



# Food and Applied Bioscience Journal



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## TABLE OF CONTENTS

## PAGE

- ***Listeria monocytogenes*: Prevalence and contamination profile in different categories of ready-to-eat foods within Ibadan metropolis, Oyo State, Nigeria** 1 - 12  
Kubrat A. Oyinlola and Augustina I. Balogun

- 
- **Chemical Antioxidant Activity of *Thunbergia Laurifolia* Linn. (Rang Chuet) Leaves and its Combined Extracts** 13 - 29  
Chattip Suntharak and Ratchadaporn Oonsrivilai

- 
- **Formulation of Reduced-Sugar, Fiber-Enriched Thai Traditional Sweet Egg Yolk Cake '*Thong Ake*'** 30 - 42  
Nitjaree Maneerat, Phimphida Sitkongden, Radchaneekorn Saiyart, Nattapol Tangsuphoom, and Chitraporn Ngampeerapong

- 
- **CFD Simulation of Heat Conduction in Curry Paste during Sterilization** 43 - 59  
Chumphon Numuang

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## CFD Simulation of Heat Conduction in Curry Paste during Sterilization

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### Abstract

Curry paste is a popular food product in Thailand, made of many fresh and dry spices that are finely ground to a solid-like homogeneous blend. The four types of curry paste KangSom (KS), GreenCurry (GC), PadPed (PP) and MasMan (MM) were used as 100 g samples in glass bottles. A water-spray with pressure-balance retort was run at 116°C to thermally sterilize by eliminating pathogenic microorganisms, and to extend the shelf-life of curry paste. Time profile of temperature at the slowest heating zone (SHZ) during thermal treatment is important for estimating the sterilization value (F0). A high quality mesh discretization was used in numerical simulations. This study used CFD simulations of heat conduction in curry paste during sterilization to get the SHZ (sim), which was compared with the experimental SHZ (exp). Thermal diffusivity ( $\alpha$ ) of each curry paste was adjusted for best fit of SHZ (sim) with SHZ (exp) according to the coefficient of determination  $R^2$ . The results were for KS ( $\alpha=1.55 \times 10^{-7} \text{ m}^2/\text{s}$ ,  $R^2=0.9990$ ), GC ( $\alpha=1.55 \times 10^{-7} \text{ m}^2/\text{s}$ ,  $R^2=0.9989$ ), PP ( $\alpha=1.65 \times 10^{-7} \text{ m}^2/\text{s}$ ,  $R^2=0.9996$ ) and MM ( $\alpha=1.45 \times 10^{-7} \text{ m}^2/\text{s}$ ,  $R^2=0.9993$ ). The sterilization values F0 (sim) from simulation and F0 (exp) from experiments were approximately equal, and so were the processing times required. In summary, CFD simulation of heat conduction can be used to describe the heat transfer in an actual food product that is solid-like and homogeneous. This study can be used as a template for guiding thermal process design by numerical simulations.

**Keywords:** CFD; Simulation; Sterilization; Slowest heating zone; Curry paste

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## 1. Introduction

Curry paste, seasoning paste, or namphrik kang, is a food product made from many fresh and dry spices, such as chili, shallot, garlic, galangal, lemongrass, kaffir lime leaves; and of food condiments such as shrimp paste, sugar, fish sauce, salt; and may be mixed with coconut milk or oil. All the ingredients are ground to a homogeneous paste. The product quality needs to comply with Thai Community Product Standard (TCPS.129-2556, 2013) or Thai Industrial Standard (TIS.429-2548, 2005) that regulate several quality characteristics of the product. The production of curry paste has transitioned from community level to an industrial scale, and is increasing due to the popularity of this Thai food ingredient. The thermal sterilization of a low-acidity food such as curry paste is done to eliminate all microorganism cells and spores for food safety, and to thereby extend the shelf-life in ambient storage. Sterilization value or  $F_0$  is the time in minutes for destroying spores of *Clostridium botulinum* ( $Z$ -value =  $10^\circ\text{C}$ ) thermally at  $121.1^\circ\text{C}$ . The minimum recommended effect is a  $12D$  reduction in *C. botulinum*, which requires heating at  $121^\circ\text{C}$  for 3 min (Lewis, 2006). The slowest heating zone (SHZ) means that inside region in a product that is the slowest heating during thermal treatment, and is typically at the geometric center of a solid food product. The data for SHZ are used to ensure that the sterilization provides safe food. The sterilization value must comply with the requirements of Notification of the Ministry of Public Health (MOPH.420-2563) Title: Food Production Processes, Processing Equipment/ Utensils and Storage Practices. The scheduled process (in temperature over time) shall meet the sterilization value  $F_0$  of at least 3 minutes. Process validation requires a study of temperature distribution (TD) and heat penetration (HP). Regarding the choice of type of sterilization retort, the thermal properties of food products depend on mode of heat transfer, solid and liquid ratio, viscosity, packaging type, and size and shape. Due to the various factors affecting heat transfer it is necessary to study TD and HP, which takes time and must be done by licensed professionals. Nowadays, a personal computer has high computing performance, and many computational fluid dynamics (CFD) software packages have been developed. Especially the CFD software OpenFOAM, named for Open Source Field Operation and Manipulation (The OpenFOAM Foundation, 2017), has been used to improve industrial processes involving heat transfer, air ventilation, fuel combustion in steam-boiler, interactions in mixture of air with water vapor or with particles, complicated flows in heat exchanger, and chemical reactors.

This work aimed to study and develop a CFD model by using finite element analysis to describe heat conduction in four types of curry paste. The results of this work demonstrate the fundamentals of heat transfer modeling and identifying the thermal diffusivity ( $\alpha$ ) of a curry paste. The application is in thermal process design by adapting sterilization conditions (temperature over time) to container shape and packaged material.

## 2. Materials and Methods

This work consisted of three parts: (1) The thermal sterilization of curry paste was examined to determine the processing time, sterilize value  $F_0$  (exp), and the time profile of temperature in the slowest heating zone, SHZ (exp). (2) The heat conduction CFD model was used to estimate the SHZ (sim) and the thermal diffusivity. (3) The  $F_0$  (exp) and  $F_0$  (sim) were calculated by using the SHZ data.

### 2.1 Thermal sterilization of curry paste

2.1.1 Material and machine: The curry paste was produced by the community enterprises in Pattani province, southern Thailand. The four types of curry paste KangSom (KS), GreenCurry (GC), PadPed (PP) and MasMan (MM) were used in this study. The composition of curry paste (% by weight), pH, water activity ( $a_w$ ) and initial temperature (IT, °C) are shown in Table 1.

**Table 1** The compositions of curry pastes in percentages by weight, and some properties.

| KS          | (%wt.) | GC                 | (%wt.) | PP          | (%wt.) | MM      | (%wt.) |
|-------------|--------|--------------------|--------|-------------|--------|---------|--------|
| Dry chili   | 28     | Green chili        | 26.5   | Lemon grass | 25     | Shallot | 30     |
| Fresh chili | 28     | Lemon grass        | 26.5   | Dry chili   | 15     | Spice   | 25     |
| Garlic      | 20     | Shallot            | 10     | Shallot     | 13     | Garlic  | 25     |
| Turmeric    | 20     | Garlic             | 10     | Garlic      | 13     | Sugar   | 5      |
| Salt        | 4      | Turmeric           | 10     | Fresh chili | 8      | Salt    | 5      |
| Total       | 100    | Galangal           | 5      | Turmeric    | 7      | Chili   | 5      |
|             |        | Shrimp paste       | 5      | Salt        | 7      | Oil     | 5      |
|             |        | Coriander seeds    | 3      | Pepper      | 7      | Total   | 100    |
|             |        | Salt               | 2.5    | Galangal    | 5      |         |        |
|             |        | Kaffir lime leaves | 1.5    | Total       | 100    |         |        |
|             |        | Total              | 100    |             |        |         |        |
| pH          | 4.62   | pH                 | 5.19   | pH          | 4.23   | pH      | 4.78   |
| $a_w$       | 0.927  | $a_w$              | 0.965  | $a_w$       | 0.944  | $a_w$   | 0.917  |
| IT(°C)      | 27.50  | IT(°C)             | 25.10  | IT(°C)      | 25.97  | IT(°C)  | 26.85  |

KangSom (KS), GreenCurry (GC), PadPed (PP) and MasMan (MM)

The glass bottle (WG-09-913-1TO) and lug-cap (CTO-0001 ) were bought from Tan Soon Huat Product Co., Ltd. The curry paste amount 100 g was filled into a glass bottle. The glass cap was closed under vacuum pressure for hermetic seal. The bottles of curry paste were used in experiments. The water-spray with pressure-balance retort OFM model PP500 was used as a sterilizing machine. The steam boiler Zu How model ZH-500G provided continuously steam at 6.0-7.0 kgf/cm<sup>2</sup> pressure. The screw type air compressor SULLAIR was used for balancing the pressure inside and outside the samples in the retort, since elevated temperature increases vapor pressure in the sample bottles. The data logger Ellab model E-Val Pro System with 12 channels was

used to record temperatures from thermocouple sensors SSA-TS type T and the sterilize value  $F_0$  (exp) was calculated at time intervals of 1 min.

**2.1.2 Thermal processing method:** First, the temperature distribution (TD) in the retort and its ability to maintain the process temperature at  $116^{\circ}\text{C}$  were tested. Starch solution (2% w/w) was used instead the curry paste as the product dummy. The dummy was fully loaded ( $n=390$ ), and then the thermocouple sensors ( $n=10$ ) were distributed in the retort. The retort was run with a heating schedule suitable for the glass containers to avoid thermal shock, and raising the temperature to  $116^{\circ}\text{C}$  for sterilization, then holding this for 20 min. The TD was studied in 2 replicate runs to obtain 20 time profiles of the retort temperatures (RT). Second, experiments on heat penetration (HP) into the curry paste were run. Bottles of curry paste with a thermocouple sensor placed at the slowest heating zone (SHZ) were used as samples ( $n=10$ ). The samples were fully loaded in the retort run with scheduled temperature rise to  $116^{\circ}\text{C}$ , and continued until data logger had reached  $F_0$  (exp) for at least 3 min. The temperature profile at slowest heating zone, SHZ (exp) was recorded by the datalogger. The HP was studied for 2 replicate runs to obtain 20 time profiles of SHZ (exp) and  $F_0$  (exp) as well. The thermal processing was separately studied for each curry paste, namely KS, GC, PP and MM.



**Figure 1** An empty glass bottle and thermocouple sleeve installed through the lid (a), the weighted 100g samples of KS curry paste filled in glass bottles (b), and the hermetic seals made under vacuum to cover samples for sterilization (c). The cases GC, PP and MM were quite similar in appearance.

## 2.2 CFD model for simulation

**2.2.1 Governing equations for fluid dynamics and heat transfer:** The mathematical relationships for the conservation of mass, of momentum, and of energy, have been written in the form of partial differential equations (PDEs). The PDEs describe the flow behavior and heat transfer in the matter. Consider a small fluid volume (or a fluid element or a control volume) as a system. The system has a boundary and a control surface. The fluid element is stationary in the flow stream with fluid flowing across the boundary, and the system has changes in mass, momentum, and energy. The 3-dimensional Cartesian coordinate system with the axes for (x, y, z) was used to locate the fluid elements.

The mass conservation equation. (Versteeg and Malalasekera, 2007) The law of conservation of mass means that the rate of change within mass of fluid control volume system equals the rate of fluid entering through the system boundary minus the rate of fluid exiting through the boundary.

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho u) = 0 \quad (1)$$

for density  $\rho$  (kg/m<sup>3</sup>), time  $t$  (s), velocity vector  $u$  (m/s), Del operator ( $\nabla$ ) and  $\nabla \equiv \frac{\partial}{\partial x} \hat{i} + \frac{\partial}{\partial y} \hat{j} + \frac{\partial}{\partial z} \hat{k}$ . In Eq. (1) the first term on left is the rate of mass change per unit volume. The next term is the rate of mass change as a result of the flow. In this study, the overall system was a glass bottle filled with curry paste and hermetically sealed as a closed system. The mass of the system is constant, no mass flows across the boundary. Therefore, it is reasonable to ignore the mass conservation equation.

The linear momentum conservation equation. (Versteeg and Malalasekera, 2007) The momentum is the ability of an object to maintain its motion. The momentum is a vector quantity, the product of mass and velocity. The law of conservation of momentum indicates that if there is no external force acting on the system, the total momentum of the system will remain constant; or the rate of change of total momentum equals the net applied force. The equation for conservation of momentum is written separately for the directions (X, Y, Z) as follows:

X-momentum

$$\frac{\partial(\rho u)}{\partial t} + \nabla \cdot (\rho u u) = -\frac{\partial p}{\partial x} + \nabla \cdot (\mu \nabla u) + S_{Mx} \quad (2)$$

Y-momentum

$$\frac{\partial(\rho v)}{\partial t} + \nabla \cdot (\rho v u) = -\frac{\partial p}{\partial y} + \nabla \cdot (\mu \nabla v) + S_{My} \quad (3)$$

Z-momentum

$$\frac{\partial(\rho w)}{\partial t} + \nabla \cdot (\rho w u) = -\frac{\partial p}{\partial z} + \nabla \cdot (\mu \nabla w) + S_{Mz} \quad (4)$$

Here the velocities in x, y, z directions are  $u, v, w$  (m/s), pressure  $p$  (kg/m s<sup>2</sup>), distance in axis  $x, y, z$  (m), dynamic viscosity  $\mu$  (kg/m s), force (from mass) per unit volume  $S_M$  (kg/m<sup>2</sup> s<sup>2</sup>) and  $s_{Mx} = 0, s_{My} = 0, s_{Mz} = -\rho g$ . Consider a small fluid particle that has a constant mass and flows at some velocity. In Eqs. (2), (3) and (4) the left-hand side is the change in momentum in one unit volume per unit time. The right-hand side is the sum of forces applied on the fluid particle in the axial directions, from external pressure, viscosity, and body forces. In this study, the glass bottle of curry paste as the system was stationary, stable, and rigid. The system had no volume change and was not affected by any force. Therefore, the conservation of momentum equation is also ignored.

The energy conservation equation. (Berk, 2009) In words, the energy of an isolated system remains constant. Energy cannot be generated or lost, but it can change its form. The energy can be transferred from one system to another. Generally, the forms of energy in fluids are internal energy, kinetic energy (due to flows), potential energy (due to gravity), heat, and work. When a nonzero force acts upon the fluid

system, it causes a change in momentum. The conservation of energy can be written as the Bernoulli equation:

$$\sum \left( h + gz + \frac{v^2}{2} \right)_i \dot{m}_i - \sum \left( h + gz + \frac{v^2}{2} \right)_o \dot{m}_o + \dot{Q} - \dot{W} = \frac{d}{dt} \left[ \left( u + gz + \frac{v^2}{2} \right)_{\text{sys}} \dot{m}_{\text{sys}} \right] \quad (5)$$

Here the quantities are enthalpy  $h$ , ( $h = u + P/\rho$ ) per unit mass of fluid, internal energy  $u$  (J/kg), pressure of system  $P$  (Pa), density  $\rho$  (kg/m<sup>3</sup>), acceleration from gravity  $g$  (m/s<sup>2</sup>), height from reference level  $z$  (m), fluid velocity  $V$  (m/s), mass flowrate of fluid  $\dot{m}$  (kg/s), heat input rate to system  $\dot{Q}$  (J/s), work rate done by system  $\dot{W}$  (J/s), and state of flow element  $i$ ,  $o$ , or  $\text{sys}$  as “in”, “out”, or “system”, respectively. In Eq. (5) the first term on left-hand side is the sum of entering energy flowrates ( $i$ ) from pressure  $P$ , gravitational potential energy ( $U_g = mgz$ ), and kinetic energy ( $KE = \frac{1}{2}mV^2$ ). The energy outflows ( $o$ ) are deducted, the rate of heat energy input in the system is added, and the rate of work done by the system is subtracted. This equals the total power conversion rate of the system. In this study, the glass bottle of curry paste as the system had zero velocity, was placed on ground level, and did no work. Therefore, the conservation of energy was reduced to the rate of heat input to the system.

While our system was affected only by the heat, heat transfer by conduction is the internal energy transfer caused by the collisions of particles and the movements of electrons in the material. The thermal conductivity is nonzero in any state: solid, liquid, or gas. From the second law of thermodynamics, the spontaneous heat transfer in an object is always from the higher temperature to the lower temperature. The rate of heat transfer through an object is described by Fourier's law of heat conduction: the rate of heat transfer is proportional to the temperature gradient and the cross-sectional area. If thermal conductivity is constant, the heat diffusion equation is a second-order partial differential equation known as Laplace's equation:

$$\frac{\partial T}{\partial t} = \frac{1}{\rho C_p} \nabla \cdot (k \nabla T) + \frac{q}{\rho C_p} \quad (6)$$

Here the symbols mean absolute temperature  $T$  (K), rate of heat generation per unit volume  $q$  (W/m<sup>3</sup>), thermal conductivity  $k$  (W/m K), and specific heat  $C_p$  (J/kg K).

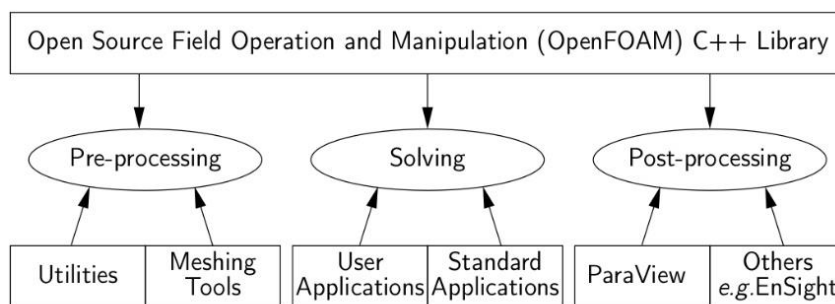
$$\frac{\partial T}{\partial t} = \nabla \cdot (\alpha \nabla T) + \frac{q}{\rho C_p} \quad (7)$$

The thermal diffusivity is  $\alpha = k/\rho C_p$  (m<sup>2</sup>/s), and the system does not generate heat by itself. Therefore, the heat conduction equation reduces to

$$\frac{\partial T}{\partial t} = \nabla \cdot (\alpha \nabla T) \quad (8)$$

Eq. (8) was used to describe the distribution of heat, or variations in temperature.

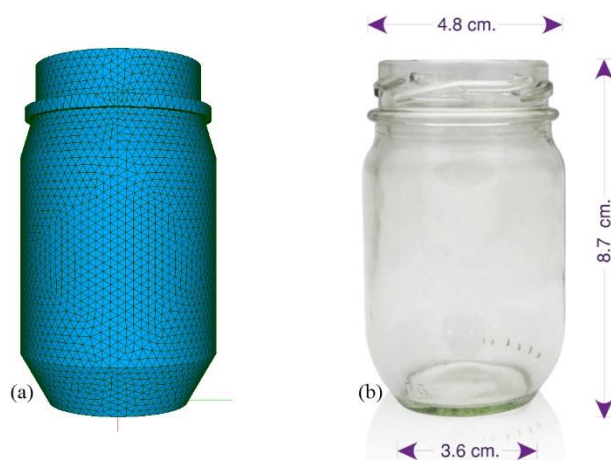
**2.2.2 Computer and software:** The personal computer used had as CPU an AMD FX-6300 processor with clock speed 3.5 GHz, and 16 GB RAM. Ubuntu 18.04.5 LTS (Bionic Beaver) Linux Operating system was installed, and the CFD software was OpenFOAM version 7. The use of OpenFOAM has three stages, namely pre-processing, solving, and post-processing, as shown in Fig 2 The other software packages used were as follows.



**Figure 2** The OpenFOAM workflow schema (The OpenFOAM Foundation, 2017)

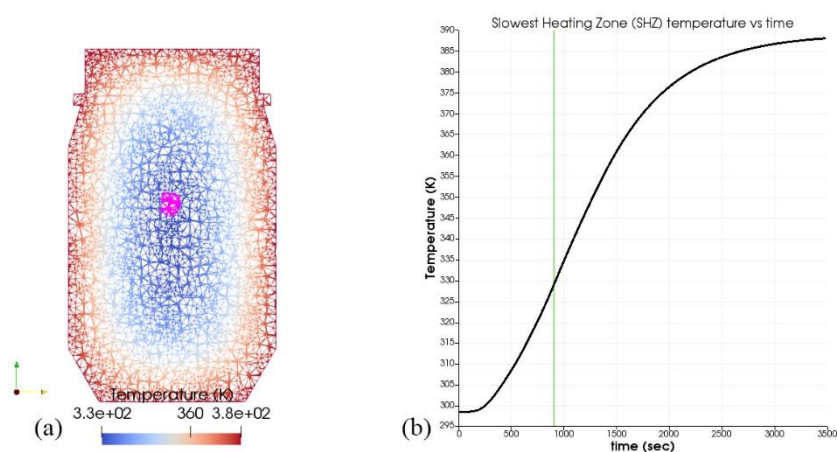
For the pre-processing step, SALOME version 9.3.0 software was used to create the 3D-geometry description of the physical problem. The 3D object was converted to a finite element mesh. The mesh was assessed for its quality. Next, in the solving step, the OpenFOAM C++ language command “LaplacianFoam” was used to numerically solve the heat transfer in a solid object. Finally, in post-processing the Paraview version 5.6.0 software was used to convert the numerical results into visualizations showing quality and quantity in colorful images, a table, and further plots of the data. (National Technology & Engineering Solution of Sandia, 2022)

**2.2.3 CFD simulation method:** The assumptions used in this study included the following. The solid food had homogeneous and isotropic (same in all directions) properties, the thermal properties were constant, the initial temperature was the same throughout the sample, the heat transfer from the heating medium was constant, the solid food did not have any phase changes, the thermal properties of glass bottle could be ignored and replaced by the thermal properties of the curry, and the effects of vapor pressure generated inside the bottles and compressed air pressure in the retort were ignorable. First, the actual size of the glass bottle was measured and its 3D mesh representation of geometry was generated, as shown in Fig 3. The high-density mesh should be of good quality. The external surface of the mesh was set to the boundary that was heated following the thermal schedule-set for the retort, from initial temperature to 116°C.

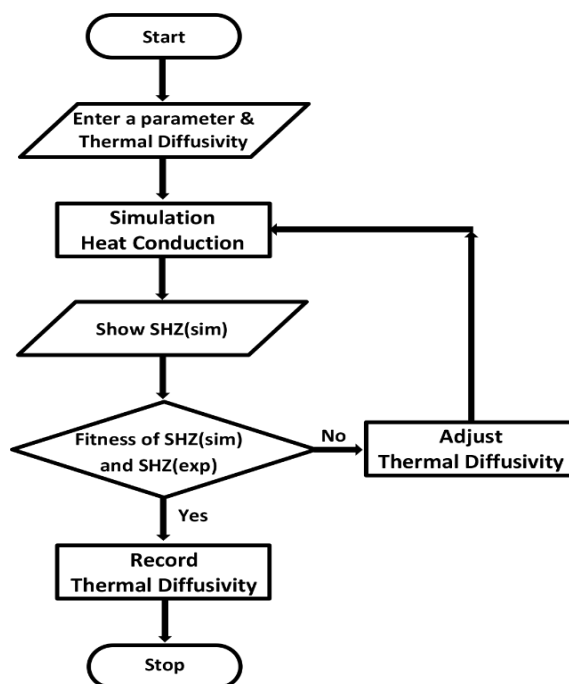


**Figure 3** The 3D mesh geometry of curry bottle for simulation (a), and specification geometry of the curry bottle according to the supplier (b)

Second, the various parameters were configured, including the thermal diffusivity as an adjustable parameter, the initial temperature at the mesh nodes, the external surface temperature following the processing schedule, the time step of simulation, and the time interval for recording results. Then the “laplacianFOAM” function in OpenFOAM solved numerically a simple Laplace equation for thermal diffusion in the solid along the mesh discretization of this study. Generally, appropriate parameters give convergence of the solution. In contrast, poor selection of the parameters can make the numerical solution diverge. Third, the simulated temperatures for SHZ (sim) were extracted. The mesh geometry was sliced into halves, and a cell representative of SHZ was selected, to plot the time profile of its temperature over the thermal processing time, as shown in Fig. 4. Trial and error was used in estimating the adjustable thermal diffusivity, by fitting the simulated SHZ (sim) to the experimental SHZ (exp). The trial and error approach is explained in Fig 5. The coefficient of determination  $R^2$  was used to decide the goodness of fit that was maximized. This approach to evaluate the unknown parameters solves an inverse problem (Betta *et al.*, 2009), (Reddy *et al.*, 2020a, 2020b) The  $R^2$  calculation is shown in Eq. (9).



**Figure 4** Cell representer of the SHZ (sim) in mesh geometry of curry bottle shown in red (a), and plot of the time profile of temperature SHZ (sim) (b)



**Figure 5** Trial and error approach to estimate the thermal diffusivity of curry paste by matching simulation results with experiments

$$R^2 = 1 - \frac{SS_{\text{res}}}{SS_{\text{tot}}} \quad (9)$$

Here the residual sum of squares is  $SS_{\text{res}} = \sum_i^n (y_i - f_i)^2$ , the total sum of squares is  $SS_{\text{tot}} = \sum_i^n (y_i - \bar{y})^2$ , the predicted value of  $y_i$  is  $f_i$ , the value of the variable to be predicted is  $y_i$ , and the mean of the observed data is  $\bar{y}$ .

### 2.3 Calculation the sterilize value (F0)

The general method with SHZ temperature data was used to calculate the sterilize value (F0). SHZ temperature data begun from an initial temperature at 0 min, then the temperature rose for thermal sterilization to 116°C, held until the processing was finished. The lethality rate calculation in Eq. (10) was used to compare numerically the relative lethality of processing temperature different from 121.1°C.

$$L = \frac{F_{121.1}^Z}{F_T^Z} = 10^{\frac{(T-121.1)}{z}} \quad (10)$$

Here z-value for spores of *Clostridium botulinum* was  $z = 10^\circ\text{C}$ , the reference temperature of 121.1°C, and SHZ temperature  $T$  (°C).

F0(exp) from the experiment was calculated from data logged by the Ellab E-Val Pro data logger using Eq. (11), and F0 (sim) from the simulation was calculated with Eq. (11) as well.

$$F_0 = \sum_{t_1}^{t_2} 10^{\frac{(T-121.1)}{z}} \Delta t \quad (11)$$

Here the overall of sterilization value is F0 (min), the process time range is from start at  $t_1$  to finish at  $t_2$  (min), SHZ temperature of product  $T$  (°C) at each time, z-value for spores of *Clostridium botulinum* was  $z = 10^\circ\text{C}$ , and the time interval used was  $\Delta t = 1$  (min).

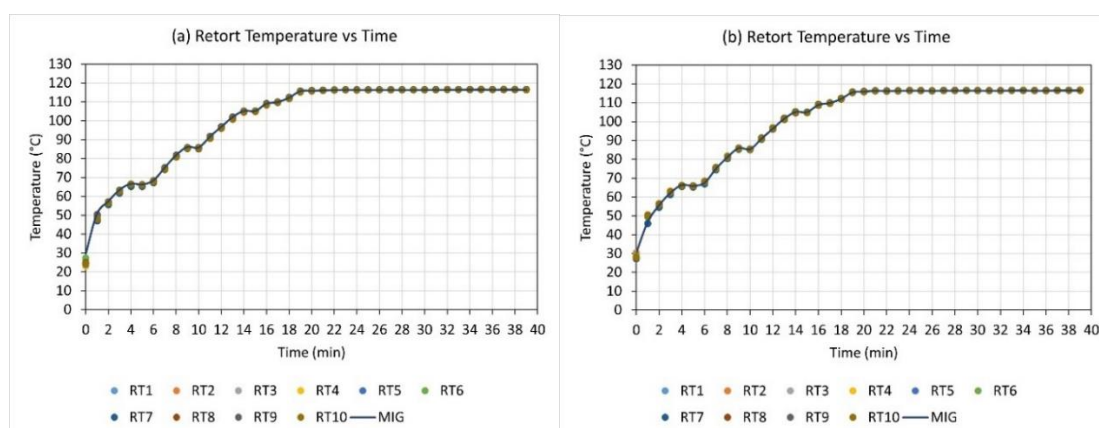
### 3. Results and Discussion

#### 3.1 Thermal sterilization of curry paste

3.1.1 Temperature distribution (TD): The data of retort temperature were recorded from 10 channels for temperature sensors (Retort temperature, RT1-10). The retort had initial temperature of 23.0-30.32°C before a run following the process schedule shown in Table 2. The temperature increase rate for suitable for glass bottles. The duration was 21 min for the retort to heat up to 116°C. The temperature in retort was well equilibrated, not cold-spots were found. The retort was capable of maintaining constant temperature throughout for 39 min. The RT completely matched a temperature reference device (Mercury in glass, MIG) in the two replicate tests shown in Fig 6.

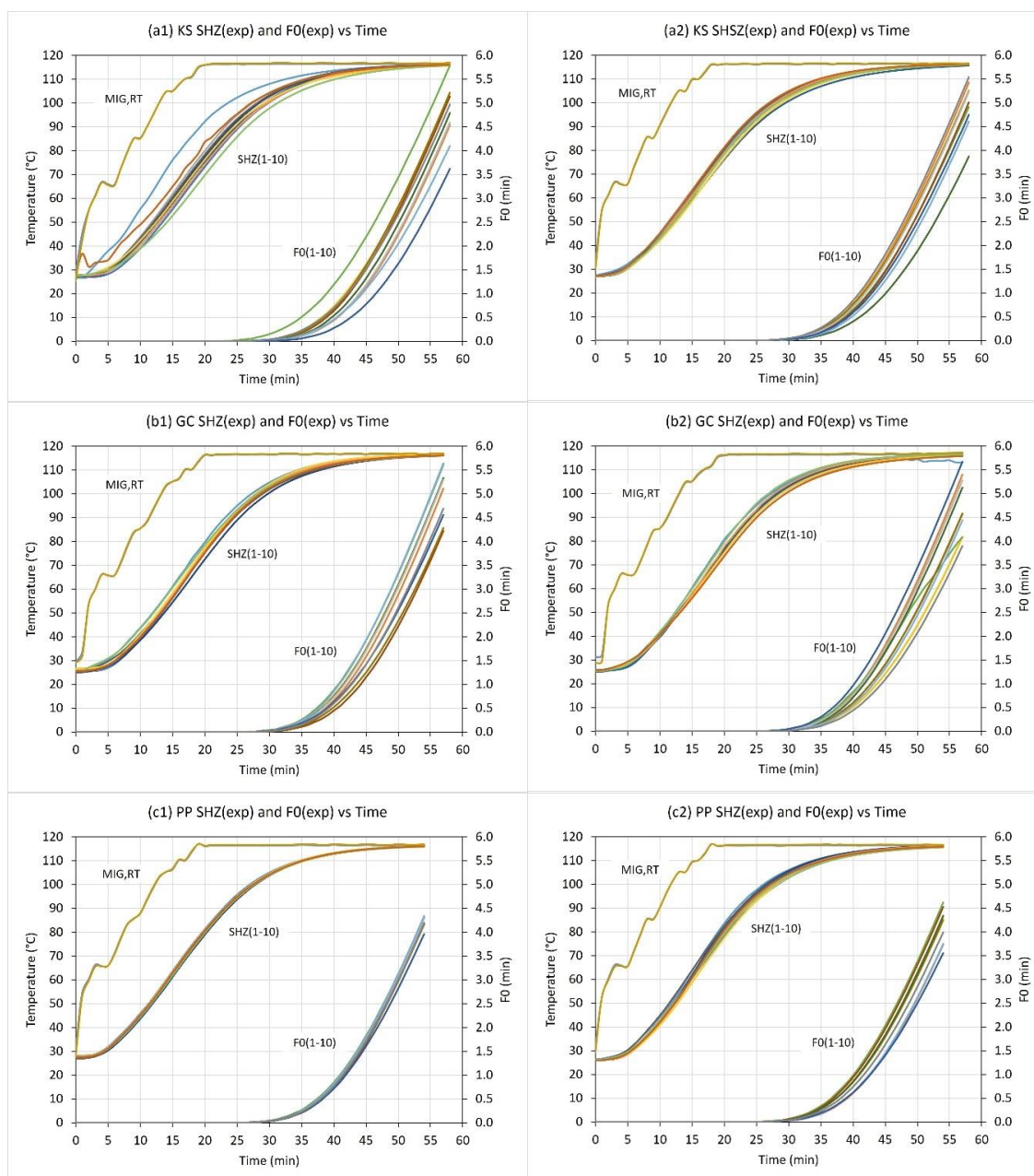
**Table 2** The appropriate temperature schedule for the water-spray and pressure-balance retort, when treating curry paste in glass bottles.

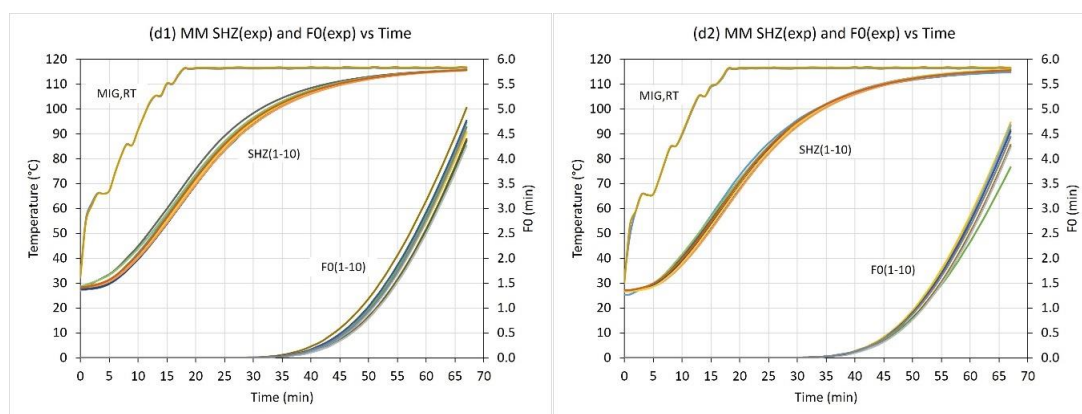
| Step | Process     | Cumulative time (min) | Set-point temp (°C) | Set pressure (mbar) | MIG_RT (°C) at time (min) |
|------|-------------|-----------------------|---------------------|---------------------|---------------------------|
| 1    | Start       | 0                     | 65                  | 350                 | 30.00°C at 0 min          |
| 2    | Heating up1 | 6                     | 85                  | 700                 | 68.03°C at 6 min          |
| 3    | Heating up2 | 10                    | 105                 | 1200                | 85.65°C at 10 min         |
| 4    | Heating up3 | 15                    | 110                 | 1500                | 105.13°C at 15 min        |
| 5    | Heating up4 | 20                    | 116                 | 1900                | 115.93°C at 20 min        |
| 6    | Sterilizing | 39                    | 116                 | 1900                | 116.24°C at 21 min        |



**Figure 6** TD results for retort temperature (RT) and temperature reference device was a mercury in glass (MIG) thermometer, with time profiles for two replicate runs in (a) and (b)

1.2 Heat penetration (HP): With reference to the TD results, the schedule in Table 2 was used for the study of HP. The SHZ (exp) and F0 (exp) data were recorded by 10 temperature sensors to assess HP. The process time for achieving a requirement of  $F_0 = 3$  min was estimated, as the result of HP testing. The plots of SHZ (exp) and  $F_0$  (exp) with time are shown in Fig 7. The initial temperature of product, the processing time, and the  $F_0$  (exp) for each curry paste are shown in Table 3. The MM had the longest processing time because of the oil in its composition: oil has a comparatively low thermal diffusivity, consistent with the study of Huang and Liu (2009).





**Figure 7** HP testing results. Product temperature SHZ (exp), mercury in glass (MIG), retort temperature (RT), and sterilize value F0 (exp) vs. time (min), from two replicate runs for each curry type

**Table 3** HP testing results. The initial temperature of curry, processing time at 116°C, and F0 (exp) from 20 time profiles of temperature for each curry

| Curry          | Initial temperature (°C) |       |       |      | Processing time (minute) | F0 (minute) |      |      |      |
|----------------|--------------------------|-------|-------|------|--------------------------|-------------|------|------|------|
|                | min                      | max   | avg   | sd   |                          | min         | max  | avg  | sd   |
| KangSom(KS)    | 26.71                    | 27.87 | 27.17 | 0.37 | 37                       | 3.62        | 5.79 | 4.89 | 0.55 |
| GreenCurry(GC) | 24.98                    | 26.76 | 25.51 | 0.47 | 37                       | 3.90        | 5.67 | 4.86 | 0.58 |
| PadPed(PP)     | 25.84                    | 28.24 | 26.82 | 0.81 | 35                       | 3.55        | 4.62 | 4.18 | 0.27 |
| MasMan(MM)     | 25.32                    | 28.63 | 27.32 | 0.76 | 49                       | 3.83        | 5.03 | 4.50 | 0.26 |

The sterilized product samples, 24 bottles of each curry, were used for microorganism analyses. The analysis results are summarized in Table 4, and they met the commercial sterilization standards. Thus, the heating schedule was suitable for the thermal processing of each curry paste.

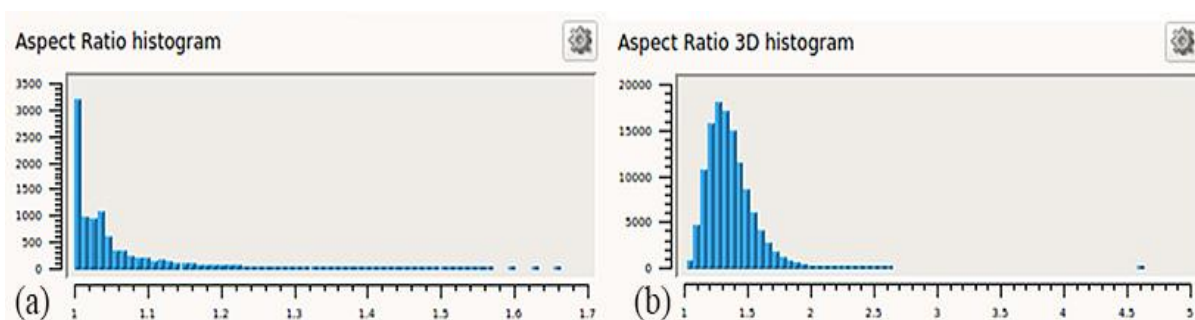
**Table 4** The results from microorganism analyses of sterilized curry samples

| List                                 | Results |      |      |      | Method                            |
|--------------------------------------|---------|------|------|------|-----------------------------------|
|                                      | KS      | GC   | PP   | MM   |                                   |
| Mold CFU/g                           | <10     | <10  | <10  | <10  | FDA BAM Online. 2001 (Chapter 18) |
| <i>Escherichia coli</i> MPN/g        | <3      | <3   | <3   | <3   | FDA BAM Online. 2017 (Chapter 4)  |
| <i>Staphylococcus aureus</i> CFU/g   | <10     | <10  | <10  | <10  | FDA BAM Online. 2016 (Chapter 12) |
| <i>Clostridium perfringens</i> CFU/g | <10     | <10  | <10  | <10  | FDA BAM Online. 2001 (Chapter 16) |
| <i>Salmonella</i> spp. / 25 g        | Na      | Na   | Na   | Na   | ISO 6579-1:2017                   |
| <i>Bacillus cereus</i> CFU/g         | <100    | <100 | <100 | <100 | FDA BAM Online. 2019 (Chapter 14) |

KangSom (KS), GreenCurry (GC), PadPed (PP) and MasMan (MM)

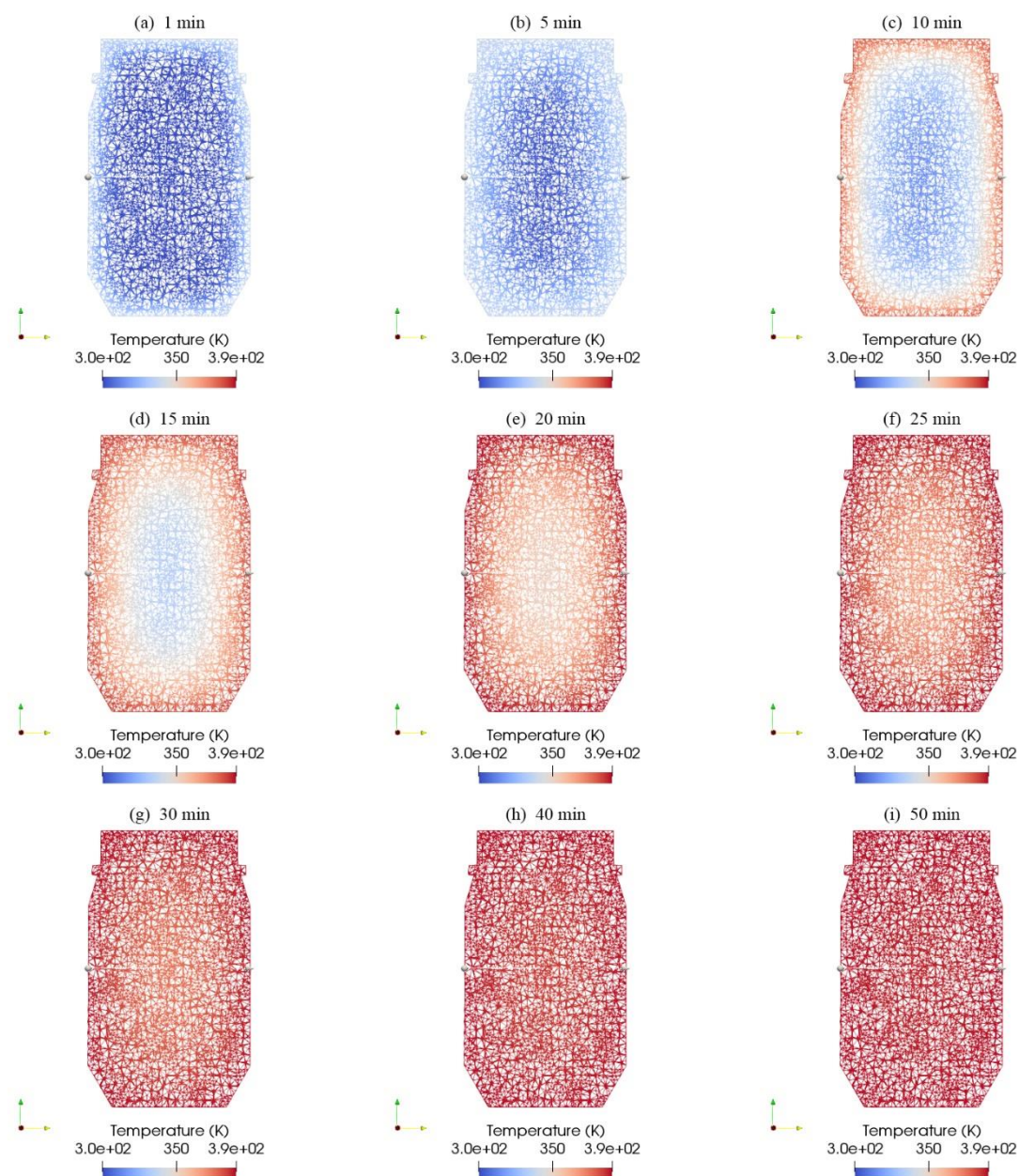
### 3.2 CFD model for simulation

The results of heat transfer simulations and thermal diffusivity: The mesh geometry consisted of elements in size range 0.05-0.5 cm, 22478 connection nodes, 128285 elements, 638 edges, 9430 triangle faces, 118217 tetrahedron volumes, and the mesh was classified as structured-meshing with uniformity. The aspect ratio and aspect ratio in 3D were defined as the ratio of longest edge to shortest edge for each element. An aspect ratio close to 1 is desired for well-conditioned computational solution. A high-density mesh enables accurate numerical solution. The mesh quality was evaluated by using the functions in SALOME, as shown in Fig 8. The curry bottle mesh has nearly 1 as aspect ratio, and the aspect ratio in 3D is also shown in a histogram. The generated mesh was of good quality. Generally, a finer mesh takes longer to calculate, but will give a higher accuracy.



**Figure 8** The quality of curry bottle mesh is indicated by an aspect ratio histogram (a), and the aspect ratio of 3D elements inside the bottle also as a histogram (b). Horizontal axis shows the aspect ratio, vertical axis is the number of elements in at this aspect ratio.

The simulation temperature was increased to 116°C following the schedule, with TD results shown in Table 2. The simulation of process time was used to infer HP as shown in Table 3. Some simulation results are shown along a cross-section plane of the PP curry bottle mesh in Fig 9. The mesh temperature is indicated on a color scale. The same color- tone on mesh area indicates the same temperature. The temperature gradient in the mesh is shown by different color shades at 10 to 25 min of the run. The slowest heating zone in the mesh was clear at 15 min. The simulation result showing the SHZ (sim) was nearly identical to the SHZ (exp) from thermal processing experiments.

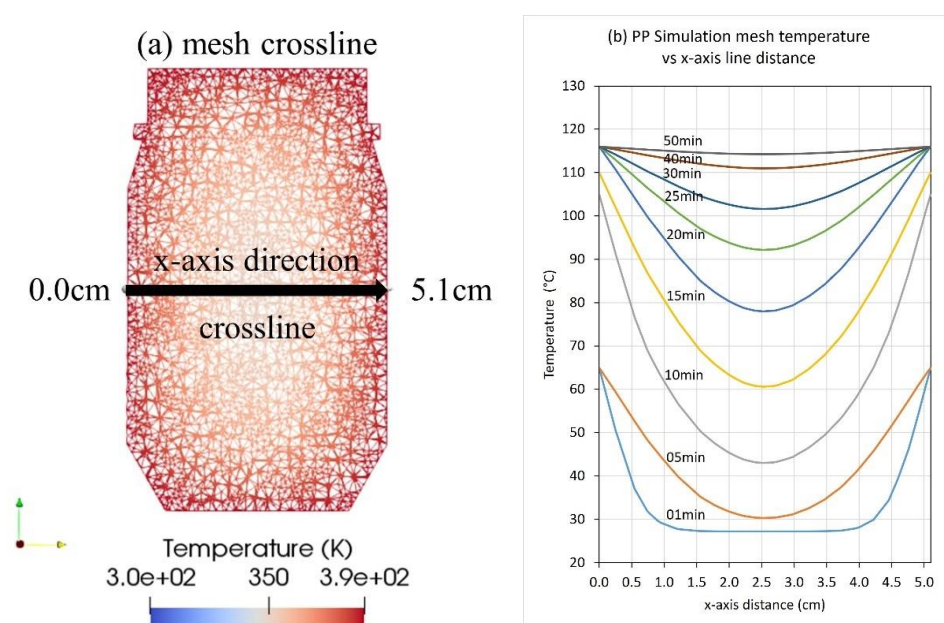


**Figure 9** A cross section of PP curry simulation mesh shows temperature changes from 1 to 50 min in a color scale

**Table 5** The thermal diffusivity was matched for simulations and experiments by trial-and-error method, maximizing  $R^2$  and the simulation sterilize value  $F_0$  (sim) and processing time at  $116^\circ\text{C}$  refer to the HP results

| Curry          | Process time<br>(minute) | Thermal Diffusivity<br>( $\alpha$ ) ( $\text{m}^2/\text{s}$ ) | R-square | $F_0$ (sim)<br>(minute) |
|----------------|--------------------------|---------------------------------------------------------------|----------|-------------------------|
| KangSom(KS)    | 37                       | $1.55 \times 10^{-7}$                                         | 0.9990   | 3.34                    |
| GreenCurry(GC) | 37                       | $1.55 \times 10^{-7}$                                         | 0.9989   | 3.31                    |
| PadPed(PP)     | 35                       | $1.65 \times 10^{-7}$                                         | 0.9996   | 3.09                    |
| MasMan(MM)     | 49                       | $1.45 \times 10^{-7}$                                         | 0.9993   | 5.19                    |

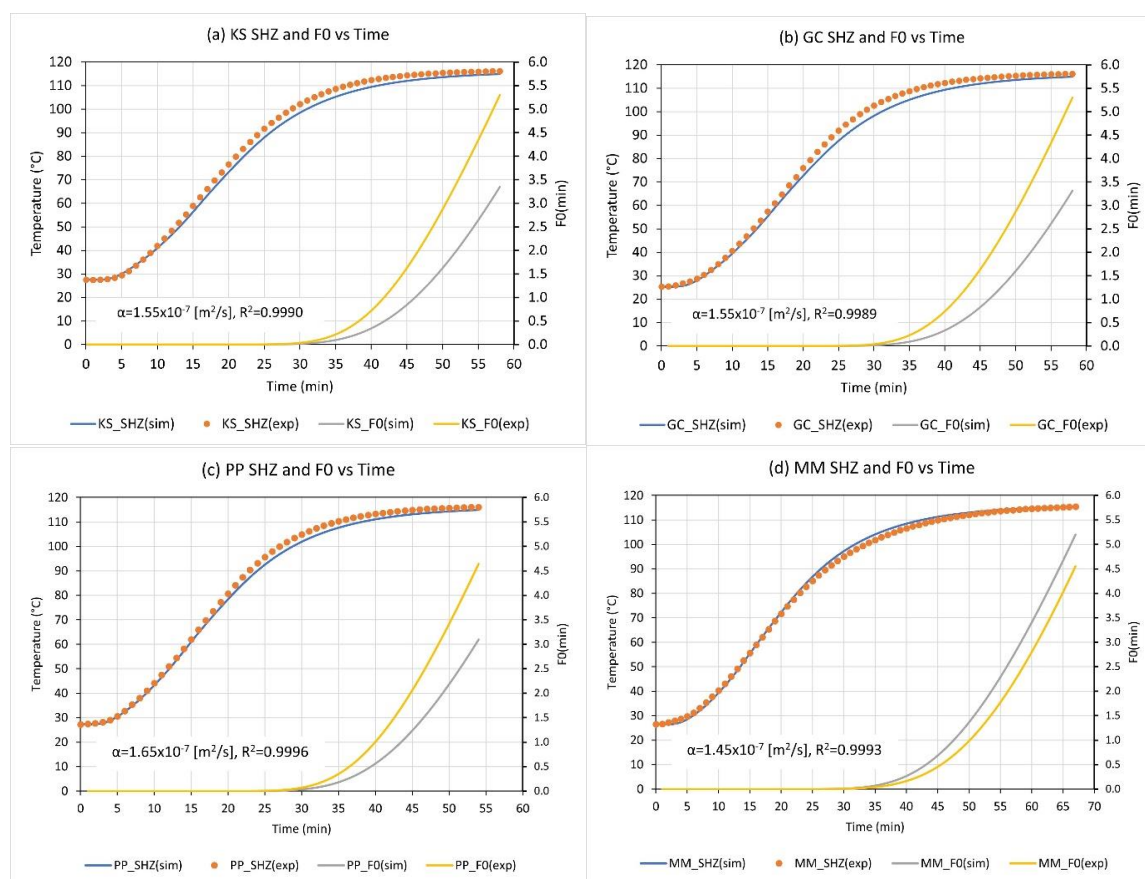
The line parallel to x-axis crosses the mesh from the left edge (0.0 cm) to the right edge (5.10 cm). This line segment was used for a temperature data reader (Fig 10a). The collected simulation temperature data along the line were plotted against the distance in the mesh, as shown in Fig 10b. The temperature profile had a V-shape, indicating the higher temperatures at outer edges and the lowest temperature in the middle, as heating was done through the outer surfaces. Over time, the temperature differences decreased, the temperature profile became shallower, and at the end of processing was uniform, at equilibrium with in the simulation mesh. The thermal conduction behavior was affected by thermal diffusivity of each material, and a higher of thermal diffusivity would give faster thermal conduction. The thermal diffusivity of each curry paste was estimated by the trial-and-error method maximizing  $R^2$  of SHZ (exp) vs. SHZ (sim). The simulation based sterilize value  $F_0$  (sim) is reported in Table 5. The simulation provides information of the most lagging temperature SHZ (sim), which was fitted to the experimental SHZ (exp) as shown in Fig. 11.



**Figure 10** The temperature profile by x-location, along a central line segment, for PP curry case

### 3.3 Calculation of the sterilize value ( $F_0$ )

The sterilize value from simulation  $F_0$  (sim) was calculated by Eq. (11) and compared with the experimental sterilize value  $F_0$  (exp), as shown in Fig. 11. Both of these increased rapidly after 30 min. The increases in  $F_0$  (sim) and  $F_0$  (exp) were slightly differed according to differences in SHZ (sim) and SHZ (exp). However, on using the same processing time, the final  $F_0$  (sim) was closely similar to  $F_0$  (exp), meeting the legal requirements of  $F_0$  not less than 3 min, as shown in Table 5. Thus, the simulation model of heat conduction reported  $F_0$  (sim) not different from  $F_0$  (exp), and would be safe for use as a guideline in thermal processing design.



**Figure 11** The SHZ temperature profiles and sterilize values experimentally F0 (exp) and from simulation F0 (sim), plotted against processing time. Thermal diffusivity and  $R^2$  are listed in each plot, for respective curry paste.

## 4. Conclusion

Thermal sterilization of curry paste in glass bottles was demonstrated with an appropriate heating schedule. The sterilize value (F0) indicated safe food products. CFD simulations of heat conduction were used to visualize temperature profiles and heat flow. The processing times and F0 values were assessed experimentally and from numerical simulations. The good agreement indicates that it is possible to use CFD heat conduction modeling to guide development of thermal sterilization processing, such as determination of processing time and F0 value. However, for safety reasons and for following the legal requirements, experimental assessments of TD and HP for the determination of processing time and F0 remain necessary.

## Acknowledgements

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## References

- TCPS 129-2556. 2013. Thai Community Product Standard. Namphrik Kaeng. Bangkok.
- TIS 429-2548. 2005. Thai Industrial Standard. Curry Paste and Seasoning Paste. Bangkok.
- Lewis, M. J. 2006. Thermal Processing. In Brennan, J. G. (Eds). Food Processing Handbook (pp. 53). Wiley-Vch, Weinheim, Germany.
- MOPH 420-2563. 2020. Notification of the Ministry of Public Health. Food Production Processes, Processing Equipment/Utensils and Storage Practices. Bangkok.
- The OpenFOAM Foundation. 2017. OpenFOAM v7 User Guide. URL. (<https://cfd.direct/openfoam/user-guide-v7/>) (30 April 2022)
- Versteeg, H. K. and Malalasekera, W. 2007. An introduction to computational fluid dynamics: The finite volume method (pp. 9-39). Pearson Prentice Hall, England.
- Berk, Z. 2009. Food Process Engineering and Technology (pp. 69-81). Academic Press, New York.
- National Technology & Engineering Solution of Sandia. (2022) Introduction to ParaView. URL (<https://docs.paraview.org/en/latest/UsersGuide/introduction.html>) (30 April 2022)
- Betta, G., Rinaldi, M., Barbanti, D. and Massini, R. 2009. A quick method for thermal diffusivity estimation: Application to several foods. Journal of Food Engineering. (91): 34-41.
- Reddy, R. S., Arepally, D. and Datta, A. K. 2020a. Estimation of heat flux in bread baking by inverse problem. Journal of Food Engineering. 109774(271): 1-10.
- Reddy, R. S., Arepally, D. and Datta, A. K. 2020b. Inverse problems in food engineering: A review. Journal of Food Engineering. 110909(319): 1-27.
- Huang, L. and Liu, L.S. 2009. Simultaneous determination of thermal conductivity and thermal diffusivity of food and agricultural materials using a transient plane-source method. Journal of Food Engineering. (95): 179-185.