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Review

Computational Fluid Dynamics (CFD) Modelling and Application for Sterilization of Foods: A Review

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Abstract: Computational fluid dynamics (CFD) is a powerful tool to model fluid flow motions for momentum, mass and energy transfer. CFD has been widely used to simulate the flow pattern and temperature distribution during the thermal processing of foods. This paper discusses the background of the thermal processing of food, and the fundamentals in developing CFD models. The constitution of simulation models is provided to enable the design of effective and efficient CFD modeling. An overview of the current CFD modeling studies of thermal processing in solid, liquid, and liquid-solid mixtures is also provided. Some limitations and unrealistic assumptions faced by CFD modelers are also discussed.

Keywords: computational fluid dynamics; CFD; thermal processing; sterilization; computer simulation

1. Introduction

In the food industry, thermal processing, including sterilization and pasteurization, is defined as the process by which there is the application of heat to a food product in a container, in an effort to guarantee food safety, and extend the shelf-life of processed foods [1]. Thermal processing is the most widely used preservation technology to safely produce long shelf-lives in many kinds of food, such as fruits, vegetables, milk, fish, meat and poultry, which would otherwise be quite perishable. Although significant advances in non-thermal processing technologies have been made in the food preservation area during the past several decades, thermal processing is still considered the most reliable and effective preservation technology, especially for developing shelf-stable products. For thermal processing, steam or hot water under certain pressure is usually applied through the wall of a container to food with sufficient heat and for sufficient process time to achieve microorganism destruction.

The most challenging subject in designing a thermal process is to provide an adequate thermal treatment to guarantee that the slowest heating zone (SHZ) within a container of a product receives critical heat to inactivate microorganisms while, at the same time, avoiding detrimental side effects (or collateral damage), usually involving degradation of the food product. Indeed, thermal treatment not only destroys microbes; the process also degrades food quality and nutritive properties due to excessive heating [2]. One of the most important goals of the canning industry is to minimize losses of quality and nutrients during thermal processing, while providing adequate heat treatment to produce the desired level of sterilization. Hence, it is necessary to predict and quantify the heat transfer rate in the container (with various dimensions and shapes to precisely develop a thermal process that not only guarantees safety, but also minimizes losses of quality and nutrients). Therefore, it is important to understand the process of heat transfer when implemented in the sterilization of food. To ensure safe thermal processing, it is also necessary to understand heat transfer mechanisms and proper predictive methodologies to choose proper processing conditions [2].

However, it is difficult to develop appropriate mathematical models for the prediction of heat transfer phenomenon during the actual thermal processing of foods, mainly due to natural convection, which is the dominant mechanism for heat transfer inside containers. To determine the SHZ inside containers, energy equations must be solved simultaneously with the associated momentum equations to calculate a velocity profile and a temperature profile, due to the fact that the fluid flow inside containers is affected by natural convection that is dependent on buoyancy forces [3]. Since the cold point within a container will continually shift and move during thermal processing by natural convection, the SHZ has been widely used as a reference zone to estimate the potential lethality. The F value is generally used as an indicator to represent the degree of sterilization acquired during the thermal process. The F value of a thermal process must be estimated based on the heat penetration curve at the SHZ. However, it is very difficult to locate the SHZ during thermal processing, since there are large variations in temperature, which arise from wide variations in the physical position of the food inside the containers. Therefore, numerical simulation models, such as computational fluid dynamics (CFD), can be used to provide numerical solutions that describe heat transfer and fluid motion to obtain an appropriate level of quality and safety from thermal processing. Numerical prediction of the transient velocity and temperature profiles during thermal processing of canned foods was initially conducted by Datta and Teixeira [4]. A simulation model for thermal processing of canned foods was then developed by Kumar et al. [5] and Kumar and Bhattacharya [6]. CFD has been improved to develop and validate mathematical models for better understanding of heat transfer mechanisms within the container during the thermal processing of foods [7–15].

The purpose of this paper is to provide a review of the current state of CFD applications in the thermal processing of foods. First, the background of sterilization, such as the inactivation of microorganisms and change of quality of the food during sterilization, will be presented. The governing equations of CFD modeling to describe the heat transfer and fluid motion during sterilization will then be discussed. An overview of the current CFD modeling studies on the thermal processing in solid, liquid, and liquid-solid mixtures will then be given. Finally, the existing current limitations and future trends of CFD models in thermal processing will be discussed.

2. Backgrounds for Thermal Treatment of Foods

Thermal Inactivation of Microorganisms

Thermal inactivation of microorganisms during thermal processing occurs logarithmically. Therefore, theoretically, a perfectly sterilized product (with a 100% degree of certainty regarding sterilization and safety) cannot be produced, regardless of the thermal processing time. However, the probability of the survival of a microorganism can be estimated with reasonable scientific certainty based on what is currently known about the heat resistance of the microorganism, the thermal processing time, and the temperature distribution within the product. Therefore, the concept of commercial lethality, i.e., a degree of sterility, needs to be introduced to design the thermal process to produce shelf-stable products. The F value is one of the most important parameters in thermal processing and has been defined as the time (at a specific z value and temperature) needed to destroy a given number of viable cells. The F value is generally used to indicate an acceptable degree of thermal sterility for a shelf-stable food product. The F value defines the destruction of microorganisms needed to ensure the safety of the product. A sterilization value, or F_{ref} value, is generally used to describe the thermal processes operating at a single reference temperature T_{ref} with 10 °C as the z value. It is defined as follows [16]:

$$F_{ref} = \int_0^t 10^{\frac{T(t)-T_{ref}}{z}} dt, \tag{1}$$

To achieve successful sterilization, this value has to be equal to, or greater than, the required F value. At the industry scale of thermal processing, this approach using the F_{ref} value has been widely used.

As discussed earlier, thermal processing of food for purposes of sterilization also serves to produce collateral changes in the form of alteration of food quality (biochemical changes), both negative effect (such as the destruction of nutrients) and positive effect (such as the destruction of microorganisms). Most reactions occurring in food, which can be described by simple reaction kinetics, are based on biochemical changes. Generally, enzymes, thermal inactivation of microorganisms, quality factors (mainly flavor, color and texture), and most nutrients follow first-order kinetics. Therefore, changes in food quality can also be modeled with regard to both processing time and temperature. However, none of these approaches can be used to directly determine the required thermal processing conditions for food. This is because there are large variations in temperature, which arise from wide variations in the physical position of the food inside the containers. To obtain an appropriate level of safety and quality from the thermal processing, CFD should be used to provide numerical solutions that describe heat transfer and fluid motion.

3. The Governing Equations in Thermal Processing

The mathematical equations of fluid motion have been developed for nearly two centuries. Firstly, the Euler equations, which describe the motion of fluid based on the conservation of energy, mass, and momentum, were formulated in 1756–1757 by Euler [17]. The Navier-Stokes equations developed by Navier and Stokes were based on the stress tensor to fluid motion with the Euler equations [18,19]. The Navier-Stokes equations are the basis of CFD studies, and can be written as follows [20]:

Energy equation: The rate of energy change of an element balances with the work done and the heat generation on the element:

$$\nabla\left(\vec{v}\cdot T\right)+\frac{\partial\left(\rho c_p\vec{v}_i\right)}{\partial t}-\lambda\nabla^2 T=s_h, \tag{2}$$

Continuity equation: The mass flows entering into an element must be equal to those leaving:

$$\frac{\partial\rho}{\partial t}+\nabla\cdot\vec{v}_i=0, \tag{3}$$

Momentum equation: The external forces affecting an element balance its rate of linear momentum change:

$$\frac{\partial\rho v_i}{\partial t}+\rho\vec{v}\cdot\nabla\vec{v}_i=\mu\nabla^2\vec{v}_i-\nabla p+\rho g, \tag{4}$$

In the momentum equation, the Boussinesq approximation has been used in many CFD applications to model the density variation caused by buoyancy [21,22]. The following equation is applied to the momentum equations by the Boussinesq approximation:

$$\rho=\rho_{ref}\left[1-\alpha\left(T-T_{ref}\right)\right], \tag{5}$$

To simulate the sterilization process of solid food or a liquid-solid mixture, the heat transfer in the solid structures has also been considered with many CFD applications [23–25]. The heat transfer in a solid can be achieved by removing a convective mixing term for temperature from Equation (2), as follows:

$$\frac{\partial\left(\rho c_p\vec{v}_i\right)}{\partial t}-\lambda\nabla^2 T=s_h, \tag{6}$$

4. Turbulence Modelling

Turbulent flow motion plays an important role in various thermal processing techniques, including sterilization, mainly due to the high heat transfer rate associated with the high velocity of flow and relatively uniform velocity field. While the Navier-Stokes equation is used to simulate laminar flows, various turbulence models have been used to treat turbulence phenomena. Since the efficiency of those models is highly dependent on the considered geometry and turbulence conditions [26], no single model is considered to be superior for all types of applications. Some of the turbulence models that are mainly used are discussed below.

The standard k-ϵ model developed by Launder and Spalding [27] has been the most popular turbulence model, and it is still widely used in the recent literature [25,28–32]. In the k-ϵ turbulence model, the local eddy viscosity in a turbulent flow is estimated from the kinetic energy (k) and the energy dissipation (ϵ). However, a weak point of the standard k-ϵ model is that an equilibrium condition is assumed for turbulence, which is that the turbulence energy produced by the large eddies is equally distributed throughout the energy spectrum [26]. Consequently, the Reynolds stress model (RSM) and the renormalization group model (RNG) can be used to overcome the weak point of the standard k-ϵ model, which can interpret the anisotropy of the greatly strained flow. Although there are CFD application studies that show that the RST and RNG models are better than the standard k-ϵ model [33–36], these models also have convergence difficulties and the limitation of computational power [37–39].

5. Applications of CFD Models in the Thermal Processing of Foods

5.1. Constitution of the CFD Model

Large-scale simulation requires an effort to gain details about field solutions, and a large amount of computing time. In the cases of CFD applications in canning, an axisymmetric approach can be used to reduce computing time. Many works of CFD applications in cans have been conducted with the axisymmetric approach, and have successfully predicted the heat transfer and fluid motion during the sterilization process of canned foods [20,40–43]. However, Tutar and Erdogdu [44] developed the simulation model in 3D (3-dimension) for canned foods, due to the axis-symmetric approach not being available for the horizontal can. Other simplifications are also used in the literature to cut down on both computing time and pre-processing. Successful 2D (2-dimension) simulations in thermal processing, when the length of one dimension is much longer than that of the other two dimensions, demonstrated an improved computing time with suitable accuracy [45–47]. Modelling only the region of interest of large systems has also been used in the thermal processing of foods [48,49]. Even though these simplification techniques have been applied successfully, it should be noted that they can also blemish the quality of the solutions.

In the computing process during CFD simulations, meshing affects the accuracy of solutions and the spatial discretization of the governing equations. To develop a CFD model with high accuracy, the mesh should be refined appropriately in regions of interest, and in areas where extreme gradients occur. However, a high mesh quality does not always lead to a superior degree of accuracy [29]. Excessive improvement of mesh quality degrades the results with certain oscillations of temperature at the early stage of simulations. Therefore, research on the effect of mesh quality on solution quality has been continuously conducted to improve CFD models [50,51]. Recently, unstructured mesh schemes have achieved mainstream use, primarily due to their ability for automatic discretization of complex CFD domains, without causing solution quality degradation [50].

Another important parameter for the development of CFD models is time-stepping, which allows the solution of a CFD model to march forward in time. The time-step for the CFD model should be set up regarding a trade-off between stability of the applied numerical scheme, temporal accuracy of the solution, and efficiency of computing time. Consequently, during a transient process, the time step has to be short enough to interpret the frequencies of importance. For explicit numerical simulation, the dimensionless Courant number is usually used to determine the required time step, in order to retain stability. The Courant number is determined based on the portion of a cell that engages in fluid flow by advection in a time step [52,53]. It has been known that the Courant number should be smaller than 0.3 to obtain a proper convergence level in the computations [54]. However, the Courant number does not directly relate to the accuracy. A simulation model with a rough mesh can also have a Courant number close to 0, but the simulation results will not be reliable. To select the maximum time step, a proper characteristic velocity and length is required, which can be determined by previous computations, experimental data, and non-dimensional numbers, such as the Strouhal number [55,56]. At first, the selection of the time step does not need to be precise. In subsequent computations of the CFD solution, the time step can be refined according to the required accuracy level. This method has been known to be the most accurate method to simulate a CFD solution during a transient process [57].

5.2. Solid and Very Viscous Foods

In sterilization, determination of the location of the "cold point", or SHZ (defined as the slowest heating point during heat treatment), is an absolutely essential step in the calculation of the required thermal processing time. The thermal processing time for each product has to be estimated to ensure that the SHZ receives adequate heat treatment to inactivate microorganisms, while minimizing losses of quality and nutrients from the products. For solid foods, the required thermal processing time can simply be calculated experimentally [58], since the SHZ always lies at the geometric center of the product. Numerical solutions of sterilization for very viscous foods or solid foods have been conducted, which are generally assumed to be heated by pure conduction. Recent numerical simulations for solid or very viscous foods focus on improving the accuracy of the simulation models. The effect of headspace in the sterilization process is generally considered to be negligible and this assumption is widely used in many literatures [8,10,51,59,60]. The simulation model for canned apple puree was developed to study the effect headspace on the temperature distribution and the position of the SHZ during pasteurization [12]. The headspace did not significantly influence the heating rate at the SHZ during pasteurization because the heat transfer of solid and very viscous foods is governed by conduction inside the food. However, in the early stages of pasteurization, the headspace lowered the position of the SHZ. This is mainly because of the lower heat capacity of air in the headspace. Another important factor disturbing an accurate prediction of the simulation model is the structural changes of the food, such as setting of starch and protein denaturation [61]. The heat transfer simulation model for fish myofibrillar protein paste was developed by Lee and Yoon [62]. During the sol-get transition, the physical properties of the paste can dramatically change, and their simulation model reflecting the phase transition showed superior accuracy when compared to the simulation model without the phase transition (Figure 1).

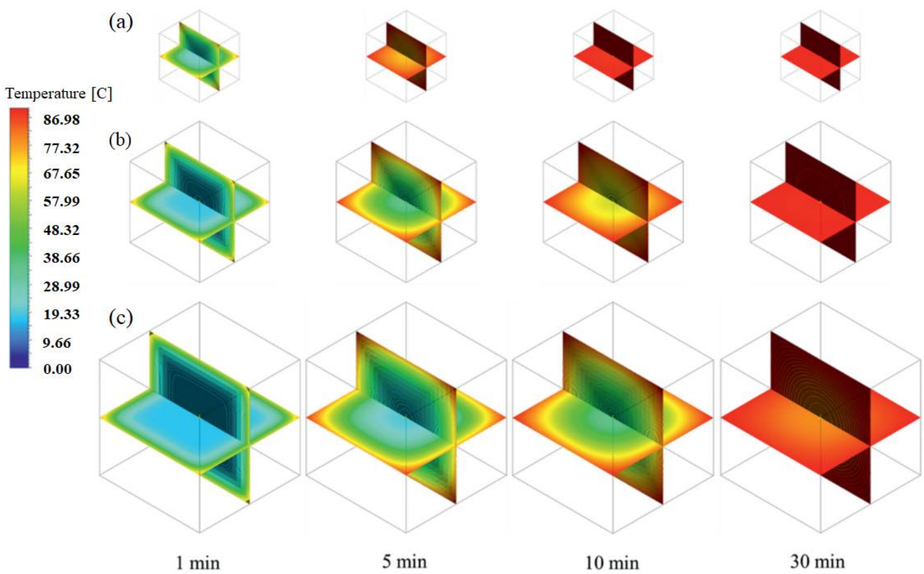

Figure 1. Estimation of the temperature profiles of surimi pastes (76% moisture) at 1, 5, 10 and 30 min for constant temperature (90 °C) water bath heating; (**a**) 2 × 2 × 2; (**b**) 3.5 × 3.5 × 3.5; and (**c**) 5 × 5 × 5 cm cubes, reproduced with permission from [62]; published by De Gruyter, 2016.

5.3. Liquid Foods

In contrast to solid food, identification of the SHZ for liquid food can be a difficult task. When liquid foods are thermally processed, fluid motion accelerates the thermal processing by improving the heat transfer rate. Hence, heat transfer of liquid food within a container is governed by both temperature variation and fluid motion [63]. CFD and numerical simulation are commonly applied in the prediction of the temperature distribution and fluid motion during the thermal processing of liquid foods [64]. During the thermal processing of liquid foods governed by natural convection, the temperature in the energy equation is coupled with the velocity in the momentum equations because the fluid motion is dependent on buoyancy force. CFD simulation models for the sterilization of liquid types of canned food were conducted by Lee and Yoon [20], and their flow patterns analyzed (Figure 2). With the application of a no-slip boundary for liquid products, the liquid close to the wall is at rest at the beginning of thermal processing. When the outer wall of the container later heats up, the liquid near the wall also heats up by conduction (nearly to the wall temperature) while the liquid at the center of the container is still at the initial temperature. Buoyancy forces are generated due to gravity and density variations in the can, and generated buoyancy forces are suppressed by the viscous force of the liquid during thermal processing. Velocity fields of the convective current depend on the resistance to flow of the liquid's viscosity and the strength of the buoyancy forces. Temperature-dependent viscosity decreases as the heating process proceeds, which leads to faster heating of the liquid food within a container by increased velocity. As the temperature of the product becomes uniform, buoyancy forces then decrease, which results in the cessation of recirculation and a reduction in velocity [6].

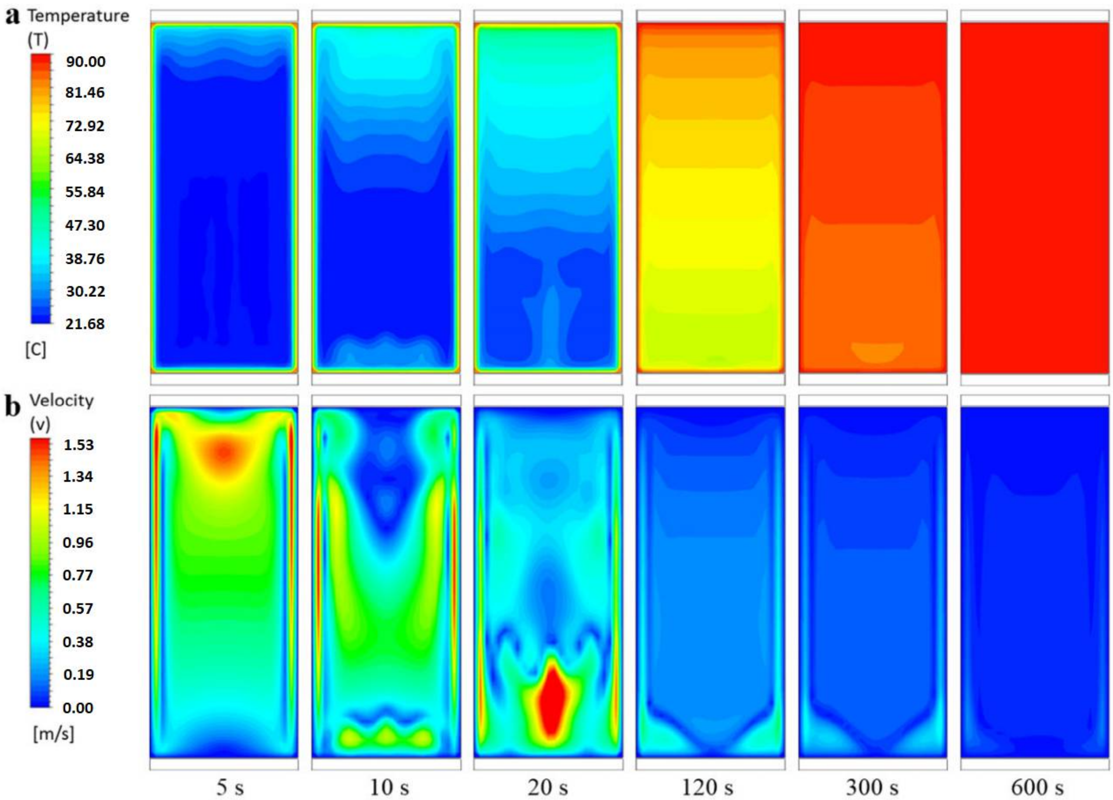

Figure 2. (**a**) Temperature, and (**b**) velocity profiles while heating at 90 °C in a cylindrical can at 5, 10, 20, 120, 300 and 600 s, reproduced with permission from [20]; published by John Wiley and Sons, 2014.

To investigate the flow pattern and the position of the SHZ during sterilization, CFD has been widely used in canned liquid foods, such as beer, carboxyl-methyl cellulose (CMC), cherry juice, corn starch, soup, soybean oil, and milk [8,11,13,20,65–69]. The CFD models for canned liquid foods were also used to estimate the required thermal processing time to provide an adequate heat treatment to inactivate microorganisms. Headspace in canned liquid foods has significant effects on the heat transfer during the sterilization process [44,70]. In contrast to the study on the effect of headspace for canned solid food, headspace in canned liquid food results in a faster heating rate compared to its rate without headspace, which is mainly due to the natural convection of fluid in canned liquid foods [61,70]. In the canning industry, rotary processing during sterilization has recently been widely used, and these processes significantly speed up the sterilization process. The effects of agitation on the heating rate and fluid motion have been investigated by CFD. Ghani et al. [71] have found that the heating rate at the SHZ was more efficient by up to four times with the rotation of cans during the thermal process. The combined effect of headspace and rotating speed was studied by Tutar and Erdogdu [44]. Various body forces, such as centrifugal, Coriolis, and gravitational buoyancy, and their interactions, affect the temperature profile and local flow patterns during sterilization with different rotating speeds. With increasing rotating speed, the headspace bubble detached from the wall and moved through the liquid foods, which significantly improved heat and fluid mixing in the liquid-air two-phase system.

The characteristics of the fluid motion inside the container during thermal processing are dependent on its geometry. Even very small alterations in the geometry of the container can cause disturbances in the thermal process. The CFD application studies have been expanded to the modification of processing conditions of products, such as the orientation and the geometry of its container. Movement of the SHZ during heating for cylindrical and conical containers with non-Newtonian fluid has been investigated by Varma and Kannan [42]. They have found that not only the geometry, but also the orientation of these containers can significantly influence the efficacy of the thermal sterilization process. Boz and Erdogdu [72] have simulated temperature profiles and velocity fields in the horizontal can using a 2D approach. However, it should be noted here that the effect of heat transfer in the horizontal direction by conduction might be significant in high-viscosity foods. Due to such significant heat transfer in the horizontal direction, this 2D approach should be prevented in high-viscosity foods. Augusto et al. [65] have also studied the effect of the orientation of beer cans on the efficiency of the pasteurization process. Their results have demonstrated that the orientation of beer cans (such as conventional, inverted, or horizontal orientation) can significantly affect the thermal profiles and flow patterns in these cans. Thus, the temperature and velocity profiles inside cans solved by momentum and energy equations can be significantly different, depending upon the geometry and orientation of the cans. Farid and Ghani [41] conducted a number of computer simulations to investigate the effect of fluid viscosity, and the orientation and size of can. Based on the numerous simulation results of the CFD models, a generalized correlation is found to determine the Fourier number, which is a dimensionless number that characterizes transient heat diffusion based on the thermal diffusivity, characteristic timescales, and length scale, from the dimensionless SHZ. An effective thermal diffusivity for a specific liquid was also calculated using the Nusselt number, which is the ratio of convective to conductive heat transfer across the boundary, to account for the effect of natural convection generalized during sterilization. Based on the scaling approach using the dimensionless number, regardless of fluid viscosity and the size of the can, a simple computational technique can be practically used for fast and rough approximation of the required sterilization time for industries.

5.4. Liquid-Solid Foods

In contrast to the heat transfer in liquid foods that is dominated by natural convection, the heat transfer within the solid elements in liquid-solid foods occurs by conduction during thermal processing [5]. Currently, CFD application studies have been expanded to the thermal processing of mixtures of liquid-solid food. The presence of solids in liquid-solid foods has been found to influence the position of the SHZ, as well as the fluid motion inside the container. In contrast to the heat transfer in liquid foods, mixtures of liquid-solid food have been found to be heated by both convection and conduction [23,73,74]. In the simulation model for pineapple slices floating in sucrose solution, pineapple slices have been presumed to be heated up by pure conduction while the solution has been presumed to be heated by natural convection recirculating inside the can [75]. Padmavati and Anandharamakrishnan [74] have also studied the CFD application for canned pineapple slices. Their results have shown that the position of the SHZ in the can is concentrated on solid food (pineapple slices) rather than at the geometric center in the can where the sugar solution is present (Figure 3). The geometry of the solid in the can also significantly influences the heating rate. The canned pineapple titbits showed a rapid heating rate due to a larger surface area and the improvement of natural convection [74]. For liquid-solid mixtures, Kiziltas et al. [10] assumed that solids are uniformly distributed in the liquid of canned peas. The results demonstrated that fluid motion inside the container slightly changed due to surface deflections and heat exchange where the flow moved through the stack of peas. However, such an unrealistic assumption, in which the solids are uniformly distributed in the liquid, may not be acceptable for accurate predictions of CFD simulations. The comparison of simulation results with experimental data showed that there is significant error in the early stage of thermal processing. The 2D approach can also be applied to the CFD simulation for thermal processing of solid-liquid foods. Cordioli et al. [23] developed CFD simulation models for canned fruit salad in both 3D and 2D. The results showed that this 2D simplification does not significantly affect the results, and the results were validated by experimental data. The effect of can-orientation for canned peach halves was studied by Dimou et al. [76], and the results showed that vertical cans exhibited a lower microbial F value due to a slower heating rate during thermal processing. Dimou and Yanniotis [77] developed the CFD simulation model for the thermal processing of asparagus canned in brine. They found that the number of asparagus spears significantly affected the fluid motion in the container, but does not significantly affect the position of the SHZ and the heating rate, which implies that the primary resistance to heat transfer occurs inside the solid. The position of the SHZ in liquid-solid mixtures is significantly varied when compared with that in liquid foods. This is because of the existence of solid foods in the container, in which solids decrease the fluid motion by natural convection, resulting in the SHZ migrating upwards. Generally, the SHZ in a mixture of liquid-solid tends to be located in solid rather than liquid, which is due to the fact that the dominant thermal resistance in liquid-solid food is conduction inside the solid.

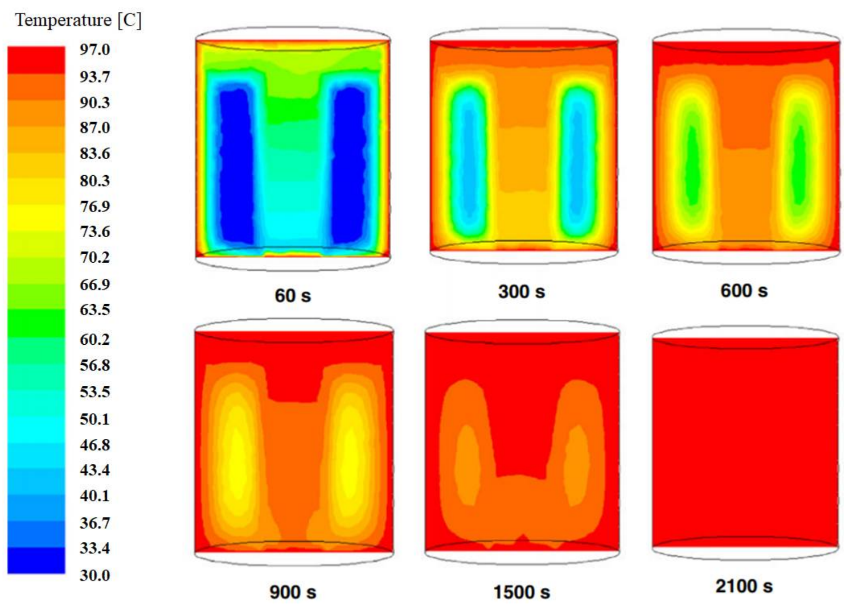

Figure 3. Temperature contours of the canned pineapple slices in sugar solution, reproduced with permission from [74]; published by Springer Nature, 2013.

5.5. CFD Studies on Microbial Inactivation

Numerous studies have been developed to evaluate the temperature changes at the SHZ and link it to microbial inactivation. Evaluating the F_0 value is the most common method to evaluate the lethality of the sterilization process, and it refers to the lethality with a z value of 10 °C at a given reference temperature [43,68,74]. It can also focus on a specific microorganism, such as *Bacillus polymyxa* and *C. Botulinum*, with the specific z value for a given microorganism as described by various studies [14,19,61]. Based on the simulation results, the required thermal processing time to achieve the desired lethality can be estimated. Microbial survivors upon the thermal processing time can be directly estimated using CFD analysis and bacterial inactivation kinetics [13,78]. The simulation results showed that the concentration of bacteria depends on both the flow pattern and temperature distribution within the pouch, and the simulation result was successfully validated by experimentally counting viable microorganisms [78]. Indeed, most biochemical reactions occurring in food can be simply expressed similar to bacterial inactivation kinetics during thermal processing [17]. The changes in the concentration of vitamin C, which is related to food quality, can also be predicted during thermal processing using vitamin destruction kinetics [13,79]. Changes in inverted sugar concentration of canned liquid food during sterilization were also simulated and measured experimentally to validate the CFD simulation model [69].

6. Current Limitations and Future Trends of CFD Modeling in Thermal Processing

The design and optimization of thermal processing systems needs to be supported by the results of CFD analysis, because modeling the effect of processing conditions in industry-scaled sterilizers or pasteurizers (such as the shape and dimensions of products, and heating and cooling rate on the sterility of food) is very complicated, and the analytical approaches give very limited interpretations. Though numerous CFD models have been developed to further the existing understanding of the physical mechanisms at work within the container of foods, the CFD model for the industry-scaled sterilizer still has some limitations on both CFD algorithms and computational power, and has not yet reached such high levels that industry-scaled computations can be precisely conducted. Recently, CFD application for the industry-scaled retort process was studied in a 3D approach [24]. The simulation model was developed to assess the temperature changes of vegetable products in retort during the sterilization process. However, even though unrealistic assumptions were considered, in which the initial temperature distribution for the retort and vegetable product were 130 and 85 °C in the process, a very large amount of computation time was required to simulate 5 min of process time among about 120 min of the sterilization process, with a low level of accuracy. Various non-thermal processing techniques, such as high-pressure processing, ultrasound and irradiation, have been applied to thermal processing to enhance its effect on product quality [80–82], and these processing procedures also need to be studied for better understanding of the combined effect of thermal and non-thermal processing. The explosive growth of CFD software packages with high computation power and capabilities in reducing cost will encourage engineers to use CFD to design industry-scaled thermal processing systems.

7. Conclusions

The objective of this review is to discuss the current state of CFD modelling in the thermal processing of foods. The constitution of the CFD model, such as the geometry, mesh and time stepping, was discussed in this study. However, more research should be conducted to improve both the accuracy and the computing time of CFD models. The heat transfer phenomena within the container during thermal processing can be categorized into three categories: (1) pure conduction heating (solid or very viscous foods); (2) convection heating (liquid foods); (3) conduction-convection heating (liquid-solid foods). While the SHZ for solid food always lies at the geometric center of the product, the position of the SHZ for liquid food depends on various properties, such as the flowability of liquid food, and the geometry and orientation of the container (because the cold point for liquid food continuously moves by natural convection during thermal processing). In contrast to the heat transfer seen in liquid foods, mixtures of liquid-solid food have been found to be heated by both convection and conduction. By introducing the microbial and chemical destruction kinetics to CFD simulations, a comprehensive understanding of food quality during sterilization can be achieved, and it can also be used to validate the simulation models. However, the CFD applications for an industry-scaled sterilizer still have some limitations on both CFD algorithms and computational power. Fast growth of CFD applications in thermal processing can be used to scale the process up, and design a combination of thermal and non-thermal processing. Some unrealistic assumptions are still widely used in CFD modelling for the sterilization of foods. Therefore, more detailed CFD modelling for the thermal processing should be studied to provide explanations for complex mass and heat transfer, as well as fluid flow phenomena. However, the CFD applications for the industry-scaled sterilizer still has some limitations on both CFD algorithms and computational power.

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Conflicts of Interest: The authors declare no conflict of interest.

Nomenclature

C_p	Specific heat capacity ($W \cdot kg^{-1} \cdot K^{-1}$)
g	Acceleration of gravity ($m \cdot s^{-2}$)
S_h	Heat source ($W \cdot m^{-3}$)
T	Temperature (K)
t	Time (min)
$\vec{v}$	Velocity component ($m \cdot s^{-1}$)
Greek symbols	
α	Thermal expansion coefficient (K^{-1})
ρ	Density ($kg \cdot m^{-3}$)
λ	Thermal conductivity ($W \cdot m^{-1} \cdot K^{-1}$)
Subscripts	
i	Cartesian coordinate index
ref	Reference

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