UNIVERSITI PUTRA MALAYSIA

DEAN VORTEX ULTRAVIOLET LIGHT PASTEURIZATION OF PUMMELO (CITRUS GRANDIS L. OSBECK) FRUIT JUICE

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By

NOR NADIAH ABDUL KARIM SHAH

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfillment of the Requirements for the Degree of Doctor of Philosophy

August 2015

Dedicated to my beloved;

husband Ir Dr Mohd Khair Hassan
parents; Hj Abdul Karim Shah & Hjh Asiah Marthan Shah
sons; Muhammad Iman & Muhammad Naim
daughter Mia Sarah
parents and siblings

Abstract of thesis submitted to the Senate of Universiti Putra Malaysia in fulfilment of the requirement for the Degree of Doctor of Philosophy

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Chairman : Russly Abdul Rahman, PhD
Faculty : Engineering

Pummelo juice has long been believed to have a connection with good health, due to their antioxidant potency and plasma lipid metabolism. Therefore, giving Malaysia an attractive opportunity to expand its influence and marketability in the international market of juices. However, conventional thermal pasteurization has been known to induce unfavorable changes to fruit juice. Thus, ultraviolet (UVC) light system is introduced as an alternative non-thermal pasteurization method to pummelo fruit juice as it is deemed suitable due to its small carbon footprints with other contributing factors such as cost saving, environmental friendly and non-toxic.

The overall aims of this research was to pasteurize pummelo fruit juice using a dean vortex UVC system to produce a healthy and safe juice with its original nutritional content intact. Therefore, the research was done in stages; where the first stage was to choose an optimum pummelo variety suitable for juice production. In the second stage, clarification treatment was done on the chosen variety to increase the clarity and subsequently, lowering the absorption coefficient of pummelo fruit juice with minimal pectin methylesterase activity. Hence forth, performance of dean vortex UVC reactor was experimentally validated with the results of Computational Fluid Dynamics (CFD) to evaluate the reactor's pasteurization efficiency. In the forth stage, the ability of this technology was evaluated to inactivate *Salmonella typhimurium* to a minimum of $5\log_{10}$ reduction. The technology was further exploited in the fifth stage, with investigation of post-UVC treatment effect on physicochemical characteristics, antioxidant capacity and most importantly, furan development of clarified pummelo fruit juice. These areas have not been explicitly explored in specifics to pummelo fruit juice in previous literatures.

From the study, UVC fluence was observed to be absorption-coefficient-dependent where, it varies according to liquid samples. UVC fluence was found to be highly correlated (R^2 = 91%, $p < 0.05$) towards retention time distribution (RTD), following Lambert-Beer's equation, which implies the UVC transmission throughout the clarified juice is ideal. The results from computational fluid design has validated the previous result that clarified juice with low absorption coefficient emulated an ideal liquid where the centrifugal forces that act on the juice is higher, thus creating an ideal mixing

condition within the convoluted tube. Low velocity demonstrated by fresh juice sample, had increased the total heat transfer rate which in turn increased the processing cost and elevating temperature which could render UVC pasteurization futile. UVC fluence was observed to be inversely proportional to velocity, temperature and liquid flow rate. Therefore, in order to produce an effective UVC pasteurization, combination of high flow rate with adequate RTD is imperative to stabilize the temperature of UVC-treated sample.

UVC fluence of 28.15, 27.63 and 133 mJ/cm^2 respectively for fresh, clarified juice and distilled water was observed to be adequate to inactivate with more than 5log$_{10}$ inactivation after one-pass of UVC treatment. *Salmonella typhimurium* reduction was also observed to be inversely proportional to liquid's flow rate with coefficient of determination, R^2 ranged from 83 to 99%. Moreover, coefficient of determination, R^2 of processing energy to inactivate *Salmonella typhimurium* in clarified juice was found to be higher (99%) and significant ($p < 0.05$) in comparison to fresh juice (93%). Post-UVC treatment, color L^* was seen to increase as pectin methylesterase activity in the UVC-treated juice had decreased ($p < 0.05$). In addition to that, ascorbic acid content was observed to decrease together with total phenolic contents and total soluble solids. UVC treatment also had a significant ($p < 0.05$) effect on the amount of antioxidant capacity of UVC-treated pummelo juice (DPPH, FRAP and ABTS) and its decrement is highly correlated to UVC-treatment and storage life. Furan development within the juice post-UVC treatment (between 0.66 to 2.4 ppb/ml) was seen to be dose and temperature-dependent ($p < 0.05$). However, the amount of furan found in the UVC-treated juice was deemed minimal in comparison to data published on thermally-treated fruit juice. Thus, clarified pummelo juice with absorption coefficient, α of 17 cm^{-1} can be safely treated with a maximum of 30 mJ/cm^2 UVC fluence using dean vortex UVC system and its storage life was prolonged to 6 weeks in comparison to less than a week for freshly-squeezed non-pasteurized pummelo fruit juice.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi syarat keperluan untuk Ijazah Doktor Falsafah

PEMPASTEURAN JUS LIMAU BALI (*CITRUS GRANDIS* L. OSBECK) MENGGUNAKAN CAHAYA ULTRAUNGU DEAN VORTEKS

Oleh

NOR NADIAH ABDUL KARIM SHAH

Ogos 2015

Pengerusi : Russly Abdul Rahman, PhD
Fakulti : Kejuruteraan

Jus limau bali telah lama dipercayai mempunyai hubungan dengan kesihatan yang baik, yang disebabkan oleh potensi antioksidan dan metabolisme lipid plasma yang tinggi. Ini memberikan Malaysia peluang yang menarik untuk mengembangkan pengaruh dan kebolehupayaan pemasaran di pasaran jus antarabangsa. Walaubagaimanapun, kaedah pempasteuran haba konvensyenal telah diketahui akan mendorong perubahan yang tidak baik kepada jus buah. Oleh itu, sistem cahaya ultraungu (UVC) telah diperkenalkan sebagai kaedah alternatif pempasteuran bukan terma untuk jus limau bali yang sesuai kerana mempunyai 'carbon footprints' yang kecil dengan faktor-faktor penyumbang yang lain seperti penjimatan kos, mesra alam dan tidak bertoksik.

Keseluruhan matlamat kajian ini adalah untuk mempasteurkan jus limau bali menggunakan cahaya ultraungu dean vorteks untuk menghasilkan jus yang sihat dan selamat dengan kandungan nutrisi yang utuh. Oleh itu, kajian ini telah dilakukan secara berperingkat-peringkat; di mana peringkat pertama adalah untuk memilih variti limau bali yang paling sesuai untuk penghasilan jus. Pada peringkat kedua, rawatan penjernihan telah dilakukan ke atas variti yang dipilih untuk meningkatkan kejernihan dan seterusnya, mengurangkan pekali penyerapan jus limau bali jus serta meminimumkan aktiviti pektin methylesterase. Selanjutnya, prestasi reactor cahaya ultraungu dean vorteks telah disahkan secara eksperimen dan menggunakan perisian komputer "*Computational Fluid Dynamics*", sekaligus menilai keupayaan reaktor UVC untuk mempasteur jus. Pada peringkat seterusnya, keupayaan teknologi ini telah dinilai untuk membunuh *Salmonella typhimurium* kepada $5\log_{10}$ pengurangan minimum. Teknologi ini dieksploitasi pada peringkat kelima, dengan penyiasatan kesan pasca-rawatan kepada ciri-ciri fizikokimia, kapasiti antioksidan dan yang paling penting, penghasilan furan pada jus buah limau bali yang dijernihkan. Melalui fakta dapatan, bidang penyelidikan ini jelas masih belum diterokai secara khusus untuk jus buah limau bali sebelum ini.

Melalui kerja penyelidikan yang dilakukan, dos UVC diperhatikan bergantung kepada pekali penyerapan yang berbeza-beza mengikut jenis sampel cecair. Dos UVC juga didapati berkait rapat (R^2 = 91%, $p < 0.05$) dengan pengagihan masa pengedaran (RTD), mematuhi persamaan Lambert-Beer, yang mengimplikasikan penghantaran UVC ke

seluruh jus yang telah dijernihkan adalah ideal. Hasil kajian daripada simulasi pengiraan reka bentuk bendalir (CFD) juga menunjukkan jus yang telah dijernihkan dengan pekali penyerapan rendah mencontohi cecair ideal di mana daya empar yang bertindak ke atas jus adalah lebih tinggi, sekali gus mewujudkan keadaan pencampuran ideal dalam tiub yang berbelit-belit. Halaju rendah yang dipamerkan oleh sampel jus limau bali segar, telah meningkatkan jumlah pemindahan haba yang seterusnya meningkatkan kos pemprosesan dan meningkatkan suhu yang boleh menyebabkan pempasteuran UVC sia-sia. Dos UVC diperhatikan berkadar songsang dengan halaju, suhu dan kadar aliran cecair. Oleh itu, untuk menghasilkan pempasteuran UVC berkesan, gabungan kadar aliran yang tinggi dengan pengagihan masa pengedaran yang mencukupi adalah penting untuk menstabilkan suhu sampel yang dirawat UVC.

Dos UVC yang berjumlah 28.15, 27.63 dan 133 mJ/cm^2 masing-masing untuk jus limau bali segar, jus limau bali yang telah dijelaskan dan air suling diperhatikan mencukupi untuk sepenuhnya membunuh *Salmonella typhimurium*, dengan kemusnahan lebih dari 5log$_{10}$ selepas satu-pas 30 Hz UVC. Pengurangan log *Salmonella typhimurium* juga dilihat berkadar songsang dengan kadar aliran cecair dengan pekali penentuan, R^2 antara 83 - 99%. Selain itu, pekali penentuan, R^2 pemprosesan tenaga untuk membunuh *Salmonella typhimurium* dalam jus yang telah dijelaskan didapati lebih tinggi (99%) dan ketara berbanding dengan jus segar (93%). Pasca rawatan UVC, warna L^* dilihat meningkat kerana aktiviti pectin methylesterase dalam jus yang dirawat UVC telah menurun ($p < 0.05$). Tambahan pula, kandungan asid askorbik diperhatikan berkurangan bersama-sama dengan jumlah kandungan fenolik dan jumlah pepejal larut. Seterusnya mengurangkan jumlah kapasiti antioksidan jus pummelo yang dirawat UVC (DPPH, FRAP dan ABTS) dan susutan tersebut berkait rapat dengan rawatan UVC dan kadar simpanan. Penghasilan furan dalam jus yang dirawat UVC (antara 0.66 – 2.4 ppb/ml) dilihat bergantung kepada dos dan suhu UVC ($p < 0.05$). Walau bagaimanapun, jumlah furan yang dijumpai di dalam jus limau bali yang dirawat menggunakan UVC dianggap minimum berbanding dengan data yang telah diterbitkan pada jus buah-buahan yang dirawat menggunakan haba.Oleh itu, jus limau bali yang dijernihkan dengan pekali penyerapan, α = 17 cm^{-1} adalah selamat dirawat dengan maksimum UVC dos sebanyak 30 mJ/cm^2 menggunakan sistem cahaya UVC dean vorteks dan hayat simpanan yang lebih panjang sehingga 6 minggu berbanding dengan kurang dari seminggu untuk jus limau bali segar yang tidak dipasteurkan.

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This thesis submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfilment of the requirements for the degree of Doctor of Philosophy.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

ANOVA	Analysis of Variance
AVE	Average
GC	Gas Chromatography
GLM	General Linear Model
GRAS	Generally recognized as safe
HACCP	Hazard Analysis and Critical Control Point
HDPE	High Density Polyethylene
HPLC	High Performance Liquid Chromatography
NIR	Near Infra-Red
PME	Pectin Methylesterase
ppb	parts per billion
RSM	Response Surface Methodology
STD DEV	Standard Deviation
STD ERR	Standard Error
TPC	Total Plate Count
USFDA	United States Food and Drug Administration
UVC	Ultraviolet Light

LIST OF NOMENCLATURES

Av	Avogadro's number, 6.023×10^{23} photons/Einstein
D_h	hydraulic diameter, m
De	Dean number
I	Fluence rate, mW/cm^2
I_o	Incident fluence rate, mW/cm^2
I_{av}	Average fluence rate, mW/cm^2
I_x	Fluence rate at the path length x, mW/cm^2
It	UVC fluence, mJ/cm^2
k	Inactivation constant, cm^2/mJ
L^*	lightness (+) or darkness (-)
L	Length of radiation section, cm
N_o	Concentration of viable microorganisms before exposure, CFU/mL
N_{av}	Average concentration of viable microorganisms at the outlet of the reactor, CFU/mL
N_i	Concentration of viable microorganisms at event level i, CFU/mL
P	Pressure, Pa
Q	Volumetric flow rate, mL/s
r	Radius, cm
R_1	Radius of inner cylinder, cm
R_2	Radius of lamp, cm
R^2	Coefficient of determination
Re	Reynolds number
t	Time, s

t_{av}	Average residence time,s
u	Velocity, cm/s or m/s
u_r	Radial velocity components, cm/s
u_z	Axial velocity components, cm/s
U_{av}	Average velocity, $U_{av} = Q/\pi\ (R_2^2 - R_1^2)$, cm/s
x	The path length of x coordinate, cm
α	Absorption coefficient with 10 base, cm^{-1}, $I_x = I_o \times 10^{(-\alpha x)}$
λ_w	Wavelength, m
λ	Penetration depth, cm
ŋ	Dynamic viscosity, Pa s
μ	Kinematic viscosity, m^2/s
ρ	Density, g/cm^3

CHAPTER 1

INTRODUCTION

1.1 An Overview on Ultraviolet Light System

Food preservation techniques are continuously being developed to conform to modern consumer demands for safe and healthier foods. Higher income, urbanization, demographic shifts, improved transportation and consumer perceptions regarding quality and safety are changing global food consumption (Huang, 2004). Modern consumers demand for tasty, healthier, organic, natural and fresh-like foods produced in an environmentally friendly manner with sustainable methods and small carbon footprints (Koutchma et al., 2009). As a consequence, in the past ten years non-thermal technologies have received increasing attention due to its potential for inactivating spoilage and pathogenic microorganisms (Noci et al., 2008). Recent interests in these technologies are not only to produce high-quality food with "fresh-like" characteristics, but also to provide food with improved functionalities such as being cost efficient, less carbon footprints and no harmful by-products.

Ultraviolet (UVC) light system is a non-thermal technology which has acquired interests among food researchers. Interest in this technology is mainly triggered by safety concerns on the harmful substances that are the by-products of conventional food processing. Recent studies have proved that UVC light treatment holds considerable promises in food processing as an alternative to traditional thermal treatment for liquid foods, as well as, post-harvest storage-life extension of fruits and vegetables and preservation methods for ready-to-eat foods. Compared with traditional thermal pasteurization method for liquid foods such as High Temperature-Short Time (HTST), UVC treatment does not affect the qualitative nature of the juice. Nutritional components, which are heat sensitive, are not destroyed by the UVC treatment with the added advantage of bactericidal characteristics (Koutchma et al., 2009).

UVC light is the electromagnetic spectrum between 200 to 280 nm. With its positive consumer image and low processing cost, UVC treatment is proven to be suitable for fruit juice stabilization (Koutchma, 2009). Its bactericidal mechanism is based on the absorption of UVC light by microbial DNA or RNA structures. The primary mechanism is the creation of pyrimidine dimers, which are bonds formed between adjacent pairs of thymine or cytosine pyrimidines on the same DNA or RNA strands. These dimers prevent microorganisms from replicating, further rendering them inactive and unable to cause infection (Harm, 1980).

The use of UVC light for water treatment is well established, however, the application of UVC on liquid foods presents a relatively new challenge to beverage producers. Compared to water, liquid foods have a range of optical and physical properties and diverse chemical compositions that influence UVC light transmittance, dose delivery, momentum transfer and consequently microbial inactivation. To achieve microbial inactivation, the UVC radiant exposure must be at least 400 J/m^2 in all parts of the product (Koutchma, 2009). Critical factors to ensure efficient UVC treatment include; transmissivity of the product, geometric configurations of the reactor, power, wavelength and physical arrangement of the UVC sources, product profile and radiation path length (Koutchma et al., 2009).

The United States Food and Drug Administration (USFDA) and United States Department of Agriculture (USDA) in 2000, have concluded that the usage of UVC light for food processing is safe and has further approved the usage as an alternative treatment to reduce pathogens and other microorganisms. USFDA issued Code 21CFR179.41, which approved the use of UVC light in the production, processing, and handling of food. In addition to that, National Advisory Committee on Microbiological Criteria for Foods (NACMCF) of USDA revised its definition of pasteurization for foods. This term now includes any process, treatment, or combination thereof that is applied to food to reduce the highest levels of microorganisms of significance to public health and acknowledging the usage of UVC light as an alternative method of pasteurization. Meanwhile in Malaysia, under the Food Act 1983 and Food Regulation 1985, Food Safety and Quality Division (FQSD) was formed. Food Safety and Quality Division in their jurisdictions, specified that all food manufacturers are to comply with USFDA regulation in regards to food processing. HACCP management system was the main safety procedure that is being enforced on all food manufacturers in Malaysia. Currently, the Government of Malaysia, specifically under the Ministry of Health has not publically released any Food Act specifically to alternative pasteurization methods for liquid foods and it is assumed to be following the USFDA regulations.

1.2 Problem Statement

In recent attempts to revamp the state of national agriculture production, Malaysian Ministry of Agriculture has come up with an agro-food policy commencing from 2011 to 2020. The policy has listed pummelo as one of the 15 potential tropical fruits that is expected to generate national gross income (for all 15 fruits) of RM 21.44 billion in 2020 (FAMA, 2010). One of the objectives in realizing the policy is to increase the income of entrepreneurial farmers through diversification of fruit products thus increasing Malaysia's productivity and export trade volume.

Pummelo is known to be the largest of all citrus fruits which can grow as large as thirty centimeters in diameter and weigh up to nine kilograms (DOA, 2010). Pummelo has been reported by Keshani et al. (2010), to have a number of beneficial bioactive compounds such as flavonoids, carotenoids, phenolics, vitamin C and anthocyanin. It also contains high amount of vitamin A, potassium, beta-carotene, folic acid and fiber as reported by Jayaprakasha et al. (2007). Pummelo has also been found to demonstrate anti-cancer, anti-inflammatory, anti-tumour and blood clot inhibition activities (Garg et al., 2001). Furthermore, with expected ratio of 2:1 (w/v) (Ni et al., 2014) of producing juice and a total brix to acid ratio of 12.54 (Florida's commercial juice standard: 13 to 18 (Kimball, 1999)), and its natural resistance towards pests, resulting in easier cultivation, higher productivity, and lower production cost. These characteristics make pummelo a promising candidate for production of a desirable and healthy juice for human consumption (Ni et al., 2014), further giving Malaysia an attractive opportunity to expand the fruit's influence and marketability in the international market of juices.

Currently, heat treatment process is the most commonly used method for microorganisms and enzymes inactivation which will indirectly extend the shelf life of juice. However, this process has long been known to have adverse effects on sensory and nutritional quality of food (Braddock, 1999). Various studies have proven that pasteurization using heat has caused detrimental effects towards juice quality. Nutritional contents, chemical, antioxidant and sensory attributes have been reported to

have been directly affected by the heat. Moreover, it is cost-prohibitive for small juice producers (Koutchma et al, 2004). Thus, a non-thermal method of pasteurization has been introduced to treat citrus juice to have a longer shelf-life without compromising on the fresh-like quality of juice with addition to its potential for inactivating spoilage and pathogenic microorganisms (Noci et al, 2008).

UVC light can be effective in treating clear liquid foods such as water and clarified juices, but it is less effective in treating turbid liquid with particulates, where UVC light is strongly absorbed, scattered and reflected. Researches on UVC pasteurization have focused on various varieties of apple juices (Basaran et al., 2004; Geveke, 2005; Murakami et al., 2006; Ye, 2007; Keyser et al., 2008; Franz et al., 2009; Ukuku & Geveke, 2010; Lu et al., 2010; Caminiti et al., 2010; Char et al., 2010; Palgan et al., 2011; Muller et al., 2011), orange juices (Tran & Farid, 2004; Keyser et al., 2008; Char et al., 2010; Muller et al., 2011), and tropical fruit juices (Guerrero-Beltran & Barbosa-Canovas, 2006; Koutchma, 2009; Keyser et al., 2008; Bhat et al., 2011; Guevara et al., 2011) against various microorganisms (*E.coli, Y. pseudotuberculosis, L. innocua, B.cereus, P. fermentans, S. aureus, L. brevis, S. typhi* and among others) with various configurations (thin film annular reactor, laminar and turbulent annular reactors, taylor-couette reactors and convoluted pipes reactors).

Nevertheless, no study have been done, specifically, on disinfecting *Salmonella typhimurium* in pummelo fruit juice utilizing a dean vortex technology – neither on the disinfection kinetics nor on developing an optimum UVC light disinfection. Dean flow refers to a secondary flow caused by flow movement in curved tubes. The secondary flow is the double spiral motion produced by a gradual bend in a closed pipe (Dean, 1927). Dean vortices that resulted from the flow will increase the juice mixing in the tube, exposing more surface area of the juice to UVC light radiation. The secondary mixing produced uniform fluence rate within the pipes has been proved to be effective in killing bacteria, viruses, yeasts and molds. Hence, dean vortex UVC system would be the main focus in this study to develop an optimum method to pasteurize pummelo fruit juice. The complex nature of the UVC system provides endless possibilities in modifying the equipment to suit the juice requirements to effectively kill the pathogens.

Moreover, no literatures have also been found to have studied in detail the effect of flow rate, residence time distribution, UVC dose, fluence rate on the reduction of *Salmonella typhimurium* in pummelo fruit juice. This study will also investigate the effects of UVC light towards juice quality, antioxidant activity, physicochemical attributes and furan developments during a storage life of 12 weeks.

1.3 Objectives

The specific objectives of this study are:

1. To determine the physicochemical properties of two Malaysian varieties of pummelo fruit juice (PO55 Ledang and PO52 Tambun).
2. To determine the most effective clarification method using a commercial enzyme (Pectinex Smash XXL) with 3 variables: enzyme concentration, incubation time and temperature with additional ultrasonic treatment to inactivate pectin methylesterase activity.

3. To evaluate the performance of dean vortex UVC light system via experimental works and calculation. Subsequently, to validate the performance using a Computational Fluid Design (CFD) software.
4. To evaluate *Salmonella typhimurium* inactivation in relation to the performance of dean vortex UVC light system and pummelo juice characteristics. To further investigate photoreactivation ability of *Salmonella typhimurium* during storage at 4°C.
5. To examine the antioxidant activity, physicochemical properties and furan development of pummelo fruit juice post UVC light treatment and subsequently, during storage at 4°C.

1.4 Scope of Research

The introductory chapter briefly reviews ultraviolet light processing, reactor configurations with various fruit juice samples. Problem statement, the objectives of research and its significance that supports the contributions of this thesis are also presented in this chapter.

Chapter 2 reviews previous studies in pummelo fruit juice, nutrition and microorganisms pertinent to the juice hampering the shelf life. This chapter also discusses previous works on ultraviolet light focusing on fruit juice products. UVC light generation method, its direct effects towards technological properties and bioactivity in foods are elaborately discussed. Technical aspects, its advantages and potential ultraviolet development in food industry are also discussed in this chapter.

Chapter 3 describes detailed experimental designs and methods used in completing this study. In addition the chapter presents the methods in obtaining all the responses, juice preliminary study, clarification treatments, *Salmonella typhimurium* counts, pre and post-UVC light treatment analysis and the statistical analysis. The experimental UVC light system setup is also comprehensively presented in this chapter.

Chapter 4 reports the findings of research investigations on the objectives mentioned previously. Preliminary study of two major Malaysian pummelo fruit varieties (PO55 Ledang and PO52 Tambun) were done to choose the best variety for juice production and further analysis. Ledang variety was chosen based on the amount of juice yield and Brix to total acidity ratio, which is the higher of the two varieties. Ledang variety then undergoes clarification treatment to improve the clarity and absorption coefficient of juice before undergoing further UVC light treatment. Enzymatic and ultrasonic treatment was then optimized to find the optimum point for Ledang pummelo fruit juice. Performance of dean vortex in relations to its UVC fluence, retention time distribution, flowrate, temperature, Dean number was then validated against the results from Computational Fluid Design (CFD) used in order to find the optimum flowrate of flowing juice in dean vortex UVC light reactor. Subsequently, the performance evaluation of dean vortex UVC light system towards *Salmonella typhimurium* inactivation is discussed. The effects of dean vortex UVC light treatment on antioxidant, pectin methylesterase activity, ascorbic acid and other physicochemical properties are elaborately discussed. Furan development and its relationship with the juice sugar content are also presented in this chapter.

A brief summary on all findings are presented in Chapter 5. The recommendations for future work are also detailed in the final chapter.

1.5 Contributions of Thesis

The contributions of this study are many since the pummelo fruit is non-seasonal and non-climateric fruit which could be planted and harvested all year long. This study if proven successful could provide the alternative pasteurization of pummelo fruit juice without giving away the 'fresh-like' properties and nutrition of the fruit juice. Ultraviolet light technology being the cheapest and the easiest pasteuriation technique can benefit Small Medium Enterprises (SME) and Agricultural Department under the Ministry of Agriculture, Malaysia thus realizing the aims of National Agro-Food Policy (2011 - 2020). The natural nutrition of the fruit juice would be retained and these benefits are considered important to consumers. Antimicrobial properties of UVC light can be a crucial advantage where, *Salmonella typhimurium* would be inactivated, thus, lowering the risks of food poisoning and ultimately prolonging the shelf life of pummelo fruit juice.

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