PREDICTION OF H^+ CONCENTRATION IN FRANKFURTERS USING NEURAL NETWORK DURING COOKING

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Background.
Meat pH is important as it affects color, bacterial growth, and water holding capacity (WHC). Acceleration of cured meat color development is encouraged by a decrease in tissue pH. Bacterial growth is considerably reduced if pH of meat is below 5.6. An increase in pH raises WHC. pH change due to heating of meat has been investigated (*Kauffman et al.*, 1964). Meat pH influences WHC, texture and tenderness (*Dutson*, 1983). *Boakye and Mittal* (1993) reported positive correlations between pH and press juice and cooking loss. During cooking of frankfurters, pH increased by 0.15 unit from 6.10 to 6.25 in the 30 to 70°C range (*Correia and Mittal*, 1991).

Objective.
The objective is to develop an ANN to predict dynamics of hydrogen ions during thermal processing of a meat emulsion, with a frankfurter geometry, for simplicity, convenience and fast calculations, so that corrections can be made in process conditions in real time.

Methods.
Modelling and simulation: Hydrogen ion transport during meat emulsion processing is due to bulk diffusion with water, molecular diffusion and chemical reactions. The following mathematical equations were developed (*Mittal and Blaisdell*, 1982a,b): Initial and boundary conditions: CIH (r, 0) = CIH0; CIH' (0, t) = 0; CIH' (R, t) = 0; diffusion of ions = -DIH. A. d CIH/dr; convection of ions = CIH. A D_m dC/dr; accumulation = V CIH' ; and rate of depletion = KR (CIH - CIHE) A. The space coordinate was eliminated as a variable by dividing the cylinder into ten concentric shells. For node 1:

$$\frac{d}{dt}CIH_1 = \left|2\frac{DIH}{r_1}\frac{(CIH_1 - CIH_2)}{\Delta r}\right| - \left|2CIH_1\frac{D_{m,1}}{r_1}\frac{(C_1 - C_2)}{\Delta r}\right| - KR(CIH_1 - CIHE)$$

For node i, (i = 2 to 9)

$$\frac{d}{dt}CIH_i = \frac{2}{\Delta r(r_i^2 - r_{i-1}^2)}\left[DIH\left(r_{i-1}(CIH_{i-1} - CIH_i) - r_i(CIH_i - CIH_{i+1})\right) + CIH_{i-1}D_{m,r-1}r_{i-1}(C_{i-1} - C_i) - CIH_iD_{m,i}r_i(C_i - C_{i+1})\right]$$

$$- KR(CIH_i - CIHE)$$

For node 10:

$$\frac{d}{dt}CIH_{10} = \frac{2r_9}{\Delta r(R^2 - r_9^2)}\left\{DIH(CIH_9 - CIH_{10}) + CIH_9D_{m,9}(C_9 - C_{10})\right\} - KR(CIH_{10} - CIHE)$$

$C = (m - m_e)/(m_i - m_e)$; $m_e = -0.102\ \ln[-R_g\ FP\ (T + 5.665)\ \ln(RH)]\ /(1.132E7)$; $D_m = \exp(8.679 + 0.135\ FP - 4341.5/\ T_{abs} + 8.55C)$

These equations were solved on a digital computer using the ISIM digital simulation language (*Dunn et al.*, 1992). The model for the equilibrium pH was given as (*Mittal and Blaisdell*, 1982a):
$pH_e = 0.0113\ T_{abs}\ \exp((4.131E\text{-}3 + 2.329E\ –3\ RH)\ FP + 148.9/\ T_{abs})$; and $KR = 785.11\ T_{abs}\ \exp(-0.133\ FP - 3935/T_{abs})$
These models were extensively validated by *Mittal and Blaisdell* (1982a) against experimental data. The normalized standard deviation between predicted and experimental concentrations varied from 0.068E-6 to 0.222E-8 mol/L. The maximum deviation was 0.015 pH unit.

Data Generation and Neural Network Model: For data generation, 8 parameters were used for inputs (Table 1), 40500 sets of data were generated. Three slab hidden layered "Ward nets" (Ward System Group, Inc., Frederick, MD) were developed to predict the hydrogen ion mobility (Fig. 1). Eight nodes in the input layer represented 8 input parameters, and two nodes in the output layer represented CIH_i and CIH_a. ANN software used was NeuroShell 2 (Ward System Group, Inc., Frederick, MD) on a computer (Pentium II, 400 MHz).

Results and discussions.
From the generated data (40500 sets), 8100 each were randomly selected as testing and production sets, respectively. The remaining 24300 were used for ANN training. Both learning rate and momentum were set at 0.5. Comparing production results (Table 2), ANN with 10-10-10 hidden nodes provided the lowest mean and maximum absolute errors, and mean and maximum relative errors. Maximum relative errors for predicting CIH_i and CIH_a were 1.71%. For all of predictions, mean absolute errors were < 0.006E-6 and maximum absolute errors were <0.03E-6. The highest mean relative error was 0.549%. All of predictions provided higher accuracy. ANN with a learning rate of 0.5 and a momentum of 0.3 achieved the best prediction results. This combination provided the lowest mean and maximum absolute errors, and mean relative errors for predicting CIH_i and CIH_a. This combination has not provided the lowest relative errors for predictions because a learning rate of 0.9 and a momentum of 0.3 provided the lowest maximum relative errors. However, selected combination provided the largest percentage of data within 1% error (99.4%) for predicting CIH_i. For predicting CIH_a, selected combination provided good results among all the combinations. The maximum absolute error for the prediction of CIH_a was 0.013E-6. The mean relative error was only 0.2%. The importance of an input variable to ANN prediction was compared by the sum of its connecting weights (Fig. 2). The t, T_a, CIH0 and FP were important to the predictions. The m_i and T_i did not affect the predictions. After neglecting m_i and T_i, the remaining 6 inputs were used to predict, but predicted CIH_a did still follow calculated CIH_a very well as maximum absolute and relative errors were 0.0191E-6 and 2.71%, respectively. However, the mean absolute and relative errors were only 0.37E-6 and 0.33%, respectively.

Conclusions.

Predicting hydrogen ion mobility during frankfurter cooking by "Ward nets" ANN using simulation data is a simple, convenient and accurate method. Prediction errors could be reduced by careful selection of hidden nodes and appropriate combination of learning rate and momentum. The maximum absolute error for prediction of CIH_a was 0.013E-6 mol/L. The mean relative error was only 0.2%. The t, T_a, CIH0 and FP were important to the outputs. Inputs M_i and T_i did not affect the predictions.

List of Symbols.

A = cross sectional area of the slab, m^2 ; C = concentration of water, dimensionless; CIH = concentration of ion, mol/L
CIHE = equilibrium concentration of ion, mol/L; CIH0 = initial concentration of ion, mol/L; D_m = moisture diffusivity, m^2/h
DIH = diffusivity of ion, m^2/h; FP = fat-protein ratio; KR = reaction rate constant, 1/h; m = moisture content, decimal db
R = frankfurter radius, m; r = radial distance, m; R_g = gas constant, J/(kg.mol.K); RH = relative humidity, decimal
R^2 = coefficient of determination; T = temperature, °C; t = time, h; V = volume, m^3; Δr = radial interval between nodes, m
Subscript: 1-10 = node number; a = ambient, average; abs = absolute; e = equilibrium; i = initial; n = node number.

References.

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Table 1. Input variables and their values for ANN training

Input variables	Values for data generation
Processing time (t), h	0.25, 1.00, 1.75, 2.50, 3.25
Fat protein ratio (FP)	1, 2, 3
Initial moisture content (mi), decimal db	1.6, 2.0, 2.4
Initial temperature (Ti), °C	4, 7, 10
Ambient temperature (T_a), °C	50, 60, 70, 80, 90
Radius of frankfurter (R), m	0.01, 0.02, 0.03, 0.04, 0.05
Relative humidity (RH), decimal	0.50, 0.65, 0.80, 0.95
Initial concentration of hydrogen ion (CIH0), mol/L	0.25E-5, 0.30E-5, 0.35E-5

Table 2. Prediction errors of CIH_1 and CIHa

Nodes in hidden layer (Ward nets) →	8-8-8		10-10-10		12-12-12		14-14-14	
	CIH_1	CIHa	CIH_1	CIHa	CIH_1	CIHa	CIH_1	CIHa
Mean absolute error, mol/L	0.004E-6	0.004E-6	0.003E-6	0.003E-6	0.004E-6	0.003E-6	0.004E-6	0.004E-6
Maximum absolute error, mol/L	0.019E-6	0.017E-6	0.015E-6	0.014E-6	0.017E-6	0.018E-6	0.021E-6	0.021E-6
Mean relative error, %	0.42	0.40	0.27	0.23	0.32	0.31	0.31	0.29
Maximum relative error, %	2.52	2.34	1.71	1.70	2.09	2.59	2.27	2.70
Percent within 1% error	92.1	93.2	98.9	99.8	97.2	98.4	97.7	98.2
Percent within 1% to 2% error	7.5	6.5	1.1	0.2	2.7	1.4	2.2	1.6
Percent within 2% to 3% error	0.4	0.3	0	0	0.1	0.2	1.1	0.2

$R^2 \geq 0.9999$ for all treatments

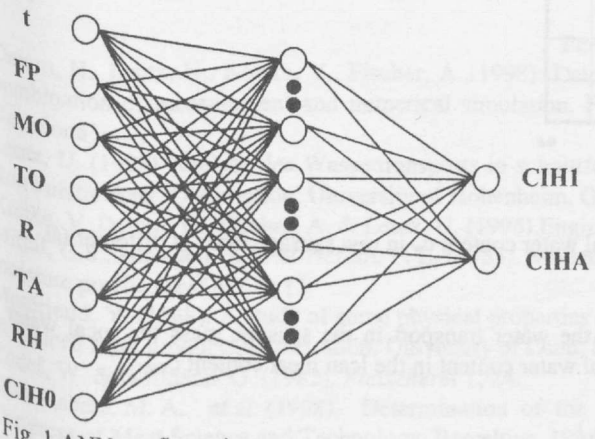

Fig. 1 ANN configuration

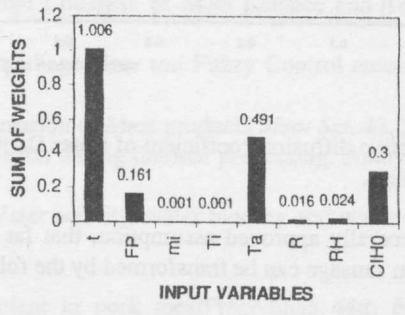

Fig. 2 Importance of input variables