Journal of Food Engineering 238 (2018) 30–43

Contents lists available at ScienceDirect

Journal of Food Engineering

journal homepage: www.elsevier.com/locate/jfoodeng

Heat and mass transfer, shrinkage, and thermal protein denaturation of kuruma prawn (*Marsupenaeus japonicas*) during water bath treatment: A computational study with experimental validation

Xiaolong Li[a], Yvan Llave[a,b], Weijie Mao[c], Mika Fukuoka[a], Noboru Sakai[a,*]

[a] *Department of Food Science and Technology, Tokyo University of Marine Science and Technology, Japan*
[b] *Department of Agro–Food Science, Niigata Agro–Food University, Japan*
[c] *College of Food Science and Technology, Guangdong Ocean University, China*

ARTICLE INFO

Keywords:
Prawn
Shrinkage
Darcy's law
Protein denaturation
Computer simulation

ABSTRACT

Excessive shrinkage of processed food lowers its perceived quality by consumers, and therefore should be avoided. This study aims to clarify the multiphysics involved in the shrinkage of prawn during heating. A model that describes changes in moisture content of prawn due to pressure-driven water transport was reported according to Darcy's law. The transport model for the heating process included a stress-strain analysis (a structural mechanics model) coupled to a virtual work principle, which is applicable to a body undergoing shrinkage in two dimensions. Simultaneous calculation of changes in internal pressure and thermal protein denaturation (TPD, using a non-isothermal kinetics method) was used to describe the physics behind shrinkage. Temperature, moisture, pressure, as well as TPD profiles and distributions were calculated, and were validated with measured results. Results indicated that shrinkage was delayed due to slow rate of water release, which promoted the increment in internal pressure. This phenomenon, in combination with actin denaturation, resulted in dramatic water release and volumetric shrinkage. The proposed model improves the understanding of the shrinkage phenomena of prawn during heating and has the potential to contribute in the reduction of food quality losses associated with shrinkage and water release.

1. Introduction

Heat-induced protein denaturation in muscles leads to myofibrillar shrinkage and water loss, which results in significant changes in texture (Schubring, 2009). Excessive shrinkage of processed foods should be avoided because such physical changes reduce the perceived food quality by consumers. Niamnuy et al. (2007) reported the effects of various parameters during the boiling process, aside from drying (such as boiling time, drying temperature, sample size and concentration of salt solution), on the quality of shrimps, including shrinkage, rehydration ability, texture, color, microstructure, and sensory quality. Although results by Niamnuy et al. (2007) were obtained during the drying process, the impact of temperature and heating time on the quality of treated shrimp was reported. The authors stated that high-quality dried shrimp should possess a low degree of shrinkage, high rehydration ability, and be soft or slightly tough when rehydrated. Moreover, Niamnuy et al. (2008) reported that during heating, weight loss and protein denaturation are considered to be the main physical and chemical factors that lead to quality changes (e.g. texture) in the cooked shrimp. Correlations between the extent of thermal protein denaturation (TPD) during heating and Ca^{2+}-ATPase activity, protein solubility, and total sulfhydryl content of prawns were reported by Mao et al. (2016). They developed a TPD kinetic model to predict the degree of protein denaturation in the prawn muscle. Interestingly, Mao et al. (2016) observed that hydrogen bonds, hydrophobic interactions, and ionic bonds were altered during TPD.

In hygroscopic materials, there is a large concentration of physically bound water, which often causes shrinkage during heating. Below the level of moisture saturation, the internal vapor pressure is lower than that of pure water, and is a function of moisture level and temperature in hygroscopic materials (Datta, 2007). Above the level of moisture saturation, the vapor pressure is a function of temperature only, and is independent of the moisture level. Therefore, above a certain moisture level, all materials behave in a non-hygroscopic manner.

Shrinkage of prawns and shrimps have been previously studied using direct measurements, such as those carried out with a caliper or micrometer, as well as with image processing techniques during heating (Hosseinpour et al., 2011; Namsanguan et al., 2004; Prachayawarakorn

* Corresponding author. Department of Food Science and Technology, Tokyo University of Marine Science and Technology, 4-5-7 Konan, Minato-ku, Tokyo 108-8477, Japan.
E-mail address: sakai@kaiyodai.ac.jp (N. Sakai).

https://doi.org/10.1016/j.jfoodeng.2018.06.010
Received 22 December 2017; Received in revised form 7 June 2018; Accepted 9 June 2018
Available online 14 June 2018
0260-8774/

Nomenclature

A	Matrix defined by Eq. (12) [m^{-1}]
B	Strain nodal displacement matrix by Eq. (12) [m^{-1}]
C_p	Specific heat [$kJ\ kg^{-1}\ K^{-1}$]
C_w	Concentration of water (kg-water m^{-3})
D	Elastic stress-strains matrix by Eq. (13) [m^{-1}]
da	Nodal displacement vector [m]
dU	Displacement vector [m]
J_w	Moisture flux [kg-water $m^{-2}\ s^{-1}$]
k	Thermal conductivity [$W\ m^{-1}\ K^{-1}$]
M_w	Moisture content [kg-water kg-solid^{-1}]
P	Internal pressure [Pa]
P_a	Atmospheric pressure [Pa]
P_e	Internal pressure in element [Pa]
P_i	Initial internal pressure in element [Pa]
r	Distance from the center in circular truncated cone coordinates [m]
S_r, S_z, S_θ	Free shrinkage coefficients in r, z, and θ directions, respectively [−]
S_V	Volumetric shrinkage coefficient [−]
t	Time [s]
T	Temperature [°C or K]
T_{max}	Maximum peak temperature of denaturation (K)
u	Dimensionless concentration of water [−]
V	Volume [m^3]
X	Protein non-denaturation ratio [−]
X_{tot}	Total protein non-denaturation ratio [−]
X_v	Measured volume change ratio [−]
z	Longitudinal distance in circular truncated cone coordinates [m]

Greek symbols

σ	Stress [$kN\ m^{-2}$]
ρ_b	Density of material [$kg\ m^{-3}$]
ε	Observed strain [−]
ε_S	Elastic strain [−]
ε_0	Initial strain [−]
λ_w	Permeability coefficient of water released [kg-water m^{-1}]
μ_w	Viscosity of water released [Pa s]

Subscripts

1	Myosin
2	Sarcoplasmic-collagen
3	Actin
after	After
amb	Ambient
before	Before
e	Element
E	Equilibrium state
i	Initial
p	Pressure in internal pressure calculation
P	Related to the extent of TPD in the estimation of viscosity and permeability
s	Sample in density measurement (Table 1)
tot	Total
T	Temperature in the estimation of viscosity and permeability
w	Water in density measurement (Table 1)
x	Gravimetric bottle plus water in density measurement (Table 1)
y	Gravimetric bottle plus water and sample in density measurement (Table 1)

et al., 2002). In addition, mathematical models that predict the distribution of moisture and temperature in prawns, aside from volume changes, have been previously reported (Erdoğdu and Balaban, 2011; Erdoğdu et al., 1999). Another approach to evaluate shrinkage is by analyzing deformation through the application of a structural mechanics model. This method has been successfully applied to the analysis of potatoes (Curcio and Aversa, 2014; Sakai et al., 2002; Yang et al., 2001), eggplants (Llave et al., 2016), beef-hamburger patties (Ishiwatari et al., 2012), and composite bodies (Itaya et al., 1995). These studies and the theory behind the structural mechanics model were summarized and discussed in a previous report (Llave et al., 2016).

Llave et al. (2016) investigated the shrinkage deformation of Japanese eggplants (*Solanum melongena*) during the roasting process using a simultaneous heat and moisture transport model, which was coupled to a structural mechanics model applicable to a body undergoing volumetric changes, as a consequence of moisture removal. A similar approach was reported by Niamnuy et al. (2008) for the drying process of shrimps, which utilized a coupled transport phenomena model and mechanical deformation. However, in the last two studies it was assumed that the samples (which are in fact hygroscopic porous medium) are fictitious continuum, and therefore Fick's second law to the moisture transport model was applied. It should be noted that when fluid flow occurs inside a solid with small pores and undergoes significant heating, fluid transport through the pores of the solid is treated according to Darcy's law (Datta, 2007). Therefore, in the aforementioned studies, it would have been more appropriate to use Darcy's law instead of Fick's law. Recently, similar approaches were adopted by Feyissa et al. (2013) and Ganapathy and Mohan (2017) to model the processes of meat roasting and heating of a hemispherical porous medium. The application of Darcy's law for the simulation of moisture transfer (based on hydrostatic conditions) implies that (a) there is no pressure gradient over a distance with no flow; (b) if pressure gradient is present, flow will occur from high to low pressure (opposite to the direction of increasing gradient; hence the negative sign in Darcy's law); (c) the greater the pressure gradient (through the same formation material), the greater the discharge rate. To our knowledge, the combined analysis of heat and moisture transfer (explained by Darcy's law), shrinkage (conducted by structural mechanics model), and TPD model of prawn during heating has not been previously reported.

This study aims to clarify the multiphysics involved in the shrinkage of prawn during heating by a developed model that describes changes in moisture content due to pressure-driven water transport according to Darcy's law. Therefore, this study includes:

- The evaluation of the shrinkage phenomena in two dimensions by a stress-strain analysis coupled to the virtual work principle using a structural mechanics model.
- The analysis of the extent of shrinkage in the prawn during the heating process by using transport equations to simultaneously describe heat and moisture transfer as well as internal pressure changes.
- The simulation of the degree of TPD in prawns that were heated under various thermal schedules. A previously reported TPD kinetic model of the three major proteins of the prawn muscle, myosin, sarcoplasmic-collagen, and actin (Mao et al., 2016) was used.