Computational Simulation for the Evaluation of a Food Softening Process Using Underwater Shockwaves

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***Abstract*—The purpose of this research is to optimize food processing using simulation results based on computational mechanics of food processing technology with high pressure induced by underwater shock waves. In order to establish the characteristics of shock wave propagation in the food and in the food processing vessel, finite element models of the food, the surrounding water, the high pressure source, and the vessel were developed using commercial finite element software. Conducting a series of computational simulations, we found that the pressure distribution is dependent on the food's unique characteristics, associated with the acoustic impedance. The different interfaces were obtained and observed. The computational results revealed that for certain food, both the transmitted and the reflected waves can be used during the food processing stages.**

***Index Terms*—food processing, computational simulation, pressure distribution, underwater shockwave**

I. Introduction

In recent years, shock wave-based methodologies and technologies for food treatment have attracted attention as a novel food processing technique. The type of shock wave considered in this study is a pulse wave with a high momentary pressure power. This pulse wave propagates faster than the speed of sound in media such as water, air, and food [1]. Shock wave propagation in water has been particularly well studied. Previous studies have reported the experimental applications of shock waves in meat and vegetable preprocessing [2], food sterilization [3], oil extraction [4], and rice powder manufacturing [5]. Novel processing methods [6] using underwater shock waves can be expected in the field of medicine if the sampling fraction of the useful component is better than that in the existing process. Regarding the development of the corresponding equipment, suitable devices must be designed to satisfy various conditions. However, investigating their design experimentally is extremely difficult given the numerous parameters that must be considered to ensure suitable food processing, and also due to the fact that the shock wave propagation phenomenon ends in a very short period of time. Thus, it is very important that a computational simulation based on the elementary process be carried out to investigate shock wave propagation in the proposed food softening process. In this paper, in order to obtain the shock wave propagation characteristics in foods such as apples, carrots, and meat, computational models of the food, the surrounding water, the silicone sheet and the high pressure source were developed using the HyperWorks (Altair®) finite element software and the Altair® RADIOSS® structural analysis solver. The pressure distribution in a variety of foods dependent on the characteristics of the different materials used was then discussed by conducting a series of numerical simulations.

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II. Multiphysics Computation and the Fundamental Equation

An appropriate numerical scheme must be selected to explain certain multiphysics events, such as underwater shock wave generation and propagation, the momentary rise in pressure, and shock wave penetration and reflection on the sides of the pressure vessel. Therefore, a finite element computation based on the Arbitrary-Lagrangian-Eulerian (ALE) scheme [7] was conducted using the HyperWorks (Altair®) commercial software.

A. *The Fundamental Equation*

In this study, the high pressure source, the object (apple, carrot, and meat), the silicone sheet and the water surrounding the object in a vessel were modeled by an equation of state. (EOS). The processing vessel, which is composed of stainless steel (SUS304), was modeled using a constitutive equation. The silicone sheet, which is protected used to protect the food from the water, was

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also modeled using a constitutive equation. Finite element discretization was carried out for all components. The vessel was discretized with a Lagrangian mesh. In contrast, the high pressure source, the water, the silicone sheet and the food were all discretized with BIMAT elements [8], which is an ALE multi-material law for 2D axi-symmetrical analysis. The Euler equations, which omit the viscosity term from the Navier-Stokes equation, can be expressed as follows.

Mass conservation law:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \boldsymbol{v}) = 0 \tag{1}$$

Momentum equation:

$$\rho \left(\frac{\partial \boldsymbol{v}}{\partial t} + \boldsymbol{v} \cdot \nabla \boldsymbol{v} \right) = \nabla \cdot \boldsymbol{\sigma} \tag{2}$$

Energy conservation law:

$$\rho \left(\frac{\partial e}{\partial t} + \boldsymbol{v} \cdot \nabla e \right) = \boldsymbol{\sigma} \cdot \nabla \boldsymbol{v} \tag{3}$$

where $\boldsymbol{v}$ is the velocity vector of the material, ρ is the material density, $\boldsymbol{\sigma}$ is the stress tensor, and e is the magnitude of the energy.

B. Pressure Calculation

The water is modeled using the linear polynomial EOS [8]. The linear polynomial EOS is linear in internal energy per unit of initial volume, E_0. The pressure is then given by

$$P = C_0 + C_1\mu + C_2\mu^2 + C_3\mu^3 + (C_4 + C_5\mu)E_0, \tag{4}$$

$$\mu = \frac{\rho}{\rho_0} - 1$$

where C_0, C_1, C_2, C_3, C_4, C_5, and E_0 are constants and are equal to: $C_0 = C_4 = C_5 = E_0 = 0$, $C_1 = 2199$ MPa, $C_2 = 5351$ MPa, $C_3 = 7324$ MPa., where ρ_0 is the initial density of water, i.e., $\rho_0 = 1000$ kg/m^3.

Given that the high pressure was induced by the underwater gap discharge (UNDGD), the source of the shock wave was simply replaced by an underwater explosion (UNDEX). Therefore, the pressure induced by the UNDEX was estimated using the Jones–Wilkins–Lee (JWL) EOS [9], which is given by

$$P = \mathrm{A}\left[1 - \frac{\omega}{R_1 V}\right] e^{-R_1 V} + B\left[1 - \frac{\omega}{R_2 V}\right] e^{-R_2 V} + \frac{\omega e}{V} \tag{5}$$

$$P_{CJ} = \frac{\rho_0 D^2}{\gamma + 1}, \ \gamma = c_p / c_v \tag{6}$$

where A, B, R_1, R_2, and ω are the JWL parameters; V is the ratio of the volume of gases produced by the explosion to the initial volume of the undetonated explosive; e is the detonation energy per unit volume with an initial value of e_0; P_{CJ} is the Chapman–Jouguet pressure, which depends on the initial density, ρ_0, of the explosive (SEP) and the detonation velocity D; and γ is the isentropic expansion factor. The constants for the SEP explosive [10] were obtained by performing a cylinder expansion test and are as follows: A = 365 GPa, B = 2.31 GPa, R_1 = 4.3, R_2 = 1.0, ω = 0.28, e_0 = 2.16 MJ/kg, P_{CJ} = 15.9 GPa, D = 6970 m/s, ρ_0 = 1310 kg/m^3. As an explosive pressure, the detonation velocity and initial density are given in Table I.

TABLE I. PEAK PRESSURE VALUE AT POINTS (D) AND (E), THEIR RATIO AS SHOWN IN FIG. 4.

	$\bar{p}_{\mathrm{I}}$,MPa	$\bar{p}_{\mathrm{II}}$,MPa	$\bar{p}_{\mathrm{III}}$,MPa	$\bar{p}_{IV}$,MPa	$\bar{p}_{\mathrm{II}}/\bar{p}_{\mathrm{I}}$	$\bar{p}_{\mathrm{III}}/\bar{p}_{\mathrm{I}}$	$\bar{p}_{\mathrm{IV}}/\bar{p}_{\mathrm{I}}$
Apple	0.540	0.931	0.510	0.184	1.724	0.9444	0.3407
Carrot	0.600	1.07	0.537	0.180	1.783	0.8950	0.3000
Meat	0.633	1.13	0.523	0.259	1.785	0.8262	0.4091

C. Constitutive Equation

The constitutive equation of the stainless steel, the silicone sheet, and the different food products has been used here since it is a simplified Johnson-Cook equation [11] which ignores thermal and strain rate effects. The equation can be written as follows:

$$\sigma = a + b\varepsilon_p^n \tag{7}$$

where a is the strain hardening of the yield stress, b is the plasticity modulus, and n is the strain hardening exponent. These values are given in Tables II and III.

TABLE II. MATERIAL CONSTANTS FOR FOOD AND THE SILICONE SHEET

	Apple	Carrot	Meat (pork)	Silicone sheet
ρ_0 ,kg/m^3	780	910	1060	1070
E ,MPa	27.7	50.4	77.1	70.8
c_0 ,m/s	1088	1360	1558	1485
$Z \times 10^6$,kg/(m^{2}s)	0.8486	1.238	1.652	1.590
ν	0.495			
a ,GPa	1×10^{21}			

TABLE III. MATERIAL CONSTANTS FOR THE FOOD PROCESSING VESSEL

ρ_0 ,kg/m^3	7930	ν	0.3
c_0 ,m/s	4570	a ,MPa	206
$Z \times 10^6$,kg/(m^{2}s)	36.24	b ,MPa	450
E ,GPa	193	n	0.5

III. COMPUTATIONAL MODELING

To estimate and visualize the underwater shock wave propagation in the food processing vessel, the silicone sheet and a series of food products, a two–dimensional (2D) axisymmetric computational model was used as shown in Fig. 1. The z–axis corresponds to the axisymmetric axis. The cylindrical inner vessel was filled with water. All regions of the computational model were discretized by four-node quadratic elements; thus, the number of elements and nodes were respectively 98896 and 99681. If the pressure extended beyond the inner pressure vessel, it was released.

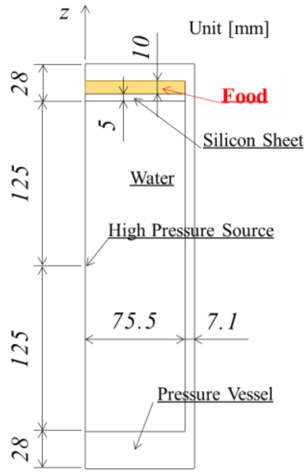


Figure 1. Computational model and its dimension.

IV. COMPUTATIONAL RESULTS AND DISCUSSION

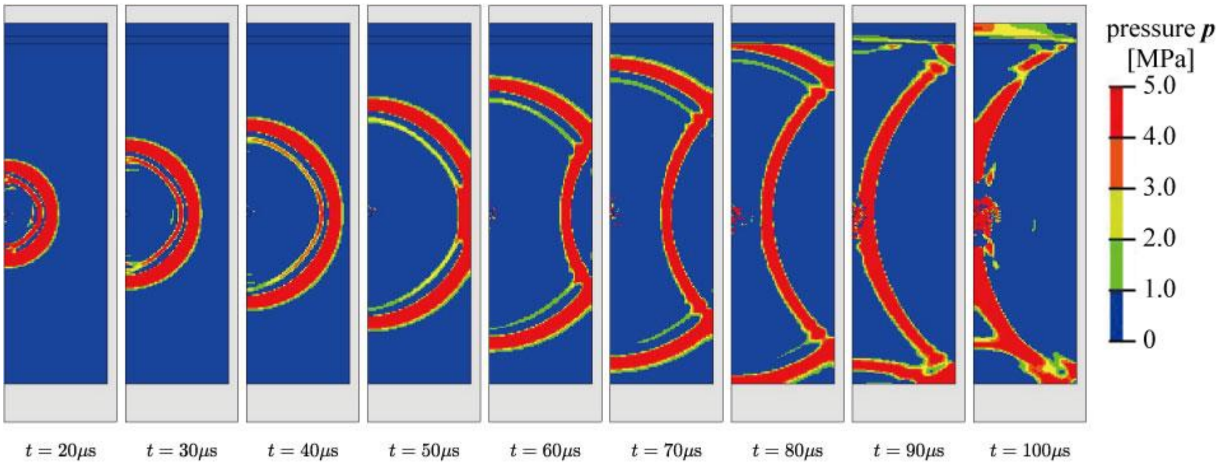


Figure 2. Pressure distribution at each computational time step.

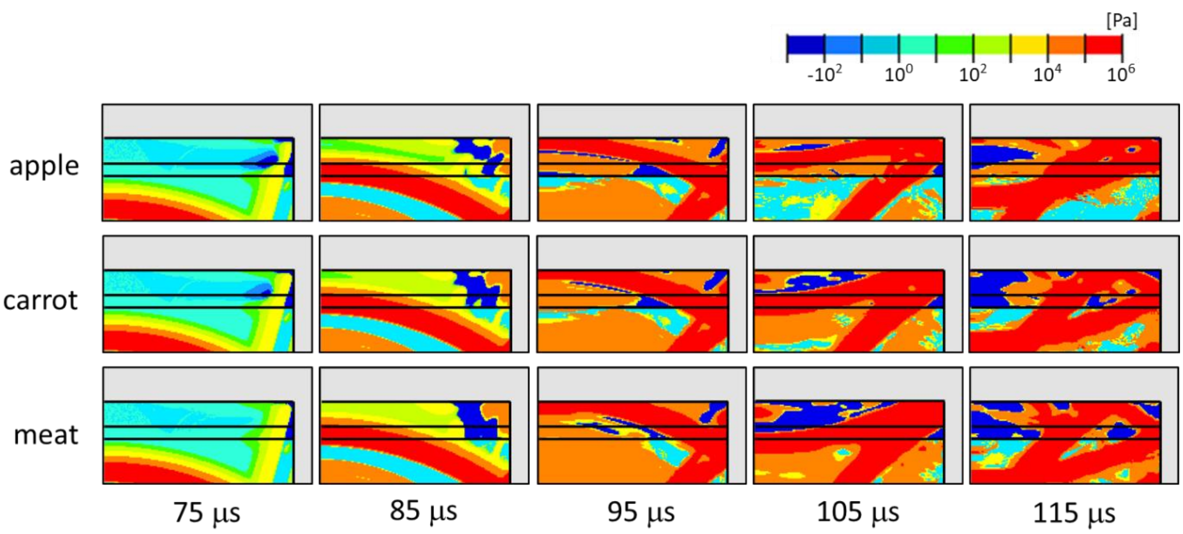
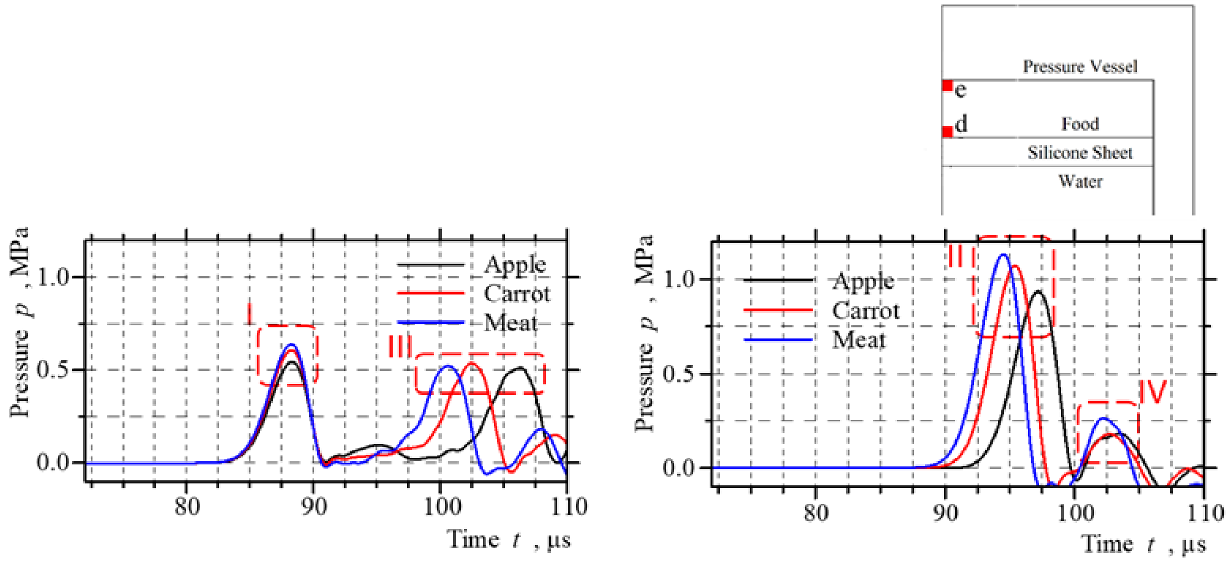


Figure 3. The effect of different target foods on the pressure distribution at each computational time step

The change in pressure distribution with time within the vessel is shown in Fig. 2. It can be seen that the pressure wave spreads radially from the central region, which corresponds to the pressure source induced by a gap discharge (GD) or a wire discharge (WD) [12]. It is also observed that the wave reflects off the vessel wall. The propagation speed of the pressure wave was calculated to be about 1600 m/s, which is larger than the speed of sound in water. This computational result is in good correspondence with the experimental results obtained from optical observations [12], [13]. This proves that the wave is indeed a shock wave. Furthermore, it is observed that the magnitude of the pressure wave changes on the surface as a result of the difference in density, as shown in Fig. 3. The peak value of the pressure propagation decreases at the interface between the water and the silicone sheet. This is caused by the fact that the density of water is lower than the density of the silicone sheet.

Fig. 4 (a) and (b) shows a snapshot of the pressure distribution at each time step with regards to the effect of the different food products used (apple, carrot, and meat) on the pressure propagation behavior. It can be seen that this pressure propagation is associated with the reflection/transmission wave at each interface of the material, which results in a density difference. In what follows we will therefore consider the shockwave propagation behavior at the interface between the silicone sheet (c) and the food (d), between the food (e) and the food processing vessel (f), and between the food (d) and the silicone sheet (c).



(a) Pressure vs time history at point (d)

(b) Pressure vs time histroy at point (e)

Figure 4. Effect of different food characteristics on the pressure vs time relationship.

A. Interface between the Silicone Sheet (c) and the Target Food (d)

Fig. 4 (a) shows the pressure history of the section of food in direct contact with the silicone sheet. The graph shows the first pressure peak, $\overline{p}_{\mathrm{I}}$, at about 88 μs, which represents the first shock wave. This peak pressure strongly depends on the magnitude of the acoustic impedance. As shown in Table II, foods with higher impedance produce a higher peak pressure. This phenomenon indicates that the target food can be softened by the instantaneously high pressure acting in a very short period of time. This result shows that this is a unique and characteristic food processing method that uses instantaneously high pressure derived from shock waves [2], [6].

B. Interface between the Food (d) and the Processing Vessel (f)

It can be seen in Table II and Table III that, as the first wave propagating through the food reaches the interface between the food and the pressure vessel, the peak pressure is larger for food with higher acoustic impedance. As larger food medium specific speed of sound, it is also observed that the time to reach the interface between the food and the pressure vessel is shorter. The peak pressure is higher than the peak pressure of the first wave observed at point (d), and the ratio, $\overline{p_{\mathrm{II}}}/\overline{p}_{\mathrm{I}}$, is higher for foods with a higher acoustic impedance as shown in Fig. 4 (b). This is due to the pressure at the interface with the food processing vessel which has large acoustic impedance. On the other hand, this first wave is reflected as a strong expansion wave at the pressure vessel-free surface interface and is incident once again on the pressure vessel-food interface. The magnitude of the ratio between the second and the first waves, $\overline{p_{\mathrm{IV}}}/\overline{p}_{\mathrm{I}}$, is approximately between 30% and 40% of the peak pressure (processing pressure) at point (d), as shown in Table I.

C. Interface between the Food (d) and the Silicone Sheet (c)

The pressure wave at the peak of the second wave reaching the food-silicone sheet interface (shown in subsection B), is slightly lower than the pressure wave at the first peak, as shown in Fig. 4 (b). It can also be confirmed that this pressure value is almost at the same level. The decrease rate of the peak pressure value depends on the reflection coefficient, and it can be confirmed that the pressure value at the apple-silicone sheet interface with a large reflection coefficient is large and so the decrease rate is low.

D. Summary of the Pressure Propagation Phenomena at Various Interfaces

Acoustic impedance affects the transmission and reflection of sound waves when they propagate through different media. The larger the difference in acoustic impedance between the two media, the more the sound waves are reflected at the boundary surface. As for the shock wave, it is reflected at the interface with a difference in density as it passes from a material with large acoustic impedance to a material with smaller acoustic impedance. At this time, if a force greater than the tensile strength of the substance is applied, a fracture due to a tensile force (spalling [14]) occurs at the interface of the material with large acoustic impedance. These results indicate that the difference in the materials which are in contact with the food affects the peak pressure value.

V. Conclusion

In this paper we optimized food processing equipment by using instantaneous high pressure induced by an underwater shock wave. The computational simulation model consisted of the processing vessel, the target food, and high pressure resources. A numerical simulation was also performed. This enabled to establish the difference in the acoustic impedance between the target food and the device and the propagation behavior of the pressure wave specific to the interface. By conducting a series of computational simulations we found that following the propagation of the shock wave in water, it reaches the section of the food in direct contact with the silicone sheet as the first wave with a peak pressure. The pressure propagating toward the pressure vessel is reflected at the food-pressure vessel interface, and the peak pressure subsequently appears on the food side of the interface. Although the peak pressure is lower than the peak pressure of the first shock wave incident on the silicone sheet, we have confirmed that the magnitude of the peak pressure of the second wave reflected from the pressure vessel is large enough for food processing. The results above suggest that the target food processing can be accurately controlled by selecting the material with the desired acoustic impedance as the material to be in contact with the food.

Conflict of Interest

The authors declare that they have no conflict of interests.

Author Contributions

Yoshikazu Higa has written this paper and contributed all the research. Hirofumi Iyama has contributed the computational simulation and modeling. Ken Shimojima and Osamu Higa have analized the dynamic characteristic of foods. Shigeru Itoh has conducted and promoted the advanced research of food processing using underwater shockwave. All authors had approved the final version.

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