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ENGLISH REPORT ON SIMULATION OF CANNED LIQUID FOOD STERILIZATION PROCESS

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ABSTRACT

Canned industry is a traditional export industry of China, and canned food is also an important export product of food industry at present. To acquire the best technological parameters of hot working, method of doing a large amount of experimental verification not only consumes much time and effort, but also requires enormous investment. Based on COMSOL Multi-physics field software and other novel research methods, this study simulated the sterilization process of canned liquid food and explored the influence of different viscosities on canned liquid food sterilization process. Results revealed that viscosity had great effects on temperature and speed during canned liquid food sterilization process, and greater viscosity tended to show a slower overall heating and smaller natural convective effect. Slowing heating zone (SHZ) caused by natural convection kept moving in the can, basically at 10~30% height. Besides, fatality rate in different positions rose as viscosity increased in the process of sterilization.

1.Introduction

Heat sterilization of canned food as a traditional processing technique is widely used due to its effectiveness and convenience (Farid and Abdul Ghani, 2004). Heated margin of canned liquid food near the wall of can makes the buoyancy decrease and move upward to produce natural convection during the heating process (Mermelstein, 1997), which makes temperature and flow speed of liquid inside can become quite complicated in the process of sterilization. Hence, it is extremely essential to simulate heat sterilization process numerically with the help of computer, thereby acquiring distribution rules of speed and temperature of liquid inside can.

Computer simulation refers to establish a mathematical model according to characteristics and requirements of system and solve the mathematical model on the computer to obtain information close to actual system. Its superiorities lie in improving economy efficiency, speedability and exhaustivity of test, shortening the progress of amplifying achievements of small test as large-scale industrial production and overcoming weaknesses during physical simulation, such as unchangeable input variables, difficulties in calculation and big error, which are convenient for studying stability and sensitivity of system as well as dynamic performance and control scheme, and meanwhile, looking for optimal plan (Anand Paul et al., 2011).

In recent years, computer simulation has been widely applied in canned food sterilization process. Simulating canned food sterilization process is able to predict changes of temperature distribution, flow speed, slowing heating zone (SHZ) and microorganism (Pedro et al., 2010; Pedro et al., 2010; Pedro and Marcelo, 2010; Feiruh et al., 2010; Selin et al., 2010; Hu, 2009). Taking water and carboxyl methyl cellulose (CMC) solution with different concentrations as experimental materials, this study drawing support from COMSOL Multi-physics software simulates distributions of temperature and speed as well as microbial fatality rate with various viscosities and verifies simulation results through temperature experiment.

2. Materials and methods

2.1. Materials and instruments

Materials included purified water (Wahaha Company, China); carboxyl methyl cellulose (CMC); chemically pure (Sinopharm Chemical Reagent Co., Ltd, China); metal can (model: 307×113, Jinri Food Co., Ltd, Ningbo, China). Instruments were automatic autoclaves sterilizer (model: G154DWS, Zealway Instrument Inc., Xiamen, China); thermal characteristics analyzer (model: KD2 Pro, High Technology Co., Ltd, Beijing, China); Data Trace RF wireless real-time temperature sensor (Mesa Laboratories Inc., USA); manual can seamer (model: YJ-C200, Easy Jet Automation Equipment, Zhangjiagang, China); rotational viscometer (model: BROOKFIELD DV-+pro, Labthink Technology Instrument Co., Ltd, Shanghai, China); densimeter (model: YL, Yilian Control Temperature Apparatus Factory, Shanghai, China); electric drill (model: J1Z-BLT-65, Bailite Electric Appliance Co., Ltd, Shanghai, China).

2.2. Experimental methods

(1)Measurement of basic heat transfer coefficients

Density and viscosity of CMC solution (1% and 2.5%) under different temperatures were measured with densimeter and rotational viscometer respectively, and then KD2 Pro thermal characteristics analyzer was used in detecting thermal conductivity and atmospheric heat capacity value at room temperature. Basic heat transfer coefficients of water were provided by COMSOL Multi-physics software.

(2)Thermal penetration test

Purified water plus CMC solution (1% and 2.5%) at room temperature were poured into metal can that was punched in advance, Data Trace temperature probe was stretched to the geometric center of can and the probe was marked and taken down, then put back after can was sealed (Figure 1). Both of metal can and one temperature sensor were put into automatic autoclaves sterilizer and sterilized for 30 min at 121 °C, and then the probe was removed to read temperatures of sterilizer as well as central point inside can.

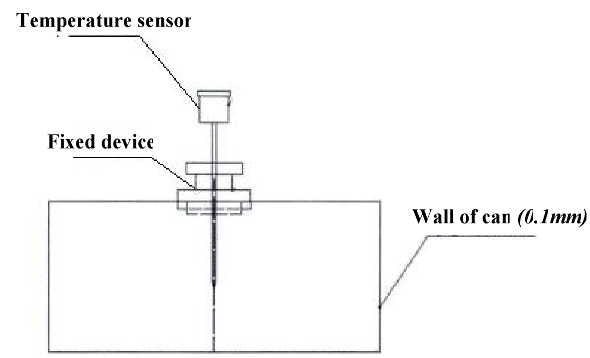


Figure 1. Temperature measuring device

(3)Numerical simulation

Temperature of sterilizer measured by wireless temperature sensor was led into COMSOL Multi-physics software by interpolation function for simulating heat transfer process using non-isothermal flow module (Adrian, 1993).

2.2.1. Model assumption

To simplify problems, the following hypotheses were made: liquid inside can was uniform and symmetrical; 3d cylindrical system was transferred into 2d axisymmetric processing; the influence of wall of can and probe on heat transfer was ignored; liquid had no slip on the inner wall of can; thermal conductivity and atmospheric heat capacity of CMC solution as constant values did not change with temperature; temperature on the outer wall of liquid was always equal to sterilizer's.

2.2.2. Control equation

Basic equation set of convective heat transfer was made up of heat exchange differential equation, every direction momentum equation, equation of continuity and energy equation. As to simplified 2d convective heat transfer, equations are as follows (Abdul et al., 1999):

Equation of continuity:

$$\frac{1}{r}\frac{\partial}{\partial r}(r\rho v)+\frac{\partial}{\partial r}(\rho u)=0 \quad (1)$$

Where r refers to radial direction; z is axial position; u expresses axial velocity of fluid; v refers to radial velocity of fluid; ρ expresses fluid density.

Energy conservation equation:

$$\frac{\partial T}{\partial t}+v\frac{\partial T}{\partial r}+\mu\frac{\partial T}{\partial z}=\frac{k}{\rho C_p}\left[\frac{1}{r}\frac{\partial}{\partial r}(r\frac{\partial T}{\partial r})+\frac{\partial^2 T}{\partial z^2}\right] \quad (2)$$

Herein, T expresses temperature; t refers to time; k stands for heat conductivity coefficient; Cp is heat capacity at constant pressure.

Momentum conservation equation:

Momentum conservation equation in the Z direction:

$$\rho(\frac{\partial u}{\partial t}+v\frac{\partial u}{\partial r}+u\frac{\partial u}{\partial z})=-\frac{\partial p}{\partial z}+\mu\left[\frac{1}{r}\frac{\partial}{\partial r}(r\frac{\partial u}{\partial r})+\frac{\partial^2 u}{\partial z^2}\right]+\rho g \quad (3)$$

Where p refers to static pressure; μ stands for viscosity; g is gravitational acceleration.

Momentum conservation equation in the r direction:

$$\rho(\frac{\partial v}{\partial t}+v\frac{\partial u}{\partial r}+u\frac{\partial v}{\partial z})=\frac{\partial p}{\partial r}+\mu\left[\frac{\partial}{\partial r}(\frac{1}{r}\frac{\partial}{\partial r}(rv))+\frac{\partial^2 v}{\partial z^2}\right] \quad (4)$$

2.2.3 Boundary conditions

Boundary conditions applied in model were shown below:

$T_w = T_{ret}$, u = 0 and v = 0 when r = R and 0 ≤ z ≤ H (5)

$T_w = T_{ret}$, u = 0 and v = 0 when z = 0 or z = H and 0 ≤ r ≤ R (6)

$\frac{\partial T}{\partial z}$ = 0 and v = 0 when r = 0 and 0 ≤ z ≤ H

(7)$T_{in} = T_i$, u = 0 and v = 0 when 0 ≤ r ≤ R and 0 ≤ z ≤ H (8)

Herein, T w refers to temperature of liquid external border; Tret expresses temperature of sterilizer; R is radius of metal can; H stands for height of metal can; T in is temperature of liquid inside can; T_i expresses initial temperature.

2.2.4. Grid division

COMSOL Multi-physics grid generator was used in dividing the whole area into standard triangular grid.

3. Results and discussions

3.1.Analysis of basic heat transfer parameters

Water and CMC solution (1% and 2.5%) were applied in modeling liquid food to explore canned food heat sterilization process under various viscosities as CMC widely used in canned food performs important functions in thickening, emulsifying, holding water and suspending.

Thermal conductivity values of CMC solution (1% and 2.5%) at room temperature were measured with KD2 Pro thermal characteristics analyzer for 5 times (Table 1), showing no obvious significance. Average value 0.576 W/ (m × K) was taken as simulation parameter, and atmospheric heat capacity under the same condition was measured to be 4100J/ (kg × K).

Table 1. Thermal conductivity values of CMC solution (1% and 2.5%)

CMC solubility	Thermal conductivity					Average value
1%	0.578	0.576	0.572	0.574	0.57	0.577
2.5%	0.572	0.583	0.534	0.575	0.607	0.575

Figures 2 and 3 display change trend of density and viscosity of CMC solution in different temperatures, and Table 2 shows it fitting parameter values. Density fluctuation well meeting the linear equation was found, which was in line with the relationship that density changed with temperature put forward by Adrian (Nelson et al., 2010). Besides, viscosity changing with temperature fitted quadratic function.

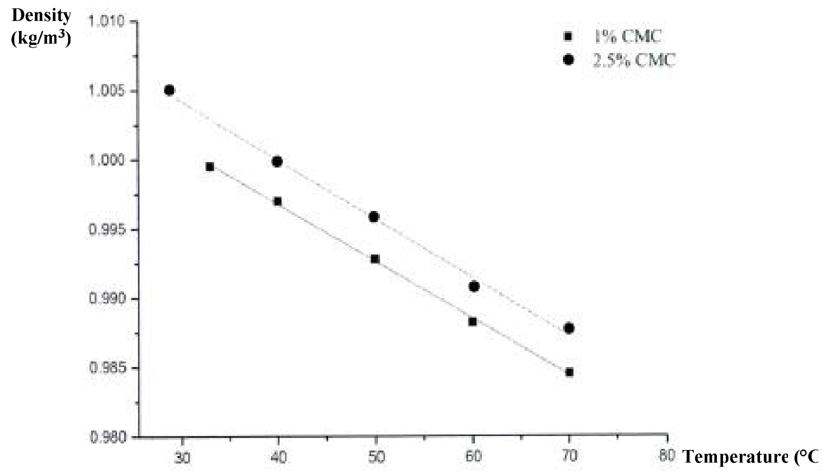


Figure 2. Changes of density of CMC solution (1% and 2.5%) with temperature

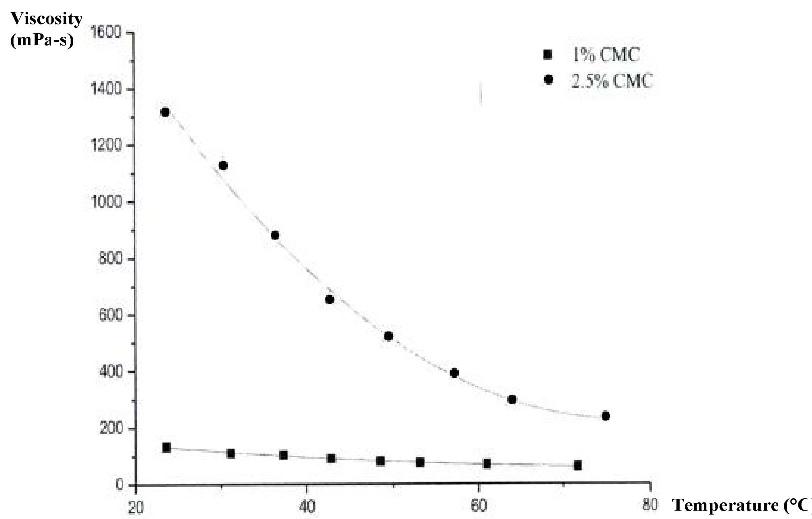


Figure 3. Changes of viscosity of CMC solution (1% and 2.5%) with temperature

Table 2. Fitting parameters of density, viscosity and temperature change

Material	Density	Viscosity
1%CMC	Y=-0.0004123x+1.012 R^2=0.997	Y=0.0235x2-3.7126x+205.76 R^2=0.993
2.5%CMC	Y=-0.0000425x+1.0126 R^2=0.994	Y=0.3963x2-60.792x+2561 R2=0.994

3.2. Comparison of model and experiment

It could be seen from Figure 4 that heating rate of water was higher than 1% CMC solution, and 1% CMC solution exceeded 2.5% CMC solution in heating rate, which might be caused by slow flow of liquid in the can with the increase of viscosity. However, in general, all the three heated up quickly and had significant convective heat transfer character.

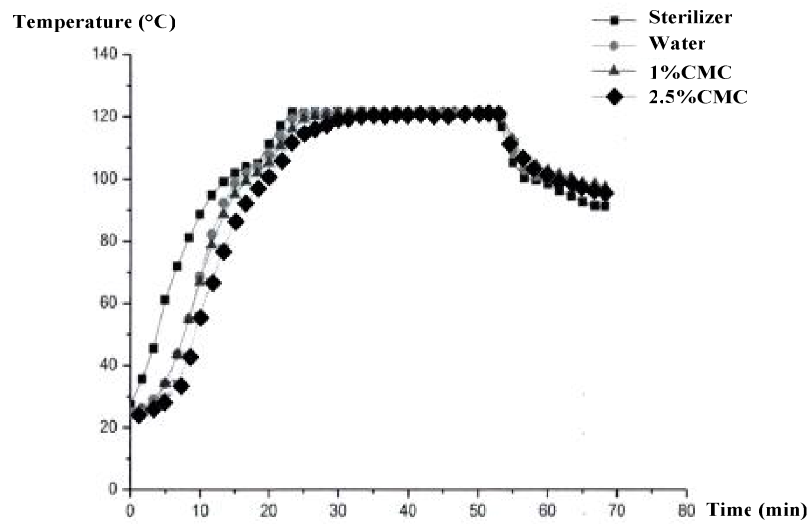


Figure 4. Temperature variation of water and CMC solution (1% and 2.5%) during sterilization

Figures 5, 6 and 7 display contrastive analysis of water and CMC solution (1% and 2.5%) in simulation and experiment respectively. For purified water, central point of model below 100 °C heated faster than experimental value, while both of them had a good fitting degree over 100 °C. It was possible that the probe interfered in the flow of liquid inside can below 100 °C, while liquid flowed intensively and the probe interfered slightly over 100 °C. As to CMC solution (1% and 2.5%), model heated up fast followed by slow comparing experimental value, which might be caused by inaccurate viscosity fitting formula, and a certain difference existed in temperature measurement range (20 °C ~ 80 °C and 121 °C) of viscosity used in this study. To improve the accuracy of model, measurement of physical parameters was required to increase to 80 °C, and even above 100 °C. In addition, heating curve of thermal convection model was not smooth enough, and jumpy, as neither grid of model nor time step were fine and dense enough. However, a finer grid and denser time step would increase calculation time and consume computing resources greatly, which is one of the shortcomings of finite element thermal convection model.

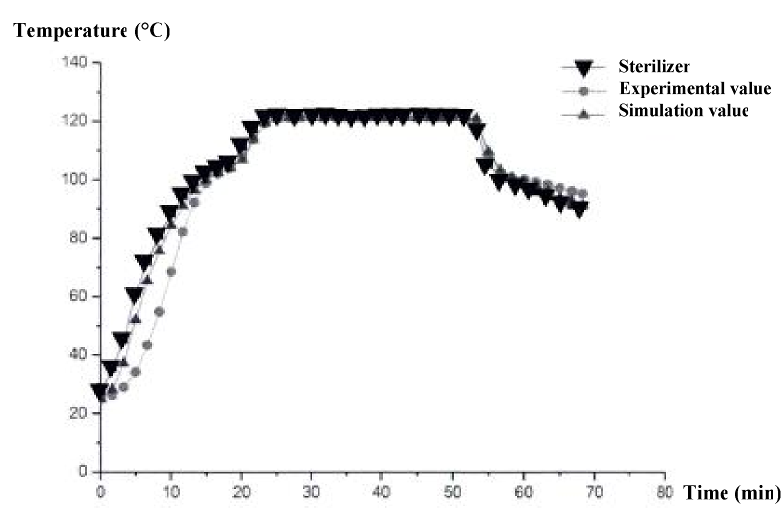


Figure 5. Temperature variations of purified water in simulation and experiment

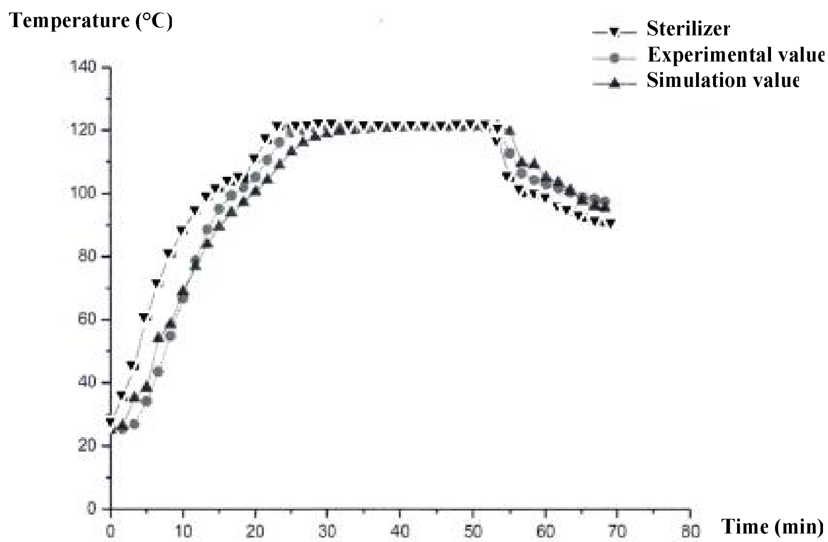


Figure 6. Temperature variations of 1% CMC solution in simulation and experiment

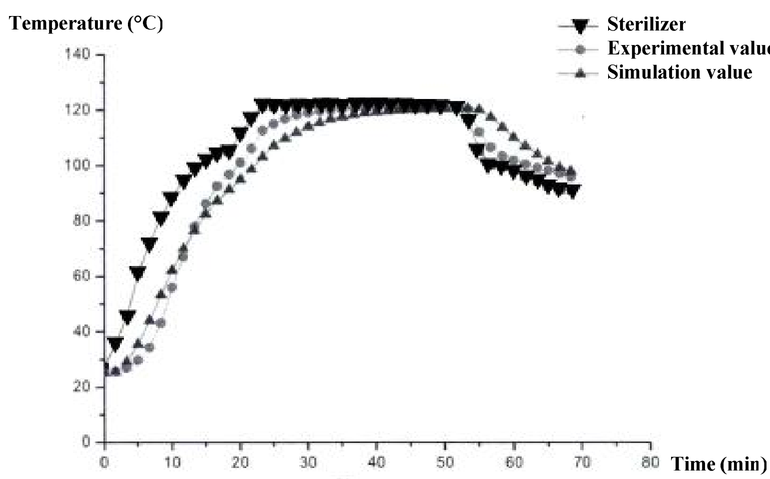
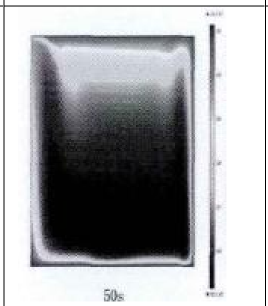
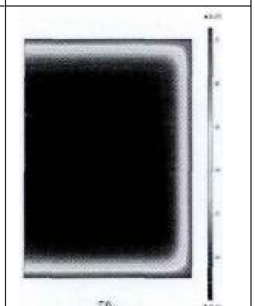
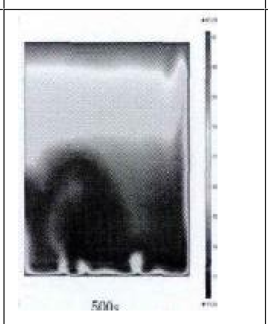
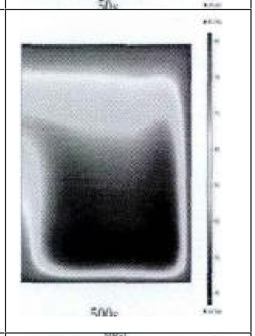
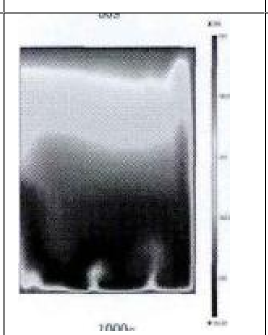
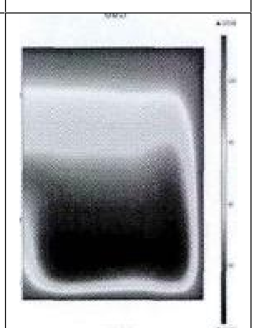
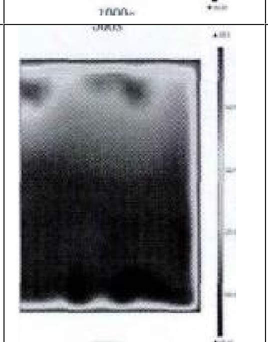
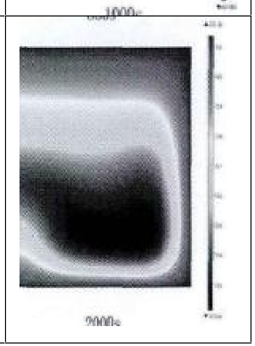


Figure 7. Temperature variations of 2.5% CMC solution in simulation and experiment

3.3. Temperature distribution

According to Figures 5, 6 and 7, model was basically identical with experimental value, so temperature distribution of each point inside the can in different times could be predicted with the help of the model. It could be seen from temperature distribution of water and 2.5% CMC solution inside can in 50 s, 500 s, 1000 s and 2000 s in Table 3 that natural convection inside pure water with relatively small viscosity had a strong influence on heat transfer when heating to 50 s, while its heat transfer of 2.5% CMC solution with large viscosity was closer to heat conduction. However, temperature went up constantly, viscosity was reduced and the influence of heat convection increased gradually as thermal sterilization proceeded. The position of SHZ inside can was found to be changeable, and was not in the geometric center of the can. It moved downward gradually. When heating to 2000 s, temperature difference of pure water inside the can was very small, while an obvious SHZ still existed in 2.5% CMC solution and was at 10% ~ 30% high, which was in line with research results proposed by Dimou (Datta and Arthur, 1988), Datta and Tekeira (Abdul Ghani and Farid, 2007), together with Ghani et al (Abdul et al., 1999). Nevertheless, Ghani and Farid (Abdul Ghani and Farid, 2006) discovered SHZ in 30% ~ 35% high through simulating thermal sterilization of canned pineapple. It was likely to be caused by pineapple slice inside can which interfered in the migration of SHZ.

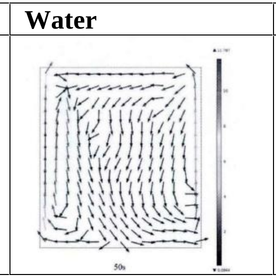
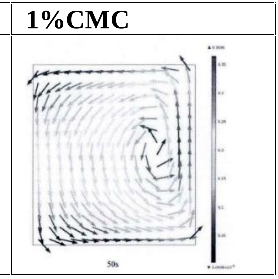
Table 3. Temperature distribution of water and 2.5% CMC solution inside can in 50 s, 500 s, 1000 s and 2000 s

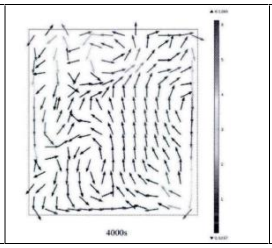
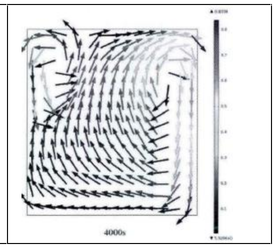
	Water	**2.5%CMC**
50s		
500s		
1000 s		
2000 s		

3.4. Velocity distribution

To better reflect liquid flow inside can in heating and cooling section during the sterilization, Table 4 displays velocity field distribution of water and 1% CMC solution in 50 s and 4000 s. It was observed that liquid near the wall of can flowed upward when heating to 50 s, and liquid near the can intermediate shaft flowed downward; when heating to 4000 s, liquid close to the can wall and can intermediate shaft flowed downward and upward respectively. During the sterilization process, water flowed strongly, while CMC solution was gentler, which was induced by increased temperature, expanded thermal volume and decreased density as liquid near wall edge was heated first. At this moment, the liquid away from wall edge had not been heated yet and was in a low temperature condition due to heat transfer time difference. Heated liquid near the wall edge was floated upward due to buoyancy which was brought by density changes, and moved to the axis direction as a result of rebound effect from the upper wall when getting to the top. However, the heavier liquid went down and touched the ground because of relatively low temperature inside can, thus generating thermal cycle (Nelson *et al.*, 2010). In the cooling stage, liquid close to can wall cooled first and density increased; and partial liquid started to flow upward once temperature went up. In 50 s and 4000 s, maximum flow speeds of water were 6.36 mm/s and 5.05mm/s respectively, and 0.394mm/s and 1.124mm/s for 1% CMC solution which were apparently smaller than water's.

Table 4. Velocity distribution of water and 1% CMC solution inside can in 50 s and 4000 s

	Water	**1%CMC**
50s		

4000 s		

3.5. Changes of fatality rate

Referring to clostridium botulinum killing, Table 4 shows maximum and minimum fatality rates inside can after water and CMC solution (1% and 2.5%) finished sterilization. A great difference was found in minimum fatality rates of three, which was possibly because water had small viscosity, but flowed fast and transferred heat evenly; while higher concentration of CMC solution tended to show a greater viscosity and slower flow, thus leading to lagging heat transfer.

Table 5. Fatality rates of water and CMC solution (1% and 2.5%)

Fatality rate (min) Tref = 121 °C, Z = 10 °C	Materials		
	Water	1%CMC	2.5%CMC
F_{max}	35.13	35.05	34.73
F_{min}	32.58	22.64	15.07

Note: Tref expresses reference temperature; Z is temperature that is required to be changed when sterilization time changes 10 times.

4. Conclusions

Based on COMSOL Multi-physics, this thesis sets up a simple 2d heat transfer model for simulating actual heat transfer process, and distributions of temperature, speed and microbial fatality rate in the whole heat transfer process are simulated using this model. Temperature and speed change sharply with the influence of viscosity during the sterilization process of canned liquid food, and greater viscosity tends to show a slower heating and smaller natural convection effect. During the sterilization process, fatality rate of canned liquid food in different positions rises as viscosity increases, which indicates that liquid food with higher viscosity is likely to induce insufficient sterilization in some positions in the static sterilization process. However, some excessively sterilized positions suggest that it is necessary to carry out rotational sterilization on food with high viscosity.

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