Using computational fluid dynamics (CFD) in the analysis of high pressure processing of food; A review

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Abstract. Non-thermal processing of food using high pressure is an advance technology and it can be applied to a large number of food products using batch or continuous treatment units. It is a non-thermal pasteurization sterilization of food by the application of high pressure of the order of thousands of atmospheres. The process retains the food quality of freshness and its nutrient content such as vitamins. HPP of foods is an emerging technology of increasing interest because it permits microbial inactivation at low or moderate temperatures. Extensive experimental works have been conducted on this process during the last decade. However, limited computational analysis of the HPP process is available in the literature. Most of the theoretical models developed assume a uniform temperature throughout the treatment chamber, which can be true only for small treatment HPP units. These models cannot be used for the scale up of the existing laboratory size HPP units to an industrial size.

The temperature of the treatment chamber will be function of position and time and is influenced by both heat generation due to compression and external heat transfer. The development of such computation is very important, as experimental testing of every single food at different operating condition can be very time consuming.

Keywords: computational fluid dynamics, high pressure processing, heat transfer.

1. INTRODUCTION

In the past decade, it has become clear that high pressure processing (HPP) may offer major advantages to the food preservation and processing industry (Barbosa et al., 1997 and Ludikhuyze et al., 1998). Next to inactivation of microorganisms and spoilage enzymes (Seyderhelm et al., 1996 and Yen and Lin 1996), promising results have been obtained with respect to application of high pressure in food processing, for gelation of food proteins (Richwin et al., 1992 and Ohshima et al., 1993) and improving digestibility of proteins and tenderization of meat products (Bouton et al., 1997 and Ohmori et al., 1991).

There is growing interest in the combined effect of temperature and pressure as an effective mean of inactivation of micro-organisms. Bacterial spores are more resistance to temperature and pressure than vegetative bacteria, and the combined pressure-temperature effect is very efficient for the treatment of spores. Also, it is known that food undergoes minimum nutrient destruction at temperatures below 100°C. Hence the application of HPP at moderate temperatures can be applied to a large number of food products; especially those contaminated with spores, which are usually sterilized thermally at 121°C. The temperature distribution in the high pressure vessel may result in a non uniform distribution of microbial inactivation and quality degradation. Without full understanding of the microbial inactivation mechanism under the combined effects of pressure and temperature, the application of such process will remain limited and expensive.

2. MATHEMATICAL MODELING OF CONDUCTIVE HEAT TRANSFER DURING HPP

Mathematical modeling is a very useful tool for quickly and inexpensively ascertaining the effect of different system and process parameters on the outcome of the process. It minimizes the number of experiments that need to be conducted to determine the influence of various parameters on the safety and quality of process. The use of approximate methods to solve problems described by partial differential equations has been employed for various reasons, the lack of availability of analytical solutions or empirical correlations, simplicity of solution technique, and ability to quickly perform parametric analysis (Abdul Ghani, and Barbosa-Canovas, 2011; Irudayaraj, 2001).

Numerical formulations are based on the classification of the governing equation. Formulations for all types of equations can be explicit or implicit. Explicit formulations are simple, but the number of computations and the instability of the formulation are some of its drawbacks. (Abdul Ghani, and Barbosa-Canovas, 2011).

Pressure is transmitted uniformly and immediately through the pressure transferring medium according to the Pascal principal, and thus the effect of pressure are independent of product size and geometry (Knor, 1993). In fact, heat transfer characterizes every process, accompanied by a period of pressure increase or decrease, because an increase or decrease of pressure is associated with proportional temperature change of the vessel's contents due to adiabatic heating (Denys et al., 2000). Heat transfer is caused by resulting temperature gradients and can lead to large temperature differences, especially in large-volume industrial vessel. These limitations should be taken into account analysis of HPP processing, especially of the industrial size. By taking into account the non uniform temperature distribution appearing during the process, it can be assured that the objective of the process has been accomplished everywhere within the food product. For this purpose, the heat conduction equation describing the time-temperature-pressure history of a product must be coupled with the parameters describing the reaction kinetics for destruction of microorganisms, enzymes, and other factors. Denys, et. al. (2000) reported that, a heat transfer model for conventional batch HPP processing of foods, serving as a basis for the above explained approach, is still absent.

A numerical model for predicting conductive heat transfer during HPP of foods was simulated by Denys, et. al. (2000). The study was developed and tested for a food simulator (ager gel). HPP process with gradual, step by step pressure build-up and pressure release, and pressure cycling HPP processes were included. The model provides a tool to evaluate batch high pressure processes in terms of uniformity of any heat and/or pressure related effect. Denaturation kinetics of the enzymatic model system *Bacillus subtilis* α-amylase (BSA) was used as an example.

A model combining numerical heat transfer and enzyme inactivation kinetics was developed by Denys, et. al. (2000a). In their work, a numerical conductive heat transfer model, for calculating the temperature evolution during HPP of foods, was tested for two food systems: apple sauce and tomato paste. Both conventional high hydrostatic pressure processes with gradual, step by step pressure built-up and pressure release were simulated. The model provides a useful tool to evaluate batch high hydrostatic pressure processes in terms of uniformity of any heat and/or pressure related effect. The uniformity of inactivation of *Bacillus subtilis* α-amylase and soybean lipoxygenase during batch high pressure processing was also evaluated. It was found that, the residual enzyme activity distribution appeared to be dependent on the inactivation kinetics of the enzyme under consideration and the pressure temperature combination considered.

A mathematical model describing the variation of the inactivation rate constant of soybean LOX as a function of pressure and temperature was studied by Ludikhuyze et al. (1998). Temperature dependence of the inactivation rate constants of LOX cannot be described by the Arrhenius equation over the entire range of temperature range, therefore development of another kinetic model was attempted. Hence, the Eyring equation, which was valid over the entire temperature domain, was used in this work. The temperature dependant parameters (k_{refP}, V_a) in the Eyring equation below were replaced by mathematical expressions reflecting the temperature dependence of the later parameters.

$$\ln k = lin \ \ k_{refP} - [\frac{V_a}{R(T+273)}(P-P_{ref})] \qquad (1)$$

Temperature dependence of activation volume V_a and inactivation rate constant k_{refP} were described by the following equations respectively.

$$V_a = a_1 T \quad \exp(-b_1 T) \qquad (2)$$

$$\ln k_{refP} = a_2 T^2 + b_2 T + C_2 \tag{3}$$

Subsequently, the proposed model structure was verified to predict likewise the extent of inactivation under variable pressure and temperature conditions, provided the kinetic parameters were re-estimated. It was observed that, the multiple application of high pressure enhanced the inactivation of soybean LOX, and the effect becoming more pronounced at low temperature.

3. MATHEMATICAL MODELING OF CONVECTIVE HEAT TRANSFER DURING HPP

During compression, the liquid will move by forced convection due to the movement of the piston used for compression. This is because; liquids at extreme high pressure are compressible. The increase of temperature induces heat transfer within the liquid and heat exchange with the walls of the pressure chamber. As a consequence, density differences occur and lead to free convection of the fluid. The fluid motion generated by forced and free convection strongly influences the temporal and spatial distribution of the temperature, which was already observed using experimental techniques (Hartman, 2002).

Thermodynamic and fluid-dynamic effects of high pressure treatment are analyzed by means of numerical simulation by Hartman (2002). Pure water is considered in the process, and it is compressed up to 500 MPa in a 4 ml chamber at different compression rates. The spatial and temporal evolution of temperature and fluid velocity fields are analyzed. It is found that the fluid motion is dominated by forced convection at the beginning of pressurization. Due to density differences, free convection sets in and dominates the fluid motion for a few seconds after the beginning of pressurization. Also, it is found that, the temperature differences occurring in the high-pressure volume depend strongly on the pressure ramp during pressurization.

The influence of heat and mass transfer effects on the uniformity of a high pressure induced inactivation was also investigated by Hartman, et al. (2003). The inactivation of *E. coli* suspended in pouched UHT milk carried out in a batch process with water as a pressure medium, which is taken as a model process. The result of the simulation showed that, significant of non uniformities of more than one log cycle in the residual surviving cell concentration is depending on the package material parameters, such as the position and the arrangement of the package in the vessel.

Numerical simulation of solid-liquid food mixture in a HPP unit was conducted using computational fluid dynamics (Abdul Ghani and Farid, 2007). In this simulation, temperature distribution, velocity and pressure profiles during high pressure compression (500MPa) of liquid food (water) and solid-liquid food mixture (beef fat and water), within a three dimensional cylinder basket was studied for the first time. The simulation for the solid-liquid mixture shows that the solid pieces were more heated than the liquid, which is due to the difference in their compression heating coefficient. Validation of the computed temperature in both cases was found to be in an agreement with those measured experimentally and reported in literature.

Modeling of the effect of compression come up time and the effects of natural and forced convection heating within a three-dimensional cylinder filled with liquid during HPP was analyzed and studied using computational fluid dynamics (Abdul Ghani and Farid, 2007b). The convection currents of liquid food in a non-adiabatic high pressure processing, was also studied. The simulation for liquid food shows the effect of forced and free convection flow on the temperature distribution in the liquid at the early stages of compression. This is due to the difference between the velocity of the pumping fluid as it enters the cylinder inlet hole (10^{-2}-10^{-3}) m s^{-1} and the velocity in the treatment chamber (10^{-8}-10^{-9}) m s^{-1}.

The modeling and simulation of the effect of the combination of high pressure and thermal treatments on food processing, focusing on the inactivation of certain enzymes was studied by Infante et al., 2009). The behavior and stability of the proposed models are checked by various numerical examples. Furthermore, various simplified versions of these models are presented and compared with each other in terms of accuracy and computational time. The models provided a useful tool to design suitable industrial equipments and optimize the processes.

4. MATHEMATICAL MODELING OF HEAT TRANSFER DURING HIGH PRESSURE FREEZING AND THAWING

In the field of high pressure freezing and thawing, most studies were dealing with the impact of high pressure freezing and thawing on quality aspects of a particular food. However, a theoretical based heat transfer model that allows predicting the temperature history within a product undergoing such a process would be very useful Denys, et al. (1997). A number of mathematical models have been proposed for freezing and thawing over the past three decades. These models allow optimization of the design of industrial freezing and thawing equipment as well as the quality of the end product (Bakal & Hayakawa, 1973; Ramaswamy & Tung, 1984). An existing theoretical model for predicting product temperature profiles during freezing and thawing processes was extended by Denys, et al. (1997) to the more complex situation of high pressure freezing and thawing processes. This requires knowledge of the product's thermal properties at any pressure applied. To take into account the influence of elevated pressure, a simplifying approach was suggested, consisting of shifting the known thermophysical properties at atmospheric pressure on the temperature scale depending on the prevalent pressure. A numerical solution for two dimensional heat transfers (finite cylinder) was chosen. A computer program was written for solving the heat transfer equations in the cylindrical content of the high pressure vessel, using an explicit finite difference scheme. The method used in the work also took into account the temperature increase of the high pressure medium during adiabatic compression and the temperature decrease during adiabatic expansion.

5. FUTURE WORK

A number of investigations have used first order kinetics for the mechanism of microbial inactivation, which is usually applied in the thermal treatment. The decimal reduction time is taken as a function of both temperature and pressure. As we have noted earlier, the adiabatic heating caused by the fluid compressing at high pressure can lead to significant temperature distribution throughout the treated food. Ignoring this temperature variation would lead to the incorrect scale up from small (laboratory) size HPP units to the large industrial size units. To date, a heat transfer model for HPP that includes the above mentioned effects is very limited. The development of such model is very important, as experimental testing of every single food at different operating condition can be very time consuming.

For all of the above reasons, the future work plan must take into consideration the study of the effects of transient pressure and the temperature distribution in the treatment chamber on the degree of sterility of food. The proposed following steps in the development of HPP model are:

1- The modified unsteady state heat conduction equation will be used to describe the heat transfer in the treatment chamber. The heat generation due to compression will be included in the equation as a heat generation term, together with any heat generated or absorbed due to latent heat of solidification of the lipid in the food.

2- The physical properties of the treated food must be taken as pressure and temperature dependant. This is suggesting the needs of an extensive experimental work to be done to measure the pressure and temperature dependence of food properties.

3- The effect of phase change of fat will be included in the analysis. However, such effect is complicated by the fact that the melting temperature of lipids increases with pressure ($10^{o}C/100MPa$). Thus lipids present in a liquid state will crystallize under pressure at room temperature.

4- It is possible to simplify the analysis by using an effective thermal conductivity that takes into account the natural convection in the liquid. Alternatively, Computational Fluid Dynamics (CFD) may be used to solve the continuity; momentum and heat transfer equations in the liquid phase.

5- The effect of transient pressure will be incorporated in the heat equation as unsteady state heat generation term.

6- Based on the suggested analysis, the pressure will be uniform in the treatment chamber, but will vary during the pressure build-up and release. The temperature is a function of position and time and is influenced by both heat generation due to compression and external heat transfer.

7- The microbial destruction rate should be calculate as a function of temperature, pressure and time, by introducing the microbial kinetics rate with the heat conduction/convection equations and integrating the combined equations within the treatment chamber at any time.

8- The destruction rate of nutrients such as vitamins due to the effect of pressure and temperature should be calculated as a function of time and position in the treatment chamber. The computation would also allow the prediction of any important changes in the physical and functional properties of the food systems.

As a result for all the above, the suggestions are as follows:

1. Build a simple mathematical model of adiabatic HPP for homogeneous liquid food. This model can be used to describe the effect of adiabatic compression on food when using a small size HPP treating chamber, where the temperature distribution can be ignored. The comparison between model predictions and experimental measurements will be useful to estimate some of the unknown thermal properties of the food materials.
2. Analyse the combination of high pressure and temperature by construct a rigorous numerical model, which takes into account the temperature distribution in the treatment chamber due to the adiabatic heating. This must be done in parallel with the experimental measurements on a large size HPP unit, to test the validity of the developed model. Finally, extend the model to account for the case that includes external heating, which is important for the pressure accelerated thermal sterilization required to treat spores.

This could be done with the help of some of the powerful software codes available, such as CFX, Fluent, Flow 3D, PHOENICS etc.

The output from the suggested research work can be used by the Industry in optimizing the food processing. This output will also provide a comprehensive analysis of some of the most important parameters in the food processing applications. The experimental work and the strong theoretical analysis will lead to a big step towards the deep understanding of the mechanism of heat & mass transfer in one of the important emerging technologies in food processing.

CONCLUSIONS

Literature review shows limited amount of work has been done for the analysis of industrial scale of HPP. Most of the previous work has been done on a small scale of HPP units where the temperature distribution is limited. The heat generated by adiabatic compression and/or for external heating or cooling requires more rigorous work to account for the effect of natural convection in the liquid phase. Further complication could appear in the applications of freezing and thawing due to the effect of the latent heat effect in the solid face.

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