Modeling of Concentrated High Intensity Electric Field (CHIEF) and Its Comparison with Other Non-thermal Liquid Food Pasteurization Technologies

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Dedication

This thesis is dedicated to my beloved family and friends.

Abstract

Non-thermal preservations of food have received rising attention due to the increase concern of environmental sustainability and the demand of safer food with improved nutritional functionalities. High pressure and electric field treatment are two non-thermal food treatment strategies that have been widely studied. Some representatives of non-thermal technologies that utilize high-pressure and electric field to pasteurize food products include High hydrostatic pressure (HHP), high-pressure homogenization (HPH), and pulsed electric field (PEF). These non-thermal technologies, together with concentrated high intensity electric field (CHIEF) are studied and compared in this thesis research.

This study used finite element (FEM) and computational fluid dynamics (CFD) methods to model and simulate the fluid flow, electric field distribution and temperature rise in CHIEF reactor. The simulation was confirmed to be valid by comparing it with experimental results. The model built in this study showed that the performance of CHIEF system was influenced by a set of intrinsic and extrinsic parameters. This model could be used to control and set variables in further optimization of the CHIEF system.

Each of the non-thermal technologies discussed in this study has its advantages and unique field of use. HHP, dynamic high-pressure treatment and PEF are relatively mature technologies, while CHIEF system is an innovative and promising non-thermal method that can potentially be used as alternative to PEF.

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Chapter 1. Introduction

1.1 Overview of Food Preservation

Food preservation has always received great attention. It is the principle objective of food processing to preserve the overall quality of food over certain duration. The main mechanisms of food spoilage include microbial spoilage, enzymatic spoilage, chemical spoilage and physical spoilage. A number of chemical and physical methods to enhance foods shelf life have been invented and studied. Common preservation technologies used to control food spoilage are thermal technologies, non-thermal technologies, and chemical preservation.

Thermal technologies consist of heating food containers in pressurized retorts (steam autoclaves or “pressure cookers”) at specified temperatures for prescribed lengths of time. Typically, the applied temperatures of thermal preservation technologies such as pasteurization, sterilization are greater than 80 °C (Teixeira 2013, Deák 2014). However, the high operation temperature in these processes will damage the nutrients within the food products. In addition, thermal treatments generally use heated water, high temperature steam, or microwave radiation as heating medium, which require high-energy utilization.

1.2 Non-thermal Technologies

Compared with thermal processing, non-thermal processes offer the advantages of low processing temperatures, low energy utilization and the retention of flavors, nutrients and a fresh-like taste, and at the same time inactivating the spoilage microorganisms and enzymes (Vega-Mercado et al. 1997). Non-thermal preservations of food have received rising attention due to the increase concern of environmental sustainability and the demand of safer food with improved nutritional functionalities, especially in developed countries (Devlieghere et al. 2004). The development of certain non-thermal technologies, such as the use of electric charges, can be dated back to as early as the 1920s (Vega-Mercado, Martín-Belloso et al. 1997).

High pressure and electric field treatment are two non-thermal food treatment methods that have been studied for many years (Farr, 1990; Knorr, Geulen, Grahl, & Sitzmann, 1994). Some representatives of non-thermal technologies that utilize high-pressure and electric field to pasteurize food products include High hydrostatic pressure (HHP), high-pressure homogenization (HPH), and pulsed electric field (PEF). These non-thermal treatments have been applied in the field of food pasteurization, changing morphology and improving the functionality and extract valuables from food products. Each non-thermal technology has its pros and cons, which will be discussed and compared in later chapters. In this thesis research, high hydrostatic pressure (HHP), dynamic high-pressure treatment, pulsed electric field, and CHIEF are studied.

High hydrostatic pressure (HHP) treatment is a relatively mature technology of food preservation that has been applied in commercial scale. It is chosen to compare with dynamic high-pressure treatment. Pulsed electric field (PEF) is a technology that shares some of the common principles with CHIEF, such as inactivating microbial through electric field. Thus PEF is chosen to compare with CHIEF.

Chapter 2. Literature Review

2.1 High hydrostatic pressure (HHP)

2.1.1 A scope of HHP treatment

High hydrostatic pressure (HHP) is one of the non-thermal processes that have been commercially used and has received specific attention as a reliable alternative to thermal processes. It is a non-thermal technology that has been commercially used in industries of meat and seafood industry (Torres and Velazquez 2005) . High hydrostatic pressure process treats the food product at or above 100 MPa and has proven its viability both economically and technically (Devlieghere, Vermeiren et al. 2004, Patterson 2014). The main applications of HHP include the non-thermal pasteurization and improvement of foods bioavailability.

The microbial inactivation effect of high hydrostatic pressure process has been confirmed positive in diary products (Yokoyama et al. 1992, de Ancos et al. 2000, Olsen et al. 2003), juice (Pilavtepe-Çelik et al. 2009, Zhao et al. 2014, Juarez-Enriquez et al. 2015), and meat (Omer et al. 2015, Yao et al. 2015, Yue et al. 2016). Though it has been widely accepted that HHP pasteurization inactivates microbial by breaking down its cell-wall structure under high-pressure conditions, no agreements have reached on the mechanism of this process. Extrinsic parameters that affect the performance of HHP treatment include temperature, pressure, treatment time, and pulse shape frequency; while the intrinsic parameters are water activity, PH, composition of the treated products, and microbial strains (Valdramidis et al. 2012). The detailed effects of these parameters had been fully researched and reviewed in previous studies (Buzrul 2012, Chen et al. 2012, Buzrul 2014, Huang et al. 2014). To understand the mechanism of HHP disinfection, many existing models were fitted to the inactivation results to study the mechanisms of HHP treatment (Doona et al. 2005, Koseki and Yamamoto 2007, Phua and Davey 2007, Pilavtepe-Çelik, Buzrul et al. 2009, Evelyn and Silva 2015). Overall the fitting result varies depending to the target microorganism, food media, and treatment conditions. However, results suggest higher pressure increases HHP's pasteurization performance. Models also indicate that bacterial inactivation of HHP have a tendency to decrease as under pressure higher than approximately 400 to 500 MPa.

Under the high-pressure treatment conditions of HHP, physical properties and functionalities of food products are likely to change. Causes of HHP treatment such as tissue and cell wall structure disruptions might lead to a better extractability of antioxidant components. As consequence, the use of

HHP technologies has extended from bacteria disinfection to improve bioaccessibility and bioavailability of nutritional and antioxidant compounds of food products (Vega-Gálvez et al. , McInerney et al. 2007, Vega-Gálvez et al. 2011, Vázquez-Gutiérrez et al. 2013, Ma et al. 2015, Ma and Mu 2016, Tao et al. 2016, Yue, Zhang et al. 2016, Zhang et al. 2016).

2.1.2 Innovative application and combined use of HHP

As mentioned previously, high hydrostatic pressure has played an important role in the field of food science and process. Its pasteurization effects, along with its ability to improve food functionalities have been widely studied and reviewed. Recent novel studies on HHP pasteurization focus on its combined performance with other thermal/non-thermal technologies. Research has proved that the combined applications of HHP with other food treatment methods have positive effects on both bacterial kill longer shelf life, and improvement of nutrient content. A summary of the innovative research of combined HHP disinfection processes is presented in table 1.

Table 1 List of innovative applications of HHP combined with other technologies

Target food product	Treatment methods	Strain type studied	Reported results	Reference
Apple juice	HHP + sonication	Aciduric bacteria, mold and yest	Complete inactivation + improved nutrient content	(Abid et al. 2014)
Smoothies	HHP + temperature	Z.*bailii* and L.*monocytogenes*	> 5 log cfu/mL reduction of L.*monocytogenes* and sublethally-injured L.*monocytogenes*	(Scolari et al. 2015)
Cherimoya pulp	HHP + enterocin AS-48	L.*gasicomitatum*, L.*gelidum*, and L.*mesenteroides*	> 5 log cfu/mL reduction and delayed recovery	(Toledo del Árbol et al. 2016)
Mango nectar	HHP + high temperature short time	Aerobic bacteria, mold and yeast	< 1 of final log cfu/mL of yeast and mold, < 1.70 log cfu/mL of aerobic bacteria	(Liu et al. 2014)
Beef	HHP + chemical preservation	Mesophilic bacteria and lactic acid bacteria	6-week storage life and maintained color attributes	(Giménez et al. 2015)
Gum arabic	HHP + acid and base treatment	N/A	Changed emulsification properties and amino acid contents	(Ma et al. 2015)
Cumin dietary fiber	HHP + Enzyme treatment	N/A	Increased soluble dietary fiber (SDF) content; Better absorption of water, fat, carbohydrate, and exhibit antioxidant content	(Ma and Mu 2016)

2.2 Dynamic high-pressure treatment

2.2.1 A scope of dynamic high-pressure treatment

Dynamic high-pressure treatment, also known as high-pressure homogenization (HPH), has been applied in the field of liquid food treatment for many years. Its common applications include bacterial inactivation, changing rheological properties of liquid food and enhance the functional properties for liquid food products (Schultz et al. 2004, Diels and Michiels 2006, Augusto et al. 2012, Dumay et al. 2013). Industrial high-pressure applications that introduce up to 800 MPa pressure normally operate discontinuously (Barba et al. 2012). On the other hand, HPH treatment is notable for continuous operation of food product under high pressure and it's capability of commercialization (Georget et al. 2014, Tan and Kerr 2015). Since pressure exceeding 400 MPa is not recommended in food treatment due to its disruption of food's nutritional values, studies on HPH mainly range from 100 to 400 MPa (Knorr et al. 2006, Heinz and Buckow 2010). Note that pressure from 300 to 400 MPa of HPH is also referred to as ultra high-pressure homogenization (UHPH) (Georget, Miller et al. 2014).

Similar to high hydrostatic pressure treatment, the performance of HPH process is affected by parameters such as pressure, feed temperature, strain type and pass number etc. For disinfection purposes, studies have reported that gram-negative bacteria have greater sensitivity to high-pressure homogenization than gram-positive bacteria (Wuytack et al. 2002, Lanciotti et al. 2006, Tahiri et al. 2006, Donsì et al. 2009). Additionally, higher pressure results in greater log reduction of pathogens, while effects of increasing the pass number is not as significant after two to three passes through the homogenizer (Donsì, Ferrari et al. 2009). For other usage of HPH treatment, including emulsification and change of physical properties, it is shown that increasing pressure and pass number leads to larger particle size reduction and wider particle size distribution. However, results also indicate that as pass number greater than two has less effect on the performance of HPH (Håkansson et al. 2009, Qian and McClements 2011). Table 2 presents a brief summary of pasteurization effects by HPH in selected liquid media.

Table 2 Inactivation results of HPH in selected food media

Target food product	Treatment conditions	Strain type studied	Best reported log cfu/mL reduction	Reference
Milk	300 MPa (75 to 85 °C)	Bacillus spores	5	(Amador Espejo et al. 2014)
Citrus juices	150 MPa	B. subtilis; G. stearothermophilus	5 2	(Georget et al. 2014)
Egg white	150 MPa	S. enterica	2.6 (2 pass) 3.6 (4 pass) 5 (17 pass)	(Panozzo et al. 2014)
Wine	50 MPa 100 MPa 150 MPa	S. bayanus	0 1.6 2.2	(Huang et al. 2014)
Orange juice	300 MPa	A. hesperidum; A. acidoterrestris	5	(Roig-Sagués et al. 2015)
Apple and carrot juice	250 to 350 MPa	Escherichia coli and Listeria innocua	5	(Pathanibul et al. 2009)

2.2.2 Innovative application of HPH treatment

Table 3 presents the innovative applications that combine high-pressure homogenization treatment with other technologies. As shown in the table, the combined technologies of HPH in recent studies focus on improving the functionalities of novel products such as nanoliposomes and protein products. Furthermore, instead of evaluating the conventional disinfection effects and changes of physical properties, research has been targeting on improvement of novel functionalities such as polyphenol stability, and the release property of nanolimposome (Zou et al. 2014, Peng et al. 2015). Improvements on particle size distribution are also observed. These innovative approaches combining HPH with different techniques have demonstrated promising results.

Table 3 List of innovative applications of HPH combined with other technologies

Target food product	**Treatment method(s)**	**Improvement of functionalities**	**Reference**
Tea polyphenol nanoliposome (TPN)	Ethanol injection method + HPH	Desired sustained release property of TPN; Improved the stability of tea polyphenol in alkaline solution	(Zou, Liu et al. 2014)
Whey protein (β-lactog	HPH + glycation treatment	Desreased antigenicity of β-lactoglobulin at pressure below 120 MPa;	(Zhong et al. 2014)

lobulin)		Increased surface sulfhydryl group content and decreased surface hydrophobicity	
Eugenol nanoliposome (EN)	Ethanol injection + HPH	More uniform particle size of EN; Long storage life (8 weeks); Improved sustained release property in EN	(Peng, Zou et al. 2015)
Vitamin C nanoliposomes	Film extraction + HPH	Increased storage stability without loss of biological activities	(Yang et al. 2012)
Wheat bran	Wet grinding + HPH	Increases the viscosity and stability of wheat bran dispersions due to HPH treatment;	(Rosa-Sibakov et al. 2015)

2.3 Pulsed Electric Field

2.3.1 A scope of PEF treatment

Pulsed electric field (PEF) is one of the non-thermal pasteurization technologies that have been widely studied. PEF involves the application of short DC electric pulses to process food at ambient or refrigerated temperatures (Barbosa-Canovas et al. 1999). PEF has been proven and confirmed to be an effective pasteurization process for pumpable food materials in the past years (Sánchez-Vega et al. 2015). PEF's disinfection mechanism is commonly accepted as the killing microorganism by cell electroporation (Barba et al. , Hamilton and Sale 1967, Sale and Hamilton

1967). Unlike HHP, PEF technology is designed primarily for treating liquid food products.

Due to its satisfactory performances on liquid products, enormous investigation regarding PEF’s pasteurization effects from bench to pilot scale has been conducted. The published studies have been well reviewed in various aspects (Barba, Parniakov et al. , Jeyamkondan et al. 1999, Raso et al. 2014, Zhao et al. 2014, Yang et al. 2016). However, limited research have been made on the commercial use of PEF technology. The scale-up technique is to connect treatment chambers parallel or in series (Min et al. 2003, Min et al. 2003). Higher energy efficiency of PEF and lower initial cost are required for easier industrial adoption (Jeyamkondan, Jayas et al. 1999, Guionet et al. 2015). To improve its energy efficiency and reach better log reduction, improvements have been made on PEF reactors (Buckow et al. 2010, Buckow et al. 2011, Knoerzer et al. 2012, Pataro et al. 2015) as well as its combined use with other non-thermal disinfection methods. Representative studies that combine PEF with non-thermal treatments such as high-pressure carbon dioxide (HPCD) and high intensity light pulse (HILP) shows promising effects on bacterial disinfection (Caminiti et al. 2011, Pataro et al. 2014). A brief summary of PEF's pasteurization effects in selected liquid media is presented in table 4 below.

Table 4 Inactivation results of PEF in selected food media

Target food product	**Treatment conditions**	**Strain type studied**	**Best reported log cfu/mL reduction**	**Reference**
Beer	35 kV/cm to 45 kV/cm (≤ 15°C)	Bacillus subtilis; L. plantarum; S. cerevisiae; Salmonella choleraesuis	5.5 to 8.4	(Walkling-Ribeiro et al. 2011)
Beer	20 kV	Lactobacillus lactis	4	(Milani et al. 2015)
Wine	20 kV (20.1 °C to 25.6 °C)	Yeasts	> 3	(Delsart et al. 2015)
Grape juice	27 kV (48.8 °C)	Salmonella typhimurium	3.4	(Huang, Yu et al. 2014)
Liquid egg	45 kV	Salmonella enteriditis	4	(Monfort et al. 2010)
Milk	43 kV (32.5 °C)	Mesophilic bacteria and lactic acid bacteria	5.3	(Cregenzán-Alberti et al. 2014)

2.3.2 Innovative application of combined PEF technology

As mentioned previously, PEF's disinfection effect and its ability to improve liquid's functionality has received great attention. However, only a few publications have discussed its combined use with other non-thermal during the past decade (Dutreux et al. 2000, Ade-Omowaye et al. 2003). In recent years, emerging research is carried out regarding the innovative applications that combine PEF with non-thermal treatment methods. These novel studies are listed in the table below. Enhancements are shown when PEF is used together with other food treatment processes. Improvements include energy consumption, longer shelf life, and greater antioxidant content in food products. However, different benefits are observed according to the processes to which PEF is added. Research also shows that the PEF's extraction efficiency on potato peels is higher than pulsed light treatment (Chauhan and Unni).

Table 5 Innovative applications of PEF combined with other non-thermal technologies

Target food product	**Treatment method(s)**	**Improvement of functionalities**	**Referenc e**
Sugar beet juice	PEF + extraction	Substantial energy saving;	(Mhemdi

		Greater sucrose concentration Color	et al. 2016)
Grapefruit juice	PEF + sonication	Increased cloud value; Non significant effects on °Brix, pH and acidity	(Aadil et al. 2015)
Grape pomase	PEF + densification	Increase in total polyphenol content; Ratio of total anthocyanins to total; flavan-3-ols increase from 7.1 to 9.0 with PEF treatment	(Brianceau et al. 2015)
Potato peels	PEF + pulsed light treatment	Enhanced the extraction of steroidal alkaloids from potato peel; PEF has higher extraction efficiency than pulsed light	(Hossain et al. 2015)
Apple Tissue	PEF + osmotic dehydration	PEF increased osmotic dehydration efficiency	(Wiktor et al. 2014)

Chapter 3. Concentrated high intensity Electric Field (CHIEF)

3.1 Introduction

Non-thermal pasteurization of food has become an important field of study in food engineering. Traditional thermal pasteurization treatment in food processes requires high temperature that might damage the food's nutritional value and sensory quality. Compared with thermal processing, non-thermal processes offer the advantages of low processing temperatures, low energy utilization and the retention of flavors, nutrients and a fresh-like taste, and at the same time inactivating the spoilage microorganisms and enzymes (Vega-Mercado, Martín-Belloso et al. 1997).

As mentioned previously, PEF has been proven and confirmed to be an effective pasteurization process for pumpable food materials in the past years. However, one of the major limitations of PEF technology is the expensive cost due to its high operation voltage and pulse frequency (Devlieghere, Vermeiren et al. 2004, Guionet, David et al. 2015).

Concentrated High Intensity Electric Field (CHIEF) is a novel, non-thermal food pasteurization process developed by researchers at the University of Minnesota. Similarly to PEF, CHIEF uses high intensity electric field to inactive bacteria in liquid food products. However, CHIEF technologies have unique characters that can reduce temperature rise and avoid contaminations oxidation, corrosion, and erosion of metal electrodes (Ruan et al. 2011).

CHIEF has proven effective in successfully killing pathogenic bacteria such as E. *coli* O157: H7, Salmonella, L. monocytogenes and Bacillus cereus in food products using AC power of medium to low voltage and frequency (Deng et al. 2015). CHIEF pasteurization of many food products such as milk, orange juice, and other high protein-rich beverages, with results of greater than 3 log reductions has been reported (Deng, Chen et al. 2015). It is considered to be one of the most promising, and perhaps leading non-thermal pasteurization technologies for liquid food due to its unique characteristics (Chen et al. 2010). However, currently few studies have been conducted to understand the mechanisms of this process. The purpose of this study is to re-verify CHIEF pasteurization effects under controlled conditions and provide experimental results for testing the modeling and simulation results described in chapter 4.

3.2. Materials and Methods

3.2.1 CHIEF System

Block flow diagram of the pilot CHIEF system (University of Minnesota, MN, USA) is shown in Figure 1. Liquid food product stored in the inlet tank is pumped through the system. The improved CHIEF system has four reactors installed in series in the treatment chamber. The treatment chamber is connected to an three-phase four-wire alternate current (AC) power supply that can provide high intensity electric power up to 10 KV at frequency of 60 Hz. Thermocouples are installed to measure the temperature of liquid immediately before and after it passes through the CHIEF reactor region.

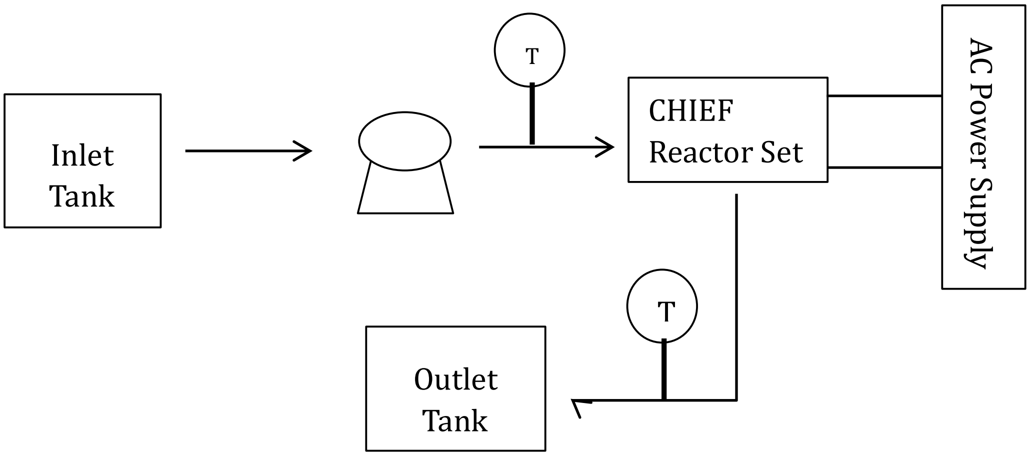

Figure 1. Block flow diagram of the CHIEF process.

3.2.2 CHIEF Reactor

Figures 2 and 3 show the 3-D and 2-D cross section of the modified cylindered CHIEF reactor. A cylindered structure is designed for the reactor to ensure the uniformity of the process (Fiala et al. 2001). Various studies targeting on the PEF technology also proves that the cylinder design of reactor provides the best treatment results (Barbosa-Canovas, Pothakamury et al. 1999, Fiala, Wouters et al. 2001, Buckow, Schroeder et al. 2010). The treated fluid flows into the reactor from the top and passes through two circular narrow chambers (0.1cm) made of dielectric material. With insulator installed between the ground and high voltage electrodes, the dielectric plates can act as electric capacitors. Thus concentrated, high intensity electric field can be applied to the chamber. The purpose of this design is to have liquid treated by high intensity electric field in the narrow chamber without coming in contact with the metal electrodes. The short treatment time in each chamber can result in less temperature rise, keeping the process under non-thermal conditions and avoid extreme temperature region in the electrodes. In addition to the structure shown below, the reactor is covered with a 32 mm thick layer of Polyethylene Furanoate to insure that the reactor is well insulated.

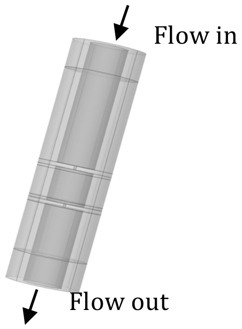

Figure 2. 3-D structure of the CHIEF reactor

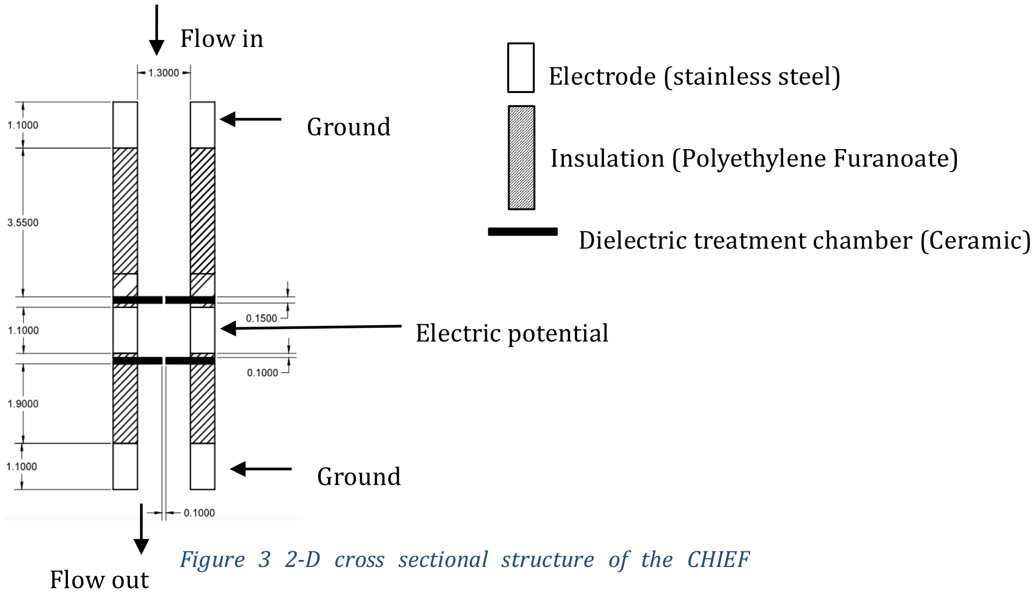

Figure 3 2-D cross sectional structure of the CHIEF

3.3 Modeling and Simulation for CHIEF technology

3.3.1 Introduction

As mentioned previously and confirmed in chapter 3, CHIEF technology is able to provide effective pasteurization results for liquid food under non-thermal conditions. However, currently few studies have been conducted to understand the mechanisms of this process. The aim of this work is to provide a better and more detailed understanding of the CHIEF process by modeling its influence factors and simulating its intrinsic fluid and electro-static characteristics.

3.3.2 Modeling Procedures

Modeling of the CHIEF system can be viewed as a combined problem of fluid mechanics, electrostatics and heat transfer. The simulation was performed using COMSOL Multiphysics® version 5.0 (COMSOL Inc. Stockholm, Sweden). Its numerical solvers combines the adaptive meshing technique with stationary solver at steady state based on the Finite Element simulation method (Zimmerman 2004, Multiphysics 2007). Due to the rotation symmetrical structure of the reactor, a 2-D axis asymmetric geometry was used instead of regular 3-D geometry or 2-D geometry to reduce the computational demand, thus allow the system to create finer meshes

(Knoerzer, Baumann et al. 2012). Mesh was generated throughout the geometry and divided the system into 8233 domain elements and 656 boundary elements. Figures 8 and 9 show the mesh system created for regular 2-D and 2-D axis symmetric model. It can be observed from figure 8 that the asymmetric mesh created in regular 2-D model will lead to inaccurate results. In other words, an asymmetry result in the regular 2-D model is introduced by the asymmetric mesh instead of the nature of CHIEF system. The Computational fluid dynamics (CFD), AC/DC, and Heat Transfer module were used to solve the system, which included the implementation of all the governing equations and principles discussed in section 3. A multiphysics coupling was added to ensure that the heat source in the heat transfer module came from the high voltage electric current. After setting up the boundary conditions at steady state, the differential equations were solved numerically within each finite element. The studied flow rate of the liquid, 2 L/min, was chosen to reach turbulence, which had Reynolds number greater than 3000 (Geankoplis 2003). Simulations were performed using water as the target fluid.

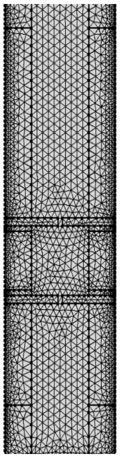

Figure 4 Mesh created for regular 2-D model

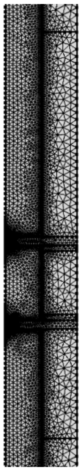

Figure 5 Mesh created for symmetric model

3.4 Governing Principles and Equations

3.4.1 Fluid Mechanics

The velocity profile of the liquid fluid can be determined through the continuity equation and the Navier-stokes equation (Navier 1827, Stokes 1845).

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

$$\rho \frac{\partial v}{\partial t} = -\nabla P + \eta \nabla^2 v + \rho g \quad (2)$$

where v is the velocity (m/s), η denotes the viscosity $(\mathrm{kg/m \cdot s})$, ∇ is the Laplace operater and ρ is the density (kg/m^3).

Turbulence of the flow is important in electric bacterial inactivation due to the high desired mass flow in industrial point of view (Knoerzer et al. 2011) and preventing hot temperature spots (Schroeder et al. 2009). The k-ϵ model is used to provide an accurate solution for turbulent flow by introducing turbulent viscosity η_T into the system (Multiphysics 2007). Hence equation (2) can be modified into:

$$\rho \frac{\partial v}{\partial t} = -\nabla P + \nabla \cdot [(\eta + \eta_T) \cdot \nabla v] + \rho g \qquad (3)$$

where

$$\eta_T = \rho \frac{C_\mu k^2}{\alpha_k \epsilon} \qquad (4)$$

Here, k (m^2/s^2) is the turbulence energy, ε (m^2/s^3) the dissipation rate of turbulence energy. C_μ and α_k are modeling constant, which have the values of 0.09 and 1, respectively (Multiphysics 2007).

3.4.2 Electrostatics

The electrostatics in the CHIEF reactor can be governed by the following Laplace equations.

$$\nabla \cdot J = Q_j \qquad (5)$$

$$J = \sigma E + \boldsymbol{j} \omega \boldsymbol{D} + J_e \qquad (6)$$

$$\sigma = \frac{1}{\rho_0 (1 + \alpha (T - T_{ref}))} \qquad (7)$$

$$E = -\nabla U \qquad (8)$$

where J (A/m^2) denotes the current density, σ (S/m) is the electric conductivity of the material, E (kV/m) is the electric field, U is the electric potential in kV, Q_j (A/m^3) is the energy value of the current source. Since AC power is added in this system, the time-harmonic equation of continuity is applied, which includes the frequency term ω (Hz) into the system (Kirsch and Hettlich 2009). Note that **j** and **D** are vectors associated with the current density and electric displacement field, which accounts for the effects of free and bound charge within materials (Cheng 1989). The electric conductivity is defined by a linear interpolation with temperature, and is described by equation (7), where $\rho_0(\Omega \cdot m)$ is the reference resistivity at T_{ref}, and α is the resistivity temperature coefficient.

3.4.3 Heat Transfer

Solving the temperature profile in CHIEF system involves heat transfer in both solid and fluid domains. The primary reason that causes temperature rise in this system is joule heating from the electric heat source, which can be characterized by equations (8) and (9), respectively.

$$\rho C_p \mathbf{v} \cdot \nabla T = \nabla \cdot (k \nabla T) + Q_e \qquad (9)$$

$$Q_e = J \cdot E \qquad (10)$$

where ρ is the density (kg/m^3), C_p denotes the heat capacity in $\mathrm{KJ/(kg \cdot °C)}$, and Q_e (W/m^3) is the electromagnetic heat source. The heat flux q from solid to liquid can be determined by:

$$q = -\boldsymbol{n} \cdot (-k\nabla T) = h \cdot (T_{ext} - T) \qquad (11)$$

where k $(\mathrm{W/(m \cdot K)})$ is the thermal conductivity, h $(\mathrm{W/(m^2 \cdot K)})$ is the heat transfer coefficient and T_{ext} and T are the surface temperatures from the solid and liquid side. Note that $\boldsymbol{n}$ is the unit vector that determines the direction of the heat flux.

3.4.4 Boundary Conditions

The fluid flow boundary condition at the inlet is

$$v = -\boldsymbol{n} v_0 \qquad (12)$$

where v_0 is the initial velocity of the flow into the reactor. The boundary velocity is set as zero at the wall.

For heat transfer in fluid, the boundary condition is set as

$$T = T_0 \qquad (13)$$

for the flow at the inlet, where T_0 is the feed temperature, 293 K in this case.

The boundary condition at the wall of the solid part can be described by

$$-\boldsymbol{n} \cdot (-k\nabla T) = Q_e \qquad (14)$$

Indicating that only the heat transfer from the electric source is studied.

3.5 Results and Discussion

3.5.1 Fluid Characteristics

Figure 10 presents the cross sectional velocity profile of fluid in the CHIEF reactor. The flow in CHIEF reactor can be characterized as Newtonian flow in pipe with changing diameter. As flow passes through the narrow liquid chamber, the flow rate will have a dramatic increase since diameter become smaller. At the selected flow rate, 2 L/min, the peak velocity magnitude will increase up to 60 m/s in the center of the narrow chamber. Flow rate becomes slower towards the side due to friction from the wall. From the r-direction velocity profile, it can be observed that swirls are formed between the two treatment channels due to the changing of diameter between 13 mm and 1 mm in the reactor, which could be a potential limitation of the CHIEF process.

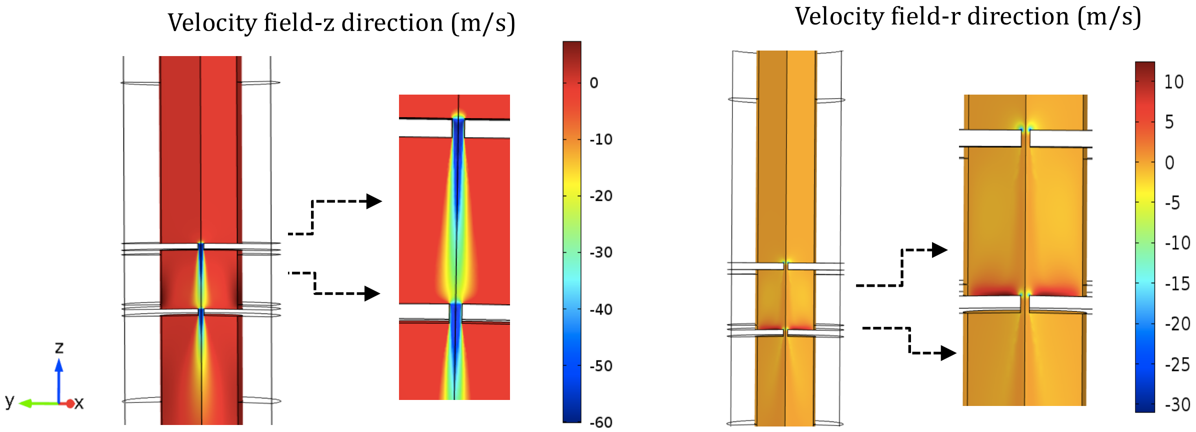

Figure 6 Velocity profile of liquid flow in CHIEF reactor (both z and r direction)

3.5.2 Electrostatics

Figures 11 and 12 shows the electric potential and electric field strength distribution in CHIEF reactor under the applied voltage of 10 kV. As expected, most of the electric potential drop happens across the dielectric material layer. From figure 12, it is clear that the highest electric field strength occurs in the dielectric material channel, which agrees with assumptions and derivations in previous literature (Ruan, Deng et al. 2011). The concentrated electric field in the dielectric channel has a low-to-high gradient from the center to the side. The maximum electric field that has been applied directly on the treated fluid is greater than 4000 kV/m. Equation (8) indicates that the electric field strength is directly related to the electric potential in each finite element. Comparing with the similar PEF technology, the small dielectric chamber in

CHIEF technology makes it possible to generate concentrated electric field with higher electric intensity. The maximum electric field strength reported for cylindered PEF treatment chamber is 70 kV/m at under the applied voltage greater than 10 kV (Schroeder, Buckow et al. 2009, Buckow, Schroeder et al. 2010, Knoerzer, Baumann et al. 2012). Lastly, it can be seen from figure 12 that reactor structure can prevent media-metal contact in the intensive electric field region, avoiding the electrode erosion and contamination.

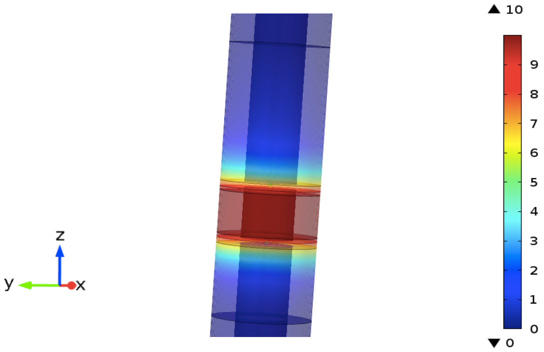
Electric potential (kV)

Figure 7. Electric potential distribution in CHIEF reactor

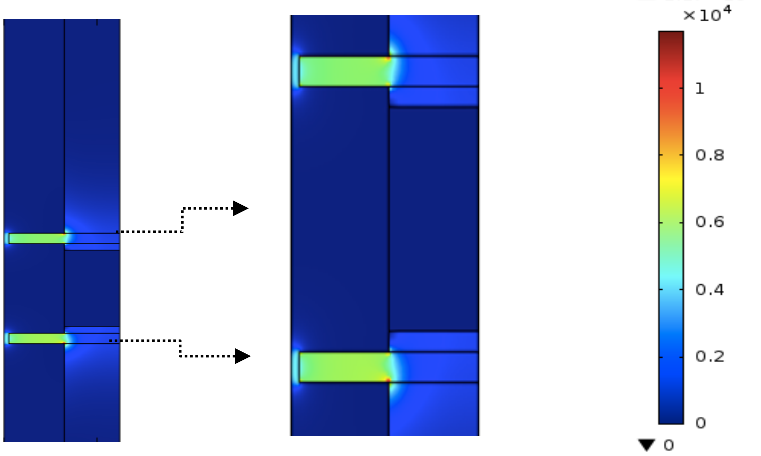
Electric field strength (kV/m)

Figure 8. Electric field strength distribution in CHIEF reactor

3.5.3 Heat Transfer

For non-thermal inactivation of bacteria in food, temperature rise in the CHIEF system is important parameter to control. As stated in previous sections, the primary heat source in the CHIEF reactor is electric heating from the high intensity electric field. Figure 13 shows the temperature profile in CHIEF reactor using water at temperature of 299.25 K, flow rate of 2 L/min, under the voltage of 10 kV (10 KHz). The simulation results show that the highest temperature spots occur at the contact point between liquid and the dielectric materials. The liquid is heated by the concentrated electric field due to the joule heating effect after it passes through the dielectric channel. As expected, the highest temperature hot spots occur at the contact point between the dielectric material and liquid (Liu 2014). After liquid is treated in the dielectric channel, temperature gradient appears from the center to the side of the reactor, which matches the result predicted from section 4.1.2. In the dielectric channel, liquid at the center is treated by lower electric field strength than liquid close to the side. Since electric field strength ranges from low (at the center) to high (at the side) in the dielectric channel, it is clear from equations (8) and (9) that greater temperature rise is caused by higher electric field strength.

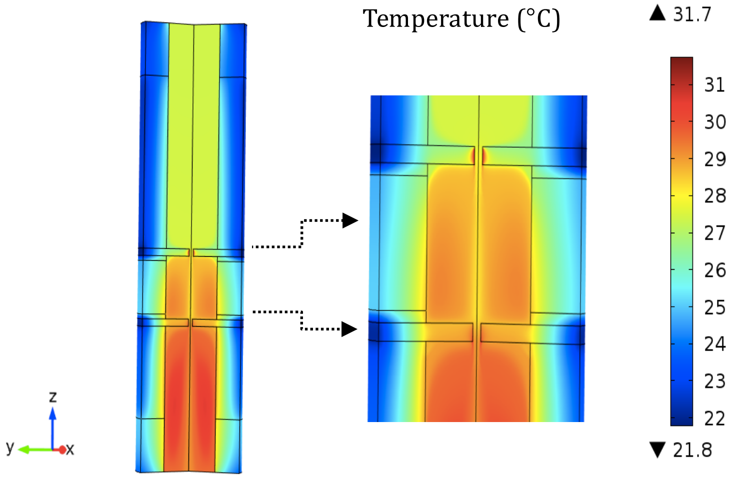

Figure 9. Temperature profile in CHIEF reactor

3.6 Model Validation

3.6.1 Experimental Procedure

E. *coli* strain ATCC 25922 was first streaked into L.B agar plates, incubated for 3 days. Then a colony from the plate was inoculated into 150ml of L.B. media in a 200ml shake flask. The flask was incubated at 37°C for approximately 48 hours. Diluted culture using DI water was passed through the CHIEF system described in section 3.2. Temperatures, electric conductivity and initial bacteria count were measured before the culture was treated. Temperature and final bacteria count for the output product were measured. Bacteria count data was determined using the 3M petrifilm dish (3M, USA).

15 sets of experiments at different conditions were conducted. The flow rate was controlled at 2 L/min to ensure turbulence inside the reactor. The diameter of the treatment chamber was 1 mm. Water electric conductivity was adjusted between the range of 60 us/cm to 150 us/cm by inoculating different amount of overnight E. *coli* into water. Electric voltage was controlled from 8 kV to 10 kV and the frequency was 60 Hz.

3.6.2 Result and Discussion

Table 6 shows the experimental conditions and the results of CHIEF's pasteurization process. As shown in the figure, CHIEF treatment provides effective log reduction to E.coli ATCC 25922 in water. The plots of log reduction verses feed temperature, voltage, electric conductivity and delta T are shown in figures 4 to 7. The plots indicate that the log reduction is not directly correlated to feed temperature or voltage. However, the bacterial kill of E.coli has the tendency to increase with electric conductivity and temperature rise. This is reasonable as temperature rise caused by joule heating can partially reflect the intensity of electric field treatment, which is then directly related to the log reduction data. Note that even though the linear model has a relatively good fit (R^2=0.87) to the log reduction vs. delta T data, temperature rise is not considered as a source of pasteurization. The small temperature rise is not able to result in greater than two-log reduction, especially with residence time less than one second in CHIEF's treatment chamber.

Table 6 Conditions and results for validation experiments

Run	Feed Temp (C)	Voltage (KV)	Electric conductivity (us/cm)	Delta T (C)	Log Reduction (-log CFU/ml)
1	19.6	9	147.3	9.6	5.99
2	19.8	8	180.8	9.55	6.32
3	24.2	10	68.2	4.95	2.7
4	23.4	10	98.3	9.15	5.97
5	22.5	10	105.5	9.125	6.87
6	23.5	10	101.4	9.625	6.72
7	26	10	75.1	6	3.48
8	25.6	10	81.3	6.6	4.06
9	26.1	10	90	8.025	5.91
10	25.9	9	127	8.75	6.11
11	23	10	108.6	9.7	6.87
12	21.2	9	122.3	8.8	6.53
13	23.8	9	131.3	9.275	6.04
14	21.9	9	135	9.725	6.85
15	21.1	9	138.2	9.525	5.53

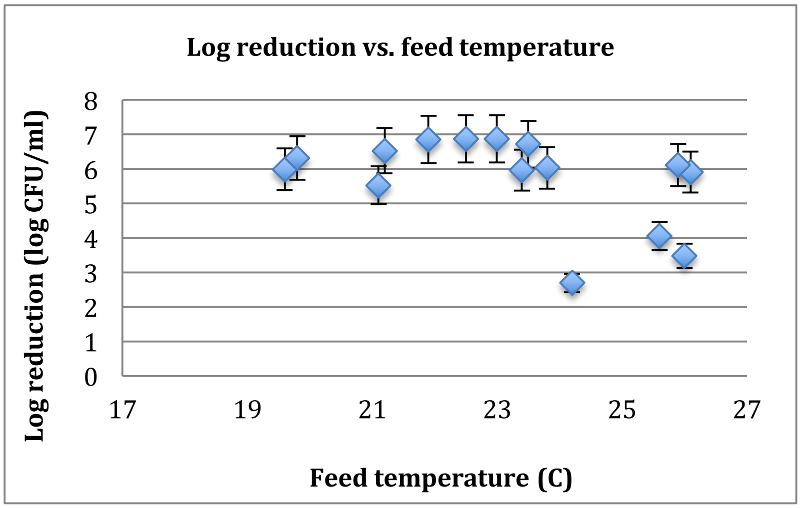

Figure 10 Plot of log reduction vs. feed temperature

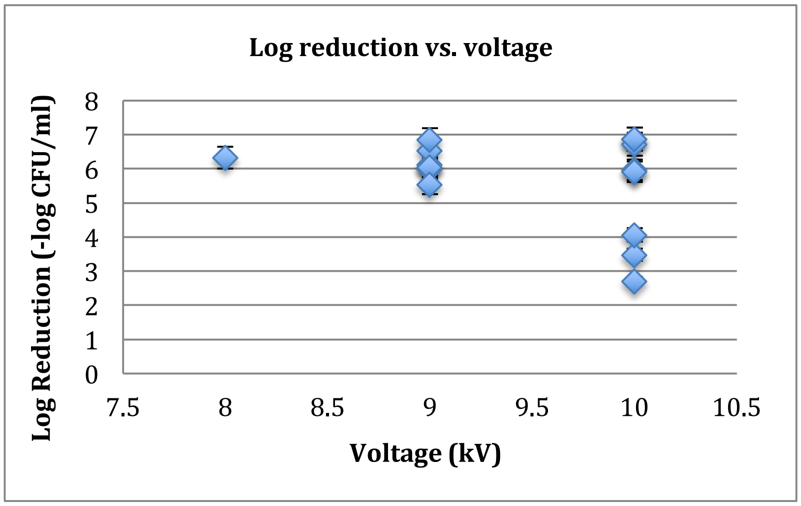

Figure 11 Plot of log reduction vs. voltage

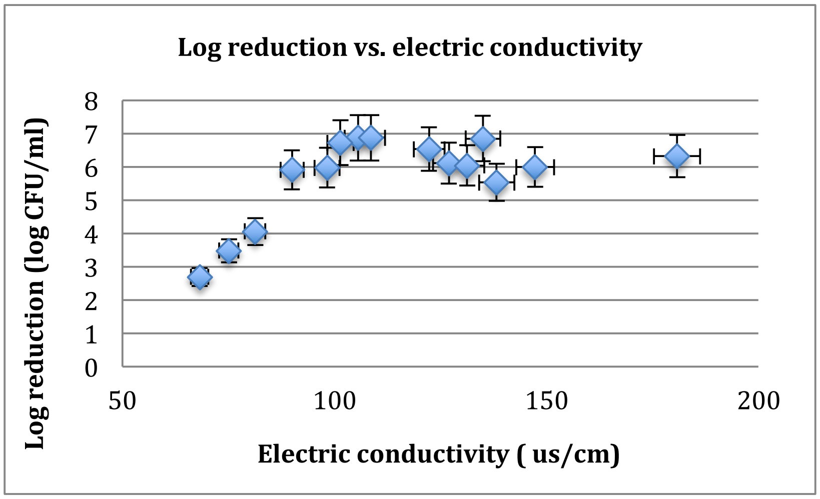

Figure 12 Plot of log reduction vs. electric conductivity

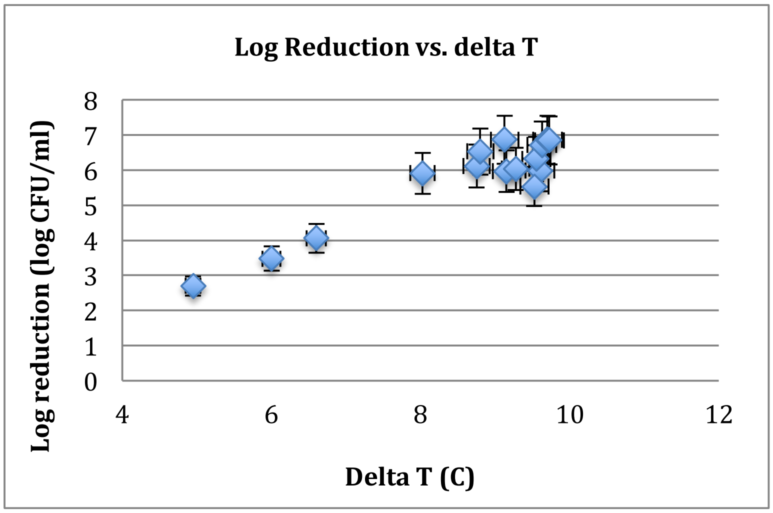

Figure 13 Plot of log reduction vs. delta T

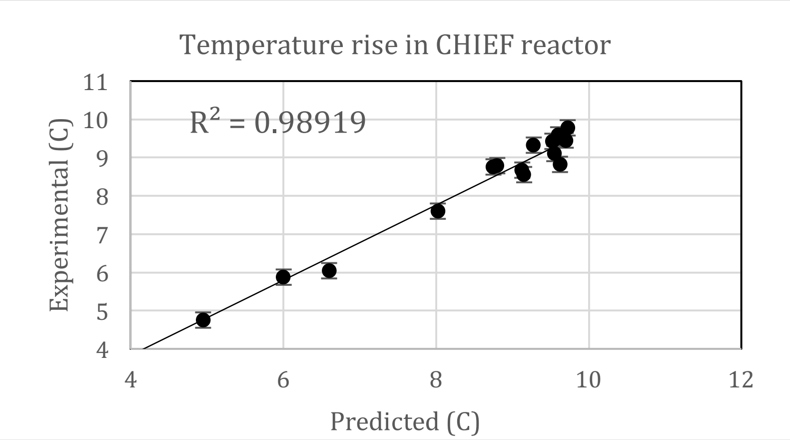

Figure 14. Experimental temperature rise in CHIEF reactor verses predicted value from the simulation

3.6.3 Conclusion

Validity of the model is tested by fitting the experimental results to the predicted ones from this model. Temperature rise is chosen as the comparison parameter as it is the most straightforward and representative output from this experiment. From figure 14, it is clear that experimental results were in a good agreement with the model. The small discrepancies may come from displacement of the thermocouple or the roughness of the wall, which will cause changes in velocity profile. The determined r square value from the plot is greater than 0.98, which indicates that the simulations can accurately describe the fluid behavior in CHIEF reactor. It is notable that log reduction from 3 to 6 were observed during the test of model validation.

Meanwhile, concentrated high intensity electric field (CHIEF) is a novel and promising way to inactivate bacteria in liquid food under non-thermal conditions. Experimental results in this study reconfirmed CHIEF's pasteurization effects on E.coli ATCC 25922 under various conditions. CHIEF is able to provide greater than 5 log reduction to the E.coli strain under non-thermal conditions. Comparing with the treatment conditions of pulsed electric field listed in section 2.3, CHIEF technology has the advantage of utilizing continuous power supply with lower voltage, which reduces the cost and avoids some scale-up issues.

3.7 Effects of Controlled Parameters

To ensure nutritional value in liquid food products are not damaged during the inactivation process while maintaining an acceptable log reduction, temperature rise and electric field strength are two extremely important variables to monitor. As discussed previously, these two dependent variables are affected by many parameters. In this section, the effects of different controlled parameters are studied using the simulation. In the CHIEF process, the important extrinsic independent variable is the applied voltage; while the intrinsic parameters include temperature, feed flow rate, viscosity and electric conductivity of the feed liquid.

3.7.1 Effect of Intrinsic Properties

Figure 15 shows the effect of electric conductivity on temperature rise and center electric field strength provided by the validated simulation at the flow rate of 2 L/min and applied voltage of 10 kV. From equation (7) and previous derivations (Ruan, Deng et al. 2011), electric conductivity has negligible effect on the electric field strength. However, equations (5) and (6) show that the electric conductivity can result in greater energy to the current source, which will further cause larger temperature rise to the liquid.

The effects of other intrinsic parameters including flow rate, and initial feed temperature are shown Figure 16 under the same extrinsic conditions. As expected, higher flow rate will result in less temperature rise due to smaller contact time for heat transfer. When feed flow rate is less than 2 L/min, the liquid flow falls in the laminar region with Reynolds number lower than 3000. It can also be reflected from Figure 16 that in laminar region, the changes of temperature rise are more dramatic than in the turbulent region. Even though turbulence can induce stability into the system, less treatment time caused by high velocity can lead to lower log reduction. Thus volumetric flows higher than 3 L/min are not recommended. The influence of feed temperature to the system is mainly through its effect on the liquid’s electric conductivity (Frenkel' 1955, Faber 1966, Buckow, Schroeder et al. 2010), which can be referred back to Figure 15 according to the actual electric conductivity measured.

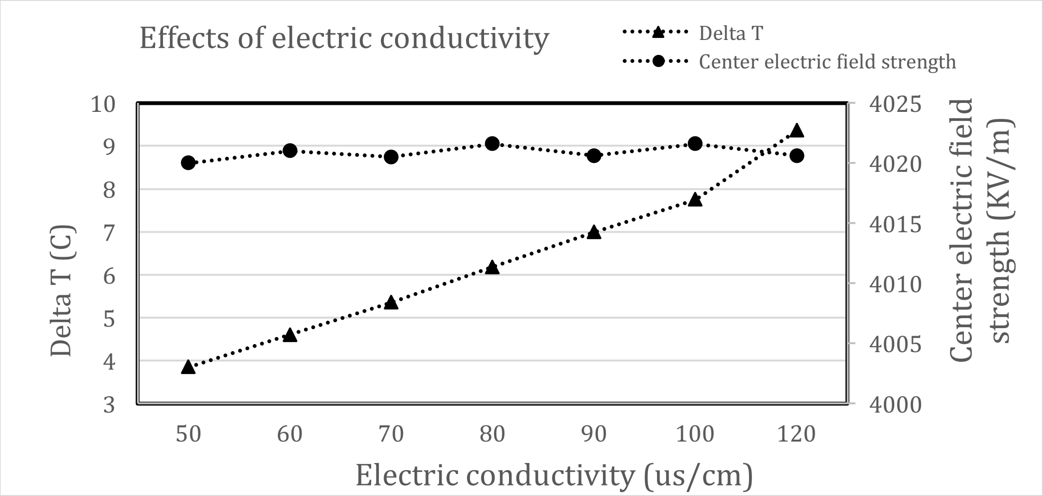

Figure 15. Effects of eletric conductivity on the performance of CHIEF reactor

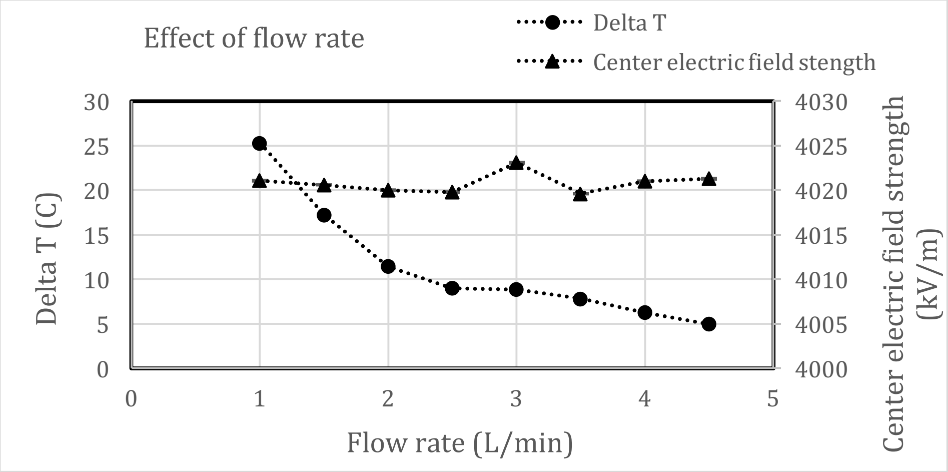

Figure 16. Effects of liquid flow rate on the performance of CHIEF reactor

3.7.2 Effects of Extrinsic Properties

Figure 17 shows the effects of the applied voltage on the dependent variables. It is clear from equation (7) that the electric field is directly related to voltage under fixed configuration between ground and high potential electrodes. Furthermore, at the same spot of interest, electric field strength should have a linear relationship against the applied voltage. Similarly, higher electric field strength will lead to larger current density and dissipation energy. Thus the outlet temperature should increase with the applied voltage. The influence of channel diameter is shown in Figure 18, which is another important extrinsic parameter. Even the circular design of treatment chamber has proven to provide best stability and uniformity of the electric field (Fiala, Wouters et al. 2001, van den Bosch 2007), changes in the diameter of the treatment channel will influence on the system's performance. Figure 18 shows the effects of different channel diameters on the temperature rise and center electric field strength. The simulation results show that the less temperature rise and greater center electric field strength occurs when small-diameter channel is used. However, this will result in larger velocity increase, which will leads to less treatment time in the reactor.

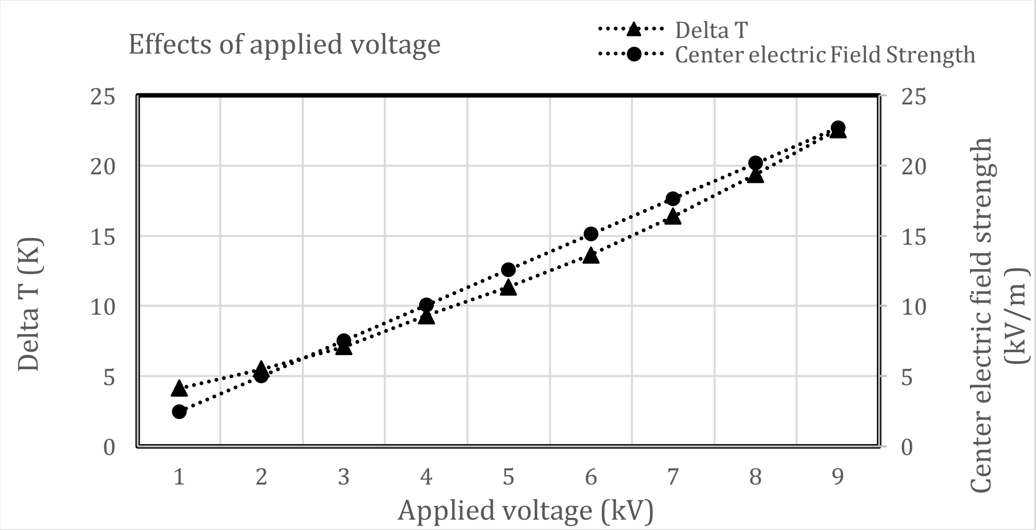

Figure 17. Effects of applied voltage on the performance of CHIEF reactor

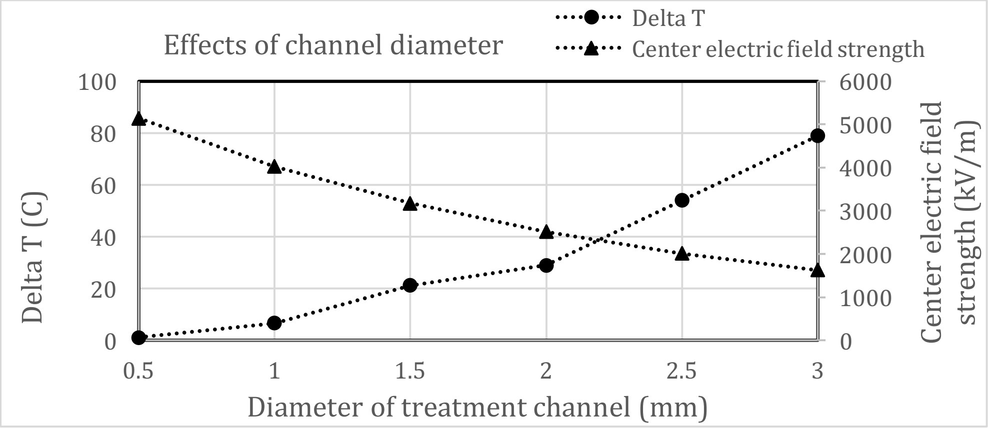

Figure 18. Effects of treatment channel diameter on the performance of CHIEF reactor

3.8 Conclusion

CHIEF's unique structure allows electric field to be concentrated in the dielectric treatment chamber of a CHIEF reactor. The resulting electric field strength is of more than 10 times higher than pulsed electric field (PEF) systems with similar scale (Schroeder, Buckow et al. 2009, Buckow, Schroeder et al. 2010, Knoerzer, Baumann et al. 2012), at the same time providing effective log reduction in pathogens. Modeling and simulation in this study provides an accurate estimate on the fluid characteristics, electrostatics and heat transfer within the system and can be used in the future for a better design and control of the system.

The evaluation of the performance of CHIEF technology includes bacteria inactivation and temperature rise. These two parameters are primarily governed by electric field strength, heat transfer, and treatment time, which are further related to voltage, channel diameter, flow rate etc. By analyzing the complex relations between these variables and their influences on bacteria reduction performances, optimization of the CHIEF technology can be performed in the next step. The modeling and simulation techniques developed from this study can be used to control and adjust the intrinsic and extrinsic parameters to reach the desired experimental conditions. Some treatment conditions of different liquid food fed at 4 °C, 2 L/min represented by the model are shown in table 7 under standard electrical properties (Zhang 1995).

Table 7 Recommend treatment conditions for selected liquid food products

Food material	Channel diameter (mm)	Applied voltage (kV)	Outlet temperature (°C)	Electric field strength (kV/cm)
skim milk	2	2	61	5.0
skim milk	1	4.6	59	18.9
beer	2	3.3	59	8.3
beer	1	9	60	36.5
Black coffee	2	3.2	57	8.0
Black coffee	1	7.8	61	31.7
Apple juice	2	2.5	59	6.3
Apple juice	1	6.3	59	25.7
Lemonade	2	3.9	61	9.8
Lemonade	1	8.8	60	35.7
Tomato juice	2	1.4	59	3.5

Tomato juice	1	2.3	60	9.7

Chapter 4. Comparisons, Conclusions and Future Perspectives

4.1 Comparison between non-thermal pasteurization technologies

4.1.1 Comparison between high pressure and electric field treatments

As mentioned in previous chapters, high pressure and electric field are two most common and effective non-thermal pasteurization technologies. These two technologies can be considered as physical pasteurization methods as no chemicals are introduced. Another similarity between high pressure and electric field is the limitation of improvements by intensifying treatment conditions. For example, improvements by increasing pressure and pass number will not be significant as they reach a certain level (Donsì, Ferrari et al. 2009). On the other hand, studies modeling the inactivation kinetics in PEF technology suggest that increasing parameters such as electric field strength will not be effective above a certain limit (Huang, Yu et al. 2014). Lastly, both high pressure and electric field pasteurization inevitably cause temperature rise. However, the increase in temperature is not significant and can be controlled with proper cooling strategies and will not affect food functionalities.

Different heat sources are responsible the temperature rise in high pressure and electric field treatments. In high-pressure treatments, temperature is increased due to the dissipated kinetic energy of piston into liquid food, while the primary heat source in electric field is joule heating (Donsì, Ferrari et al. 2009, Knoerzer, Baumann et al. 2012). Currently, high-pressure processes including high hydrostatic pressure and dynamic high-pressure treatment are relatively more industrial adopted than electric field pasteurization due to its high energy input in large scale operation (Guionet, David et al. 2015).

4.1.2 Internal comparison between non-thermal pasteurization methods

All the non-thermal pasteurization methods described in this thesis are effective and have different applications. High hydrostatic pressure is suitable for large-scale, batch operation in food industry. It can be applied to pasteurize both solid and liquid food, as well as change the foods functionalities. On the other hand, dynamic high-pressure treatment can only be applied to liquid food but owns the advantage of continuous processing. It is also widely used in emulsification, and extraction of nutrients in food products. In addition, high hydrostatic pressure offers larger pressure treatment range than dynamic high-pressure treatment.

Comparing with concentrated high intensity electric field (CHIEF), pulsed electric field (PEF) has been more thoroughly investigated in the past years. PEF system has recently been used in industry in a few studies (Toepfl 2011). However, since PEF uses DC electric pulses, an industrial pulse generators are required for large-scale PEF systems (Loginova et al. 2011). Even though CHIEF is an innovative process that has not yet industrialized, its ability of using AC current with medium to low frequency and voltage can avoid the use of pulse generator. Moreover, CHIEF's low operational voltage and frequency make its pilots system suitable to small-scale liquid food producers. However, the small treatment diameter of CHIEF system may cause swirling of liquid. On the other hand, one of the major accomplishments in the latest PEF processing chambers is to have treatment cells that have the same diameter as the piping system (Buckow, Baumann et al. 2011, Medina-Meza and Barbosa-Cánovas 2015). A summative table is shown below for the comparisons between the non-thermal technologies.

Table 8 presents a more detail comparison between CHIEF and PEF systems with similar scale. Results in the table show that the energy requirement for CHIEF technology is less than PEF systems with similar scale studied in previous literature (Liu et al. 2013, Qin et al. 2014, Grimi et al. 2014). Continuous AC power supply used by CHIEF is more accessible than the high voltage pulsed generator for PEF technology.

Table 8 Comparison of non-thermal technologies

	High hydrostatic pressure	**Dynamic high pressure treatment**	**Pulsed electric field**	**Concentrated high intensity electric field**
Advantages	Large scale; High pressure (up to 800MPa); Able to treat both liquid and solid	Semi-continuous; Widely used in change of functionalities	Continuous treatment; Greater control of parameters; Effective log reduction at low temperature	Continuous treatment; Effective log reduction at low temperature; Medium to low voltage & frequency AC power supply; Less electrode erosion and

				contamination
Disadvantages	Mostly batch operation; High temperature rise associated to high pressure	Relatively low pressure (450 MPa); Can only treat liquid food or small particle size food	High voltage; DC electric current; Large energy input	Might cause swirling due to small diameter; Preliminary stage to pilot scale (not yet industrialized)

Table 9 Comparison between CHIEF and PEF systems with similar scale

	PEF	**CHIEF**
Treatment conditions for >3 log reductions	20 kV to 50 kV	3 kV to 10 kV
Maximum electric field strength	40 kV/cm at U = 40 kV 40 kV/cm at U = 40 kV 33.3 kV/cm at U = 30 kV	Able to reach 40 kV/cm at U< 10 kV
Energy requirement	13.3 to 53.1 kJ/kg	13 kJ/kg

4.2 Conclusion and future perspectives

In conclusion, each of the non-thermal technologies discussed has its unique field of use. Among these technologies, high hydrostatic pressure (HHP), dynamic high-pressure treatment and pulsed electric field (PEF) are non-thermal methods that have been widely used and studied in the past. Concentrated high intensity electric field (CHIEF) is a non-thermal liquid food pasteurization process developed to be an alternative to PEF technology. CHIEF's unique structure allows it to become a promising non-thermal pasteurization technology, especially for individual liquid food producers. The modeling and simulation techniques developed from this study are accurate and can be used to better control and adjustments of CHIEF system, preventing unnecessary damage of nutrients in food. However, its detailed inactivation kinetics is a problem to be solved. In the future, more modeling can be performed to predict the accurate log reduction under various conditions. In addition, CHIEF's innovative application can be studied along with its combined use of other food treatment methods.

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