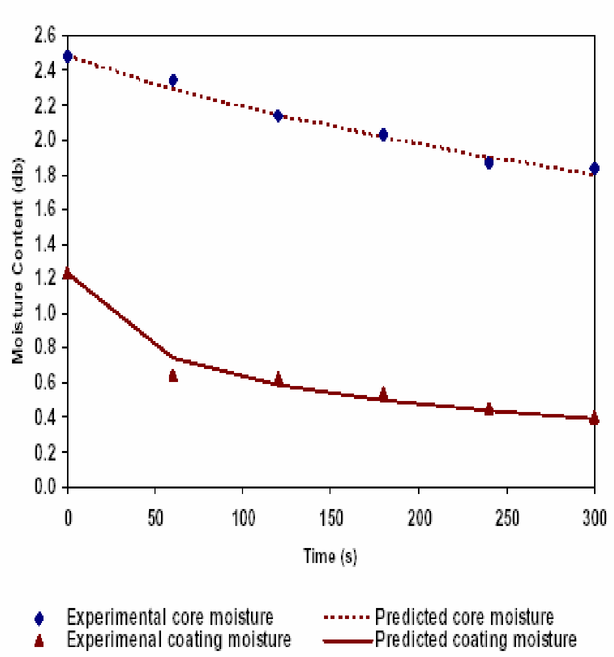

Figure 11: Moisture Content Profile of the Core and Coating Layers of the Chicken Nugget Deep-Fried at 160 C.

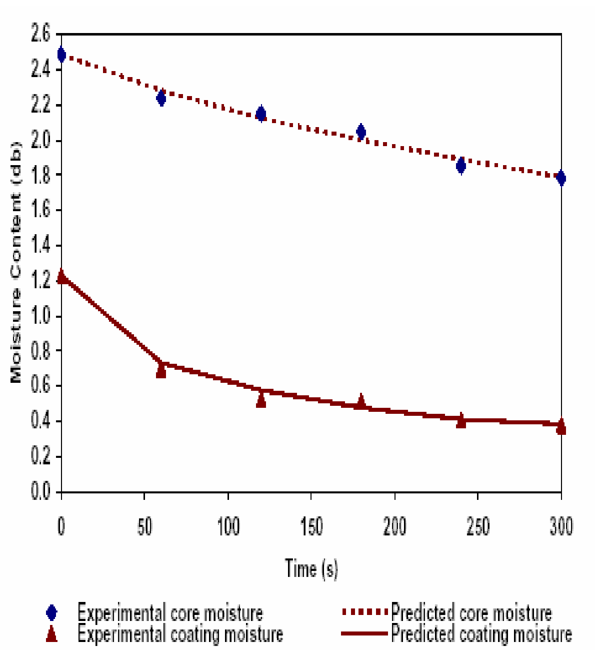

Figure 12: Moisture Content Profile of the Core and Coating Layers of the Chicken Nugget Deep-Fried at 170 C.

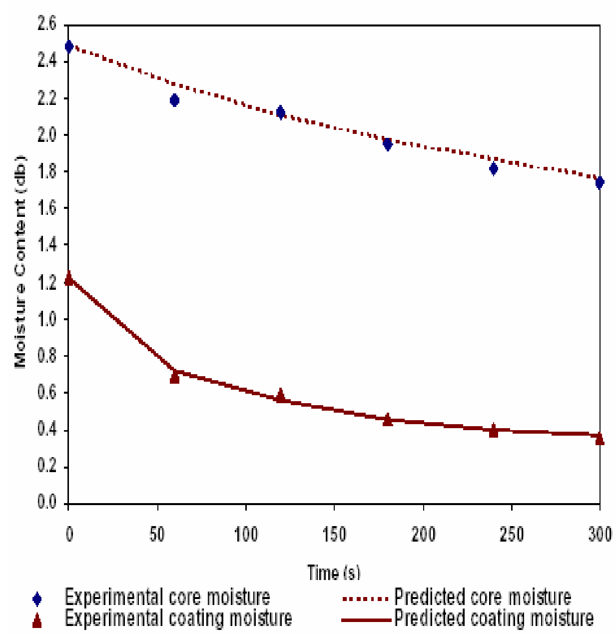

Figure 13: Moisture Content Profile of the Core and Coating Layers of the Chicken Nugget Deep-Fried at 180 C.

(270-300 s). A good agreement between the observed and predicted results was obtained. The RMSD for temperature, σ_T was 1.0299, 0.8776 and 0.7163 C frying at the 160, 170 and 180 C oil temperatures, respectively, indicating small deviation between predicted and observed value.

The types of oil used for the purpose of frying snacks were considered carefully. The average percentage (%) of lipid is an important factor involving both cost and fat content of snack products. The flavor and the consumers' acceptability of this flavor were also considered in this work. The average percentage of lipid absorption for the olive oil is low at 9%. Low lipid absorption would decrease cost because more oil would be left after each snack was fried. Also, low lipid absorption would decrease the overall fat content of the snack product creating a more desirable product. The inherent stability value of olive oil is low (1.5) suitable for frying.

Figure 15 shows excellent performance with the controller operation. There are several smaller disturbances in the form of extruder power changes and other unmeasured disturbances that are reflected in changes of the manipulated controller variables (especially the takeout conveyor speed). The controller is capable of quickly rejecting all disturbances and therefore has near perfect performance for the hour 290-303.

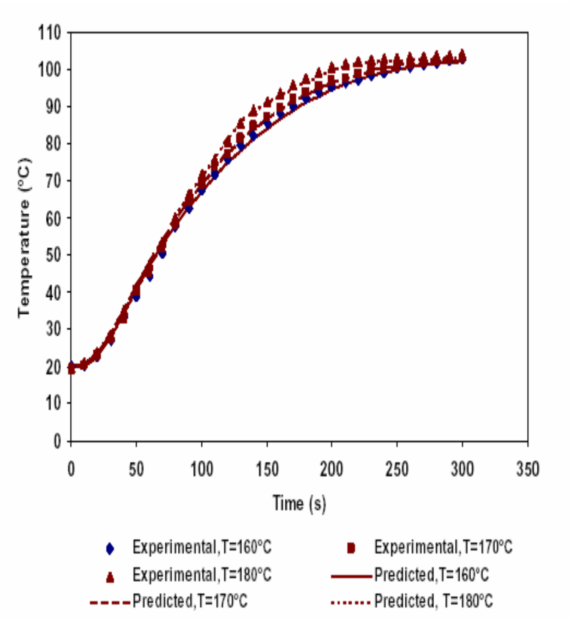

Figure 14: Center Temperature Profiles of Chicken Nuggets During Deep Fat Frying at 160, 170 and 180 C

CONCLUSION

A mathematical model of the simultaneous heat and mass transfer of chicken nuggets (parts) during frying – Deep Fat Frying (DFF) was presented using moving boundary concept. The proposed model reasonably predicted the heat and mass transfer profiles of the frying chicken nugget.

Dynamic analysis of the process showed that color of the product brightens when the temperature of the oil is increased. The color turned to a darker yellow as a result of a browning reaction because the product was more cooked. The moisture content of the product also responded inversely to an oil temperature positive change. Increasing the temperature caused more water to evaporate from the product during frying. The oil content increases due to an increase in oil temperature. The oil occupied the spaces left by the water during frying. Therefore, increasing water loss during frying resulted in increased final oil content of the product. By increasing the submerged speed, the color value and moisture content increased while the oil content decreased. This is because by increasing the submerged conveyor speed the residence time of the product in the fryer decreased. The product was exposed to the hot oil for a shorter period, and therefore, the color turned lighter as less water evaporated during frying. As a result of less cooking, less oil was absorbed by the product.

Conclusively, the oil used in frying not only acts as the heat transfer medium, but also enters into the food product, providing flavor.

The following factors affect the frying process of foods:

Depending on the process:
a) Temperature
b) Frying time
c) Fryer type – batch or continuous

Depending on the frying oil:
a) Properties of the oil – chemical and physical
b) Additives and contaminants

Depending on the food:
a) Properties of the food – chemical and physical
b) Preparation
c) Ingredients interchange with the oil.

However, to ensure that fried foods are prepared and served in a manner that delivers maximum taste while being as health conscious as possible.

These four underlying principles must be appreciated:

1) finding the right fryer,
2) selecting the right oil,
3) using best practices or “right cooking processes, and
4) providing the right maintenance.

NOTATIONS USED IN CALCULATION OF THERMAL ENERGY

A surface area of the fryer casing, m^2
c_1 specific heat of water, kJ/ (kg K)
c_2 specific heat of the raw product, kJ/ (kg K)
c_3 specific heat of the fat, kJ/kg K)

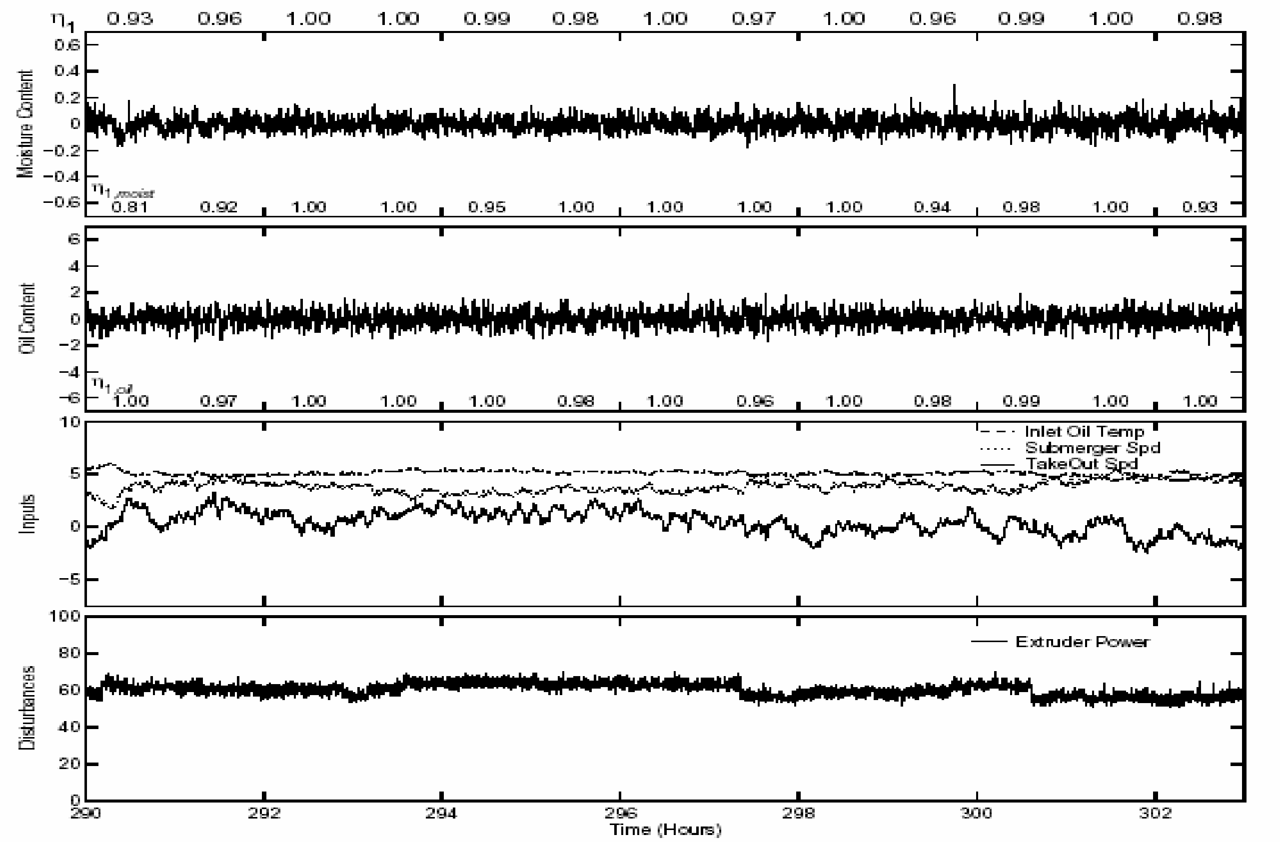

Figure 15: Controller Performance Monitoring Results.

Vc — overall heat transfer coefficient for the casing environment through the fryer casing, kJ/s

m — weight of water introduced into the fryer KJ/s

m_1 — weight of the raw product, kg/s

m_2 — weight of the fried product, kg/s, K

T_1 — temperature of the raw product,

m_3 — weight of fat absorbed by the food, kg/s

T_2 — temperature of water boiling point, K

m_4 — weight of water on the surface of the raw

T_3 — temperature of frying fat, K

T_4 — temperature of fat placed in the fryer, K

T_5 — ambient temperature, K

T_6 — temperature of the heating oil, K

x_5, x_6 — coefficient of power loss caused by the of water contained in the raw product, fryer ventilation system kJ/s

p_1, p_2, p_3 are densities (kg/m^3) of the core, coating and crust layer, respectively.

c_{p1}, c_{p2}, c_{p3} are specific heats (kJ/[kg C]) of the core, coating and crust layer, respectively.

k_1, k_2, k_3 are specific heats (kJ/[kg C]) of the core, coating and crust layer, respectively.

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