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Dumpling Cooking - Modeling and Simulation

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Abstract: A dynamic model that considers heat transfer laws, internal heat distribution, and different cooking strategies was developed to simulate dumpling cooking. The cooking strategies that were considered include refilling water, changing heating power, and adding dumplings. The concept of degree of doneness (DoD) was used to gauge the appropriate level of cooking dumplings. Experiments were designed to determine the acceptable range of DoD. The developed model enables the prediction of water and dumpling temperatures, water evaporation, and dumpling quality. The model, which reflected the evolution of dumpling cooking, may be used as a basis to optimize the process for energy saving and full automation purpose.

Keywords: dumpling, model, heat conduction, mass transfer, DoD, etc.

1. RESEARCH BACKGROUND AND MOTIVATION

Dumpling is a kind of food that consists of small pieces of dough wrapped around a filling that may include meat, vegetables, or other ingredients mixed together (David, B. et al. 2014). The dumpling was firstly recorded by Zhang Ji in his book "Guang Ya" as early as the 2nd century AD. To date, dumplings have become increasingly popular as traditional festival food and convenient frozen food in many countries.

However, current dumpling cooking methods show some drawbacks. First, the cooking method that involves adding water and dumplings employs different heating powers depending on cooks; in other words, an optimized cooking protocol for dumplings is lacking. Second, the traditional way of cooking dumplings is complex and requires continuous monitoring; thus, an automatic cooking maching is highly needed. Third, dumpling cooking remains to be optimized; our previous experiments showed that heating dumplings in a microwave saves energy but results in poor taste. The potential is even more attractive when considering the huge consumption of dumplings every year.

Various models have been developed for food cooking processes. Several models have been established to predict changes in the temperature, fat content, mass loss, and other properties of food during the evolution (Shilton, Mallikarjunan, & Sheridan, 2002; Sandro, Viviana, & Salvadori, 2010). However, previous studies seldom modeled cooking as a process with control methods that can affect food quality. Linnemann AR et al. invetsigated the hygiene standards and degree of doneness (DoD) for cooked food. (Linnemann, & Van, 2007). Basing on the study of Linnemann and Van, Deng li proposed an evaluation criterion model that quantitatively expresses the DoD of cooked food under various cooking processes (Deng, 2013). These studies enabled the development of our model.

2. DESCRIPTION OF THE MODEL

As shown in Fig. 1, the exterior dumpling model considers the relation of heat and mass transfer to cookware, water, dumplings, and external environment. This model was developed to predict the temperature and evaporation of water during cooking. The model can also be used to predict the internal temperature pattern and thus the DoD of dumplings. The dumpling DoD model was set up to indicate the evolution of dumplings, which was enabled by the concept of DoD and a new evaluation standard for cooked dumplings.

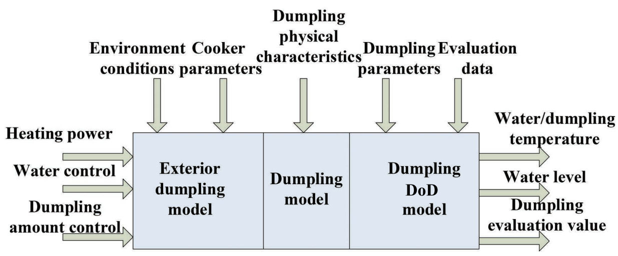


Fig. 1. System model with input, output, and working parameters

The model has three important assumptions. First, the dumplings are completely unfrozen before cooking to easily predict the heat transfer coefficient of dumpling surface. Second, the dumplings have spherical geometry and equally spaced concentric layers. Third, the water inside the cookware is completely stirred during the process to avoid adhesion between dumplings and maintain uniform heat. Temperature measurements reflect that these assumptions are generally reasonable.

2.1 Exterior dumpling model

Fig. 2 presents a schematic of the different elements included in the model. This setting follows the general custom of dumpling boiling. Constitutive equations were obtained from expressions of fluxes of heat convection and transfer, water evaporation, and energy conservation.

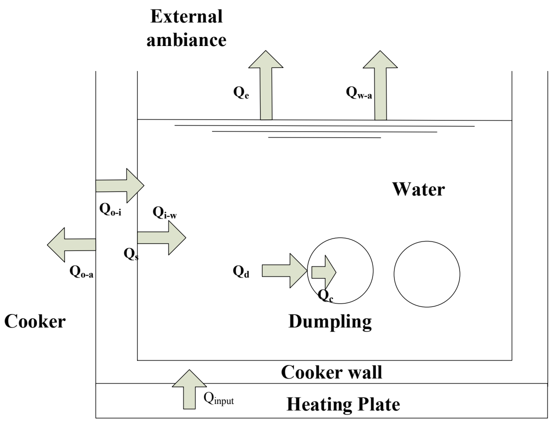


Fig. 2. Exterior-Dumpling model

Considering that the cooker is made of metal with good heat conduction effect, the authors simplify the heat conduction through the cooker into a process between two layers, i.e., dividing the cooker into internal and external layers, which follow formulas on energy conversion (McCabe, Smith, & Harriott, 2005):

$$Q_{input} - Q_{o\to i} = 0.5 M_b c_b \frac{dT_i}{dt} \tag{1}$$

$$Q_{o\to i} - Q_{i\to w} = 0.5 M_b c_b \frac{dT_o}{dt} \tag{2}$$

where Q_{input} is the external heat input, in J; $Q_{o\to i}$ is the heat transferred by the cooker wall, in J; and $Q_{i\to w}$ is the heat transferred by heat convection between the water and the internal wall, in J. The mass of each part is assumed to be half of the total mass. This simplification enabled the dynamic characteristics of heating cookers with relatively thick walls and also reduced the computing complexity.

The heat conduction $Q_{o\to i}$ consists of two parts: the heat conducted through the cylindrical wall and through the boiler bottom. This process can be formulated as (McCabe, Smith, & Harriott, 2005):

$$Q_{o\to i} = \frac{T_i - T_o}{\ln \frac{d_o}{d_i} 2\pi h \lambda_b} + \frac{T_i - T_o}{b/(\lambda_b A_1)}$$

where b, d_o, d_i, h, and A_1 are the physical parameters of the cooker. λ_b is the heat conductivity coefficient of the cooker, in $w/m \cdot K$, which is determined by its material.

Convective heat fluxes from any compartment A to compartment B, were expressed and calculated using the same general equation:

$$q_{A\to B} = S \cdot h_{A\to B} \cdot (T_B - T_A)$$

where S represents the contact area of different compartments; T_B and T_A are the temperatures of the two compartments; and $h_{A\to B}$ represents the heat transfer/convection coefficient, which is dependent on the temperature difference, fluid properties, and composition.

Heat transfer occurs between:

- The internal wall and water inside. Heat is transferred either through the cylindrical wall of the cooker or through the bottom of the cooker. ($Q_{i\to w}$)
- The external wall and the surrounding air. Heat is lost from the heating system. ($Q_{o\to a}$)
- The water surface and the surrounding air. Heat transfer is driven by the temperature difference between water and air. ($Q_{w\to a}$)

Table 1 presents the different heat transfer coefficients used. These coefficients were further experimentally determined through parameter estimation.

Fick's law (McCabe, Smith, & Harriott, 2005) states that water is endothermically converted from liquid to gaseous phase because of the difference in vapor partial pressure. The heat flux can be expressed as:

$$Q_v = \Delta M \cdot q$$

where ΔM is the mass of vaporization; q is the enthalpy of vaporization, in J/kg, which is a constant value under certain saturated vapor pressure and temperature. Since Dalton (1802) published the first empirical investigation, many equations have been developed to calculate the evaporation rate ΔM from the water surface:

$$\dot{m} = h_e(P_w - P_a)/h_w$$

where h_w is the heat transfer coefficient of water, and P_w and P_a are the partial vapor pressure of the water and air at the corresponding temperature, in Pa. Most of the equations developed so far only differ in h_e and are related to particular thermal conditions and applications (Steeman, T'Joen, & Belleghem, 2009). h_e considerably changes during cooking when the water temperature varies from a relatively wide range (e.g., 10°C to 100°C). We can express h_e as

$$h_e = a e^{bT_w} + c e^{dT_w}$$

where T_w is the water temperature, in K. We successfully made the formula effective at a wide range of cooking temperature by introducing coefficients a, b, c, and d.

Heat transfer occurs between dumplings and water. In this research, the heat balance between water and dumplings was considered according to the relationship between temperature change and heat absorption. The characteristic temperature of the dumplings is selected to obtain the heat absorption rate (McCabe, Smith, & Harriott, 2005):

$$Q_{w\to d} = c_d M_d \frac{dT_d}{dt}$$

where c_d is the specific heat capacity, in $J/kg \cdot K$; M_d is the mass of the dumplings, in kg; T_d is the characteristic temperature of the dumplings, in K. In the present study, the temperature in the middle of the diameter was selected.

Different heat/mass transfers have been discussed to date. The energy balance equation for water can be directly expressed as:

Table 1. Values of heat transfer coefficient

Coefficient	Mean value	Type of transfer	Correlation Source	
$\alpha_{i\to w}$	3000	Water and boiler internal wall heat transfer	$\alpha_{i\to w} = 1.86\mathrm{Re}^{1/3}\mathrm{Pr}^{1/3}(\frac{\mu}{\mu_s})^{0.14}(\frac{d}{l})^{1/3}$	Mccabe,2005
$\alpha_{0\to a}$	4.81	Air and boiler external wall heat transfer	$\alpha_{0\to a} = C\frac{\lambda_a}{L}(\frac{\rho_a^2 g\beta\Delta t L^3}{\mu_a^2}\cdot\frac{c_a\mu_a}{\lambda_a})^{1/3}$	Mccabe,2005
$\alpha_{w\to a}$	4.81	Water and air heat transfer	$\alpha_{w\to a} = C\frac{\lambda_a}{0.9d_i}(\frac{\rho_a g\beta\Delta t(0.9d_i)^3}{\mu_a^2}\cdot\frac{c_a\mu_a}{\lambda_a})^{1/3}$	Mccabe,2005
λ_d	3000	Dumpling and water heat transfer	$\lambda_d = \frac{h_w R}{B_i}$	Mccabe,2005
λ_b	16.2	Boiler internal heat transfer	B_i is experimental determined	Mccabe,2005
α_d	1.6*10(-7)	Dumpling stuffing heat transfer	Experimental determination	See 3.2

$$Q_{i\to w} - Q_v - Q_{w\to a} - Q_{w\to d} = c_w M_w \frac{dT_w}{dt}$$

2.2 Dumpling model

This model reflects the temperature pattern inside dumplings during cooking. This pattern indicates the DoD of dumplings.

The dumpling is modeled as a layered ball with 10 equally-spaced concentric layers, as shown in Fig. 3. With the water temperature modeled in Section 3.1, the temperature distribution inside a dumpling is approximated (Huang, & Mittal, 1995).

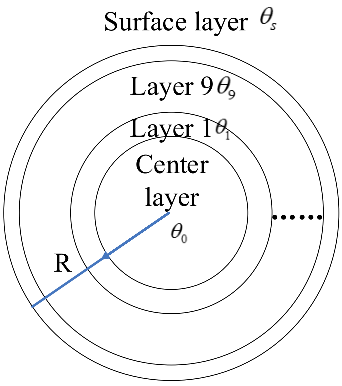


Fig. 3. Dumpling model

The temperature change at the center layer can be indicated as(Huang, & Mittal, 1995)

$$\frac{d\theta_0}{dt} = 300\frac{\alpha_d}{R^2}(\theta_1 - \theta_0)$$

where θ_0 is the temperature at the center of the dumpling, in K; θ_1 is the temperature the first layer of the dumpling, in K; R is the characteristic diameter of the dumpling, in m; and α_d is the heat transfer coefficient determined by stuffing, in $w/m^2 \cdot K$. On the basis of the layer set relations and temperature difference, the temperature at layers 1 to 8 can be expressed as

$$\left.\frac{d\theta_i}{dt}\right|_{i=1\sim 8} = 100\frac{\alpha_d}{R^2}(\frac{2i+3}{2i+1}\theta_{i+1} - 2\theta_i + \frac{2i-1}{2i+1}\theta_{i-1})$$

The node of of the ninth layer can be expressed as

$$\frac{d\theta_9}{dt} = 100\frac{\alpha_d}{R^2}(\frac{160}{57}\theta_s - 4\theta_9 + \frac{68}{57}\theta_8)$$

where θ_s is the temperature at the surface of the dumplings, in K.

On the basis of the temperature of dumplings surface and the water contact, the temperature at the surface node can be indicated as

$$\theta_s = \frac{B_i T_w + 20\theta_9}{20 + B_i}$$

$$B_i = \frac{h_w R}{\lambda_d}$$

where B_i is Biot number, which determines the consistency of the temperature of the solid; λ_d is the heat conductivity coefficient between the dumplings and the water, in $w/m \cdot K$, which is related to the physical property of the dumpling wrapper during cooking.

2.3 Dumpling DoD model and evaluation standard

The effect of heating temperature on food quality evolution can be determined by the dynamics of heating quality change. To estimate the contribution of cooking time and temperature to the doneness of dumplings, the authors introduced the concept of DoD from existing research (Deng, 2013):

$$M = \int_0^t 10^{\frac{T - T_{ref}}{Z_M}} dt$$

where Z_M is the Z value of quality factor, in K; t is the heating time, in min; T_{ref} is the reference temperature, in K; and T is the temperature inside the dumplings, in K. The reference temperature and quality factor of cooking doneness can be obtained from previous work (Bengt Christina, S., & Christina, T., 2000), and the physical properties of dumplings can be verified through experiments (Hendrickx et al. 1996; Wang et al. 2010). Stuffing of different types of dumplings has different characteristic T_{ref} and Z_m values; nevertheless, the formulation can be employed to model different types of dumplings.

A suitable range of M for different type of dumplings from the aspects of appearance, taste and flavor was obtained. And according to the principles for sample selection (Saaty, & Vargas, 2012), 10 of 100 questionnaires were selected and object to mathematical analysis, favor is needed in order to determine the proper mature time under different heating conditions, for later process optimization. In the present study, we determined the standards of DoD for cooked dumplings and then decided the weight of each factor that influences our evaluation through Analytic Hierarchy Process(AHP); Then, we obtained a comprehensive index for measuring the doneness of the dumplings. Using the expert evaluation method, we obtained a statistically acceptable range of the M value. The validity of this result was checked through further experimentation.

3. EXPERIMENT VALIDATION AND RESULTS

3.1 Dumpling model

The dumpling cooking model was validated by experimental data. The experiment setup and important parameters are shown in Fig. 4 and Table. 2.

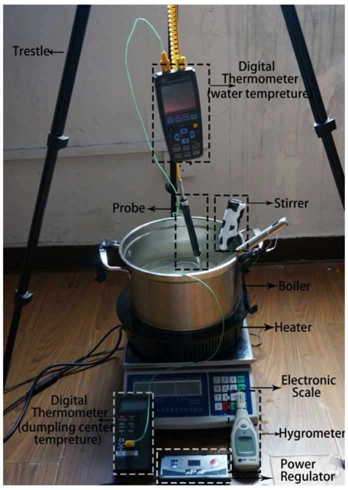


Fig. 4. Experiment setup

Table 2. Experimental tools parameters

Cooker			
Size (mm)	$\phi 240 \times 140$	Thickness at bottom (mm)	12
Material	201 type stainless steel	Thickness at sides (mm)	1
Heater			
Max power available (W)	2000	Min power available (W)	1000
Dumplings			
Max power available (W)	2000	Min power available (W)	1000
Size (cm)	$\phi 2$	Weight (g)	12
Fillings	Pork	Wrapper	Wheat flour

The experimental settings are shown in Table 3. The main results are shown in Fig. 5. Each graph compares the simulated values (solid lines) and experimental results (dash lines). The experiments aim to test the predictive ability of our dynamic model in different conditions and with different possible control methods (including changing heating power, adding water, etc.).

Exp.1 and Exp.2 in Fig. 5 show that the model predicted well the temperatures of water and dumplings as well as the evaporation rate of water when the heating power is changed during the process. Obviously there exists a time delay between temperature change between dumplings and water because of the heat resistance effect of dumplings. The measured water temperature constantly increased until the water reached a boiling temperature, at which

Table 3. Experiment design

Number	Water setting	Power setting	Dumpling	Energy Cost for each dumpling
1	2.5kg (0s)	1200W (0s) $\longrightarrow$ 1600W(270s) $\longrightarrow$ 2000W(1020s)	5	424.8KJ
2	2.5Kg(0s) +200g(270s) +200g(1140s)	2000W (0∼1320s)	5	528KJ

the evaporation rate was maximum. The simulation results were also consistent with the phenomenon when water and dumplings were added to the cooker.

Overall, the model for cooking environment and dumplings was valid for most cooking strategies and can be used for later optimization. Moreover, the corresponding energy costs on each dumpling are 424.8 and 528 KJ. Therefore, a large energy saving potential can be obtained for optimization when different cooking strategies are employed.

3.2 DoD model

To obtain the evaluation formulation, we selected 10 representative samples of tasting evaluations.

Basing from principles mentioned before, we could get judgment matrix A as follows (Saaty and Vargas, 2012):

$$A = \begin{pmatrix} 1 & 1/17 & 2/13 \\ 7 & 1 & 2 \\ 13/2 & 1/2 & 1 \end{pmatrix}$$

The consistency of judgment matrix A can be validated as follows:

$$\lambda_{\max} = 3.0427$$

where $\lambda_{\max}$ is the maximum eigenvalue of judgment matrix A

$$C.I. = \frac{\lambda_{\max} - n}{n-1} = \frac{3.0427 - 3}{3-1} = 0.02135$$

where C.I. is the Consistency Index.

$$R.I. = 0.58(n = 3)$$

where R.I. is the Random Consistency Index.

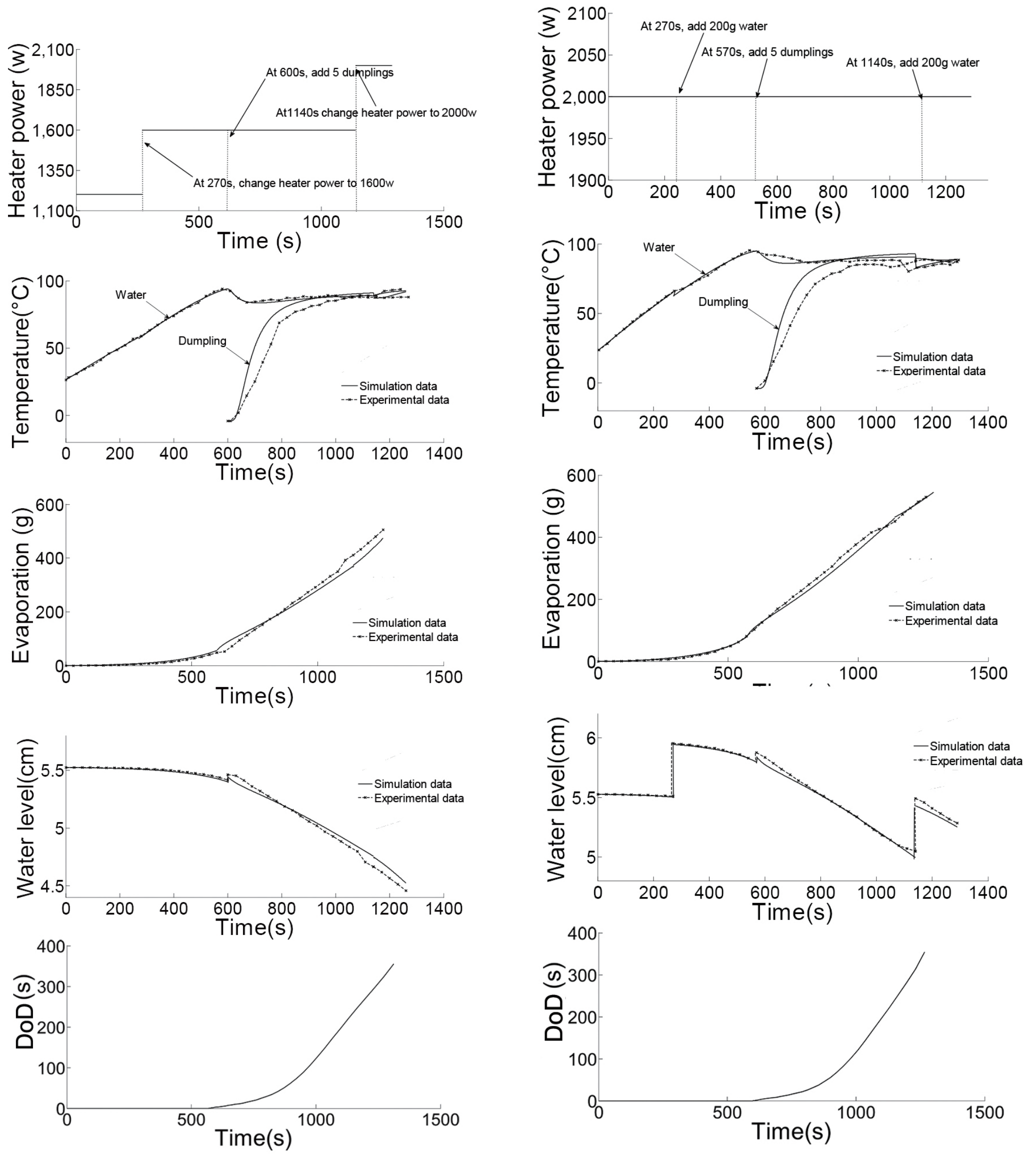
$$C.R. = \frac{C.I.}{R.T.} = 0.0368 < 0.1$$

where C.R. is the Consistency Ratio.

The result passed the consistency check. In particular, the judgment matrix and object data are consistent with each other, or the sample is highly feasible for evaluating dumpling doneness. Using the AHP method, we can determine the comprehensive evaluation index:

$$Y = 0.0671x_1 + 0.5778x_2 + 0.355x_3$$

where x_1, x_2, and x_3 are the evaluation factors of appearance, flavor, and taste, respectively.



(a) Exp. 1

(b) Exp. 2

Fig. 5. Experiment and simulation

Compared with appearance, taste and flavor contributed more to the evaluation of cooked dumplings.

To determine the acceptable range of DoD for eating, the authors collected evaluations (on taste, appearance, flavor respectively) for dumplings with different heating, and analyzed the evaluation standard. The results are shown in Fig. 6.

After considering all three factors, we selected an overall evaluation value of 8.5 or a DoD range of 220 - 490 as the standard for specific well-cooked dumplings to optimize eating experience. DoD can be used to gauge the appropriate level of cooking dumplings when the temperature distribution inside a dumpling is available. Meanwhile, the DoD value can be used as an important constraint in later cooking optimization.

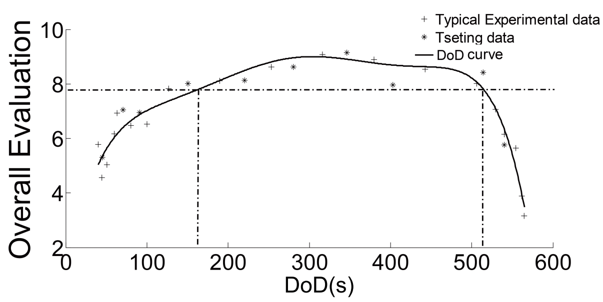


Fig. 6. Dumpling DoD value model and experimental validation

4. CONCLUSIONS AND FUTURE DIRECTION

The model developed describes well the trends of important variables and reveals the mechanism of dumpling cooking. In future studies, important physical parameters of the model should be accurately estimated to improve its predicting ability.

In consideration of the energy saving potential of different cooking schemes as shown in the expriments above, dynamic optimization methods will be employed to optimize dumpling cooking. New cooking schemes will consider both the energy consumption and dumpling taste for optimization, along with constraints of cooking. In future works, a new dumpling tool will be proposed using existing computer control technologies and mechanical structure designs to reduce possible constraints in manual operation and to save both time and energy during dumpling cooking.

Table 4. Nomenclature

A_1	Bottom surface area of the boiler (m^2)	T	Temperature (T)
A_2	Side surface area of the boiler (m^2)	$\alpha_{A\rightarrow B}$	Heat transfer coefficient between A and B $(W/(m^2 \cdot K))$
b	Bottom thickness of the boiler (m)	α_d	Thermal diffusivity of dumplings (m^2/s)
B_i	Biot number	β	Coefficient of cubical expansion $(1/K)$
c	Heat capacity $(J/(kg \cdot K))$	ρ	Density (kg/m^3)
d_i	Diameter (m)	λ	Heat conductivity coefficient $(W/(m \cdot K))$
G_r	Grashof number	μ	Dynamic viscosity $(Pa \cdot s)$
g	Acceleration of gravity (m/s^2)	$\theta_0 \sim \theta_9$	Non-dimensional dumpling temperature from node 0 to 9 (K)
h	Water level (m)	θ_s	Non-dimensional dumpling temperature at surface node (K)
h_w	Heat transfer coefficient of water $(W/(m^2 \cdot K))$	ΔM	Mass flux (kg/s)
M	Mass (kg)	**Subscript**	
Nu	Nusselt number	a	Air
Pr	Plante number	B	Boiler
Q_{input}	Heat flux from external to internal of the boiler (W)	D	Dumpling
$Q_{A\rightarrow B}$	Heat flux from A to B (W)	i	Inside of the boiler
Q_v	Latent heat of vaporization (J)	O	Outside of the boiler
q	Latent heat of vaporization (J/kg)	w	Water
Re	Reynolds number (m)		
R	Radius of dumpling (m)		
t	Time(s)		

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