HYDRODYNAMIC CAVITATION USING ORIFICE PLATE CONFIGURATIONS AND ARRANGEMENTS FOR TERTIARY TREATMENT OF PALM OIL MILL EFFLUENT

MUHAMMAD NOOR HAZWAN JUSOH

UNIVERSITI TEKNOLOGI MALAYSIA
HYDRODYNAMIC CAVITATION USING ORIFICE PLATE CONFIGURATIONS AND ARRANGEMENTS FOR TERTIARY TREATMENT OF PALM OIL MILL EFFLUENT

MUHAMMAD NOOR HAZWAN JUSOH

A thesis submitted in fulfilment of the requirements for the award of the degree of Doctor of Philosophy (Civil Engineering)

Faculty of Civil Engineering
Universiti Teknologi Malaysia

JUNE 2017
…to my lovely wife Shafiah Dolhakim
daughter Sarah Noor Liyana
parents Jusoh Jaafar and Kamariah Che Soh
thank you for your du’a, support and patience all this while…
ACKNOWLEDGEMENTS

In the name of Allah, the Almighty who gives such opportunity to further my study at this PhD level. I would like to take this opportunity to thank all the persons who have contributed in the different aspects of this study. They have all made it possible for me to commence and complete this enormous task. I would like to acknowledge and commend them for their effort, cooperation and collaboration that have worked towards the success of this study. Their positive attitude and support have taken me ahead and will also sustain the vitality of this study which serves as a contribution to both the academic and teaching/educational professional world. The work would not be possible without the contributions and involvement of the host of participants who I think will take pride in this work. All the good things happened from this journey is attributed to Allah who gives the strength and patience to me and to those persons involved to enjoy the ride in completing our trust.

To my parents, Jusoh Jaafar and Kamariah Che Soh; and mother in law, Tajiah Ahmad, thank you for your supports. The only my lovely wife, Shafiah Dolhakim thank you for being so understanding and caring for these years. My sweet little princess, Sarah Noor Liyana thank you for making wonderful and colourful life during my tough times. The whole family members deserve my wholehearted thanks as well. I am deeply grateful to my passionate supervisor, Professor Dr. Azmi Aris for patiently taking me through this difficult task of educational research. The guidance, advice, and knowledges that have shared for the past six years will not be forgotten. I would like to acknowledge the contribution of my colleagues, friends, educators, evaluators with whom I have worked during this inquiry. I wish to acknowledge Universiti Teknologi Malaysia and Ministry of Higher Education, Malaysia for supporting the study under Research University Grant Scheme (Vot No. Q J130000.2522.04H81) and MyBrain15 scholarship.
ABSTRACT

Hydrodynamic Cavitation (HC) is one of Advanced Oxidation Processes (AOPs), which generates and utilises hydroxyl radicals (HO\textsuperscript{·}) as its oxidising agent. It has been studied for different applications to treat pharmaceuticals waste, seawater and microalgae, where much effort has been conducted to enhance its performance such as using pH, aeration and hydrogen peroxide (H\textsubscript{2}O\textsubscript{2}). However, the production of HO\textsuperscript{·} using multiple-plate combination has not yet been studied. The use of pH, aeration and H\textsubscript{2}O\textsubscript{2} has proven to give significant improvement for HO\textsuperscript{·} formation, but these have not being studied previously using multiple-plate combination. The use of HC as a tertiary treatment for POME has not being reported before. Therefore, in this study, the enhancement of the HC has been investigated using double and triple orifice plate configurations and arrangements. The best system was then tested on biologically treated palm oil mill effluent (BT-POME). As the colour of POME is difficult to remove the performance of ponding treatment system was evaluated to understand the causes of colour in POME. The experiments were conducted in a lab-scale HC system, treating 10 L samples for reaction time ranging from 30 to 180 min. The effect of pH (2-7), aeration (2-10 L/min) and H\textsubscript{2}O\textsubscript{2} dosing (50-200 mg/L) were explored. The performance of the HC system was based on iodine liberation, and removal of colour and chemical oxygen demand (COD). The byproducts of BT-POME degradation was identified. Additionally, the performance of an existing ponding system treating POME was assessed and the relationship between colour and few selected parameters were studied. Within the range of the experimental conditions used in this study, the HC orifice plate configurations and arrangements were found to have significant effects on HO\textsuperscript{·} generation. The iodine liberation for both double and triple plate were higher than that of a single plate. The HO\textsuperscript{·} generation was also affected by the arrangement and the distance between the plates; arrangement plate of P3P2 with 10 cm distance gave the highest iodine liberation (1296 mg/L). The performance of HC was enhanced under the effect of pH, H\textsubscript{2}O\textsubscript{2} and aeration as compared to HC alone. For the conventional ponding treatment system, the anaerobic pond played the most significant role in treating POME with removal up to 97%. Among the pollutants analysed, colour has strong relationship with phenolics, tannin, lignin and carotene, indicating the roles of these compounds in causing colour of POME. The degradation of BT-POME by the HC system was not encouraging as only up to 14.7% of colour was removed, with lower removal of COD. The addition of H\textsubscript{2}O\textsubscript{2} and aeration have significant effect in removing COD, while pH and addition of H\textsubscript{2}O\textsubscript{2} have significant effect on colour removal. The degradation of BT-POME, particularly phenolics and tannin/lignin was found to form catechol and p-benzoquinone as by-products. The study showed another approach in improving HC system performance but further work is required before the system can be applied in treating BT-POME effectively.
ABSTRAK

Hydrodynamic Cavitation (HC) adalah salah satu Proses Pengoksidaan Lanjutan (AOPs) yang menghasilkan dan menggunakan radikal hidroksil (HO·) sebagai agen pengoksidaan. Ia telah dikaji untuk pelbagai kegunaan dalam merawat sisa farmaseutikal, air laut dan mikroalga, dan banyak usaha telah dijalankan untuk meningkatkan prestasinya seperti penggunaan pH, pengudaraan dan hidrogen peroksida (H₂O₂). Walau bagaimanapun, penghasilan HO· menggunakan beberapa plat berliang belum pernah dijalankan. Penggunaan pH, pengudaraan dan H₂O₂ telah terbukti memberikan peningkatan yang bererti kepada pembentukan HO·, tetapi tidak pernah dijalankan menggunakannya gabungan beberapa plat. Penggunaan HC sebagai rawatan tertier untuk POME tidak pernah dilaporkan sebelum ini. Oleh itu, dalam kajian ini, peningkatan HC telah dikaji menggunakan susunan dan konfigurasi dua dan tiga plat berliang. Sistem yang terbaik kemudiannya diuji pada air sisa kilang minyak sawit yang telah terawat secara biologi (BT-POME). Disebabkan warna POME adalah sukar untuk disingkirkan, prestasi sistem kolam rawatan telah dinilai untuk memahami penyumbang kepada warna POME. Ujikaji telah dijalankan di dalam sistem HC berskala makmal, merawat 10 L sampel dengan masa tindakbalas dari 30 hingga 180 minit. Kesan pH (2-7), pengudaraan (2-10 L/min) dan dos H₂O₂ (50-200 mg/L) telah dikaji. Prestasi sistem HC adalah berdasarkan kepada penghasilan iodin, dan peningkiran permintaan oksigen kimia (COD) serta warna. Hasil sampingan penguraian BT-POME telah dikenalpasti. Sebagai tambahan, prestasi sistem kolam rawatan POME seda ada telah dinilai dan kaitan diantara warna dan beberapa parameter pilihan telah dikaji. Dalam jual keadaan eksperimen yang digunakan dalam kajian ini, susunan dan konfigurasi plat berliang HC didapati mempunyai kesan yang signifikan kepada penghasilan HO·. Penghasilan iodin bagi dua dan tiga plat adalah lebih tinggi berbanding plat tunggal. Penghasilan HO· juga dipengaruhi oleh susunan dan jarak diantara plat; susunan plat P3P2 dengan jarak 10 sm menghasilkan iodin tertinggi (1296 mg/L). Prestasi HC dipertingkatkan menggunakan pH, H₂O₂ dan pengudaraan berbanding HC sahaja. Bagi sistem rawatan kolam konvensional, kolom anaerobik berperanan penting dalam merawat POME dengan peningkiran sebanyak 97%. Dikalangan bahan pencemar yang dianalisis, warna berhubung kuat dengan fenol, tanin/lignin dan karotena, menunjukkan sebati ini berperanan menghasilkan warna dalam POME. Penguraian BT-POME oleh sistem HC adalah tidak memberikan peningkiran warna dalam catatan peningkiran COD yang rendah. Penambahan H₂O₂ dan pengudaraan memberi kesan yang bererti kepada peningkiran COD, sementara pH dan penambahan H₂O₂ memberi kesan yang bererti kepada peningkiran warna. Penguraian BT-POME, khususnya fenol dan tanin, lignin didapati menghasilkan katekol dan ρ-benzokuinin sebagai hasil sampingan. Kajian ini menunjukkan pendekatan yang lain dalam meningkatkan prestasi sistem HC tetapi kajian lanjutan diperlukan sebelum sistem ini boleh digunakan merawat BT-POME dengan berkesan.
TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>CHAPTER</th>
<th>TITLE</th>
<th>PAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>DECLARATION</td>
<td>ii</td>
</tr>
<tr>
<td></td>
<td>DEDICATION</td>
<td>iii</td>
</tr>
<tr>
<td></td>
<td>ACKNOWLEDGEMENTS</td>
<td>iv</td>
</tr>
<tr>
<td></td>
<td>ABSTRACT</td>
<td>v</td>
</tr>
<tr>
<td></td>
<td>ABSTRAK</td>
<td>vi</td>
</tr>
<tr>
<td></td>
<td>TABLE OF CONTENTS</td>
<td>vii</td>
</tr>
<tr>
<td></td>
<td>LIST OF TABLES</td>
<td>xii</td>
</tr>
<tr>
<td></td>
<td>LIST OF FIGURES</td>
<td>xv</td>
</tr>
<tr>
<td></td>
<td>LIST OF ABBREVIATIONS</td>
<td>xxiii</td>
</tr>
<tr>
<td></td>
<td>LIST OF SYMBOLS</td>
<td>xxv</td>
</tr>
<tr>
<td>1</td>
<td>INTRODUCTION</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>1.1 Preamble</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>1.2 Problem Statement</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>1.3 Objectives of the Study</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>1.4 Scope of the Study</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>1.5 Significance of the Study</td>
<td>6</td>
</tr>
<tr>
<td>2</td>
<td>LITERATURE REVIEW</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>2.1 Introduction</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>2.2 Advanced Oxidation Processes</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>2.3 Cavitation</td>
<td>11</td>
</tr>
<tr>
<td></td>
<td>2.3.1 Comparison between Acoustic Cavitation and Hydrodynamic Cavitation</td>
<td>12</td>
</tr>
</tbody>
</table>
2.4 Cavitational Mechanisms
   2.4.1 Growth Phase of the Cavity Cluster
   2.4.2 Radius of the Cavity Cluster
2.5 Applications of Cavitational Technology in
   Water and Wastewater Treatment
2.6 Factors affecting Hydrodynamic Cavitation of
   Orifice Plate
   2.6.1 Geometry of Orifice Plate
   2.6.2 Inlet pressure
   2.6.3 Hydrogen Peroxide
   2.6.4 Aeration
2.7 Potassium Iodide Dosimetry
2.8 Palm Oil Industry
   2.8.1 Palm Oil Mill Effluent
   2.8.2 Palm Oil Mill Effluent Treatment
      Technologies
      2.8.2.1 Conventional Treatment
      2.8.2.2 Anaerobic System
      2.8.2.3 Aerobic System
      2.8.2.4 Tertiary treatment
2.9 Conclusion and Future Research

3 METHODOLOGY
3.1 Introduction
3.2 Equipment and Materials
   3.2.1 Hydrodynamic Cavitation Reactor System
   3.2.2 Orifice Plate
   3.2.3 Chemicals
   3.2.4 Wastewater
      3.2.4.1 Potassium Iodide Solution
      3.2.4.2 Biological Treated Palm Oil Mill
         Effluent
3.3 Analytical Methods
3.3.1 Total Organic Carbon
3.3.2 β-carotene
3.3.3 Phenolics
3.3.4 Tannin and Lignin
3.3.5 Catechol
3.3.6 ρ-Benzoinone

3.4 Experimental Procedures
3.4.1 Iodine Standard Calibration Curve
3.4.2 Carotene Standard Calibration Curve
3.4.3 Phenolics Standard Calibration Curve
3.4.4 Hydrodynamic Cavitation Process
  3.4.4.1 Single-Plate
  3.4.4.2 Double-Plate Arrangements
  3.4.4.3 Triple-Plate Arrangements
3.4.5 Effect of Reaction Conditions
  3.4.5.1 Effect of pH
  3.4.5.2 Effect of Aeration
  3.4.5.3 Effect of Hydrogen Peroxide
3.4.6 Assessment of Existing POME Ponding Treatment System Performance
3.4.7 Degradation of Biological Treated Palm Oil Mill Effluent using Hydrodynamic Cavitation
  3.4.7.1 Effect of pH
  3.4.7.2 Effect of Aeration
  3.4.7.3 Effect of Hydrogen Peroxide
3.4.8 Decomposition of Colour Causing Compounds
3.4.9 Identification of By-products
  3.4.9.1 Catechol Standard Calibration Curve
  3.4.9.2 ρ-Benzoinone Standard Calibration Curve
3.5 Analytical Equations 71
3.6 Data Analysis 73

4 RESULTS & DISCUSSION 74

4.1 Introduction 74
4.2 Effect of Inlet Pressure on Cavitation Characteristics 75
4.3 Effect of Inlet Pressure on Hydroxyl Radicals Generation 79
4.4 Effect of Plate Configuration and Arrangement on Iodine Liberation 83
  4.4.1 Single-plate 83
  4.4.2 Double-plate 86
  4.4.3 Triple-plate 89
  4.4.4 Effect of Plate Arrangement 92
    4.4.4.1 Double-plate Arrangement 92
    4.4.4.2 Triple-plate Arrangement 95
  4.4.5 Relationship between Cavitation Number and Cavitation 97
  4.4.6 Relationship between Ratio of Total Perimeter of Orifices to Total Area of Orifices and Cavitation 104
  4.4.7 Relationship between Ratio of Total Area of Orifices to Cross-sectional Area of Pipe and Cavitation 108
  4.4.8 Cavitation Yield 112
4.5 Effect of pH, Hydrogen Peroxide and Aeration 116
  4.5.1 Effect of pH 116
  4.5.2 Effect of Hydrogen Peroxide 118
  4.5.3 Effect of Aeration 120
4.6 Treatment of palm oil mill effluent 122
  4.6.1 pH 123
  4.6.2 Biochemical Oxygen Demand 125
4.6.3 Chemical Oxygen Demand 127
4.6.4 Total Organic Carbon 129
4.6.5 Total Suspended Solids 131
4.6.6 Volatile Suspended Solids 133
4.6.7 Total Phosphorus 135
4.6.8 Total Nitrogen 138
4.6.9 Ammoniacal Nitrogen 140
4.6.10 Oil and Grease 142
4.6.11 Carotene 144
4.6.12 Phenolic 145
4.6.13 Tannin-lignin 147
4.6.14 Colour 150
4.7 Degradation of Palm Oil Mill Effluent 154
4.7.1 COD Removal 154
   4.7.1.1 Effect of pH 155
   4.7.1.2 Effect of Hydrogen Peroxide 156
   4.7.1.3 Effect of Aeration 160
4.7.2 Colour Removal 163
   4.7.2.1 Effect of pH 163
   4.7.2.2 Effect of Hydrogen Peroxide 165
   4.7.2.3 Effect of Aeration 168
   4.7.2.4 Colour Removal in Relation with
      Specific Organic Compounds 170
4.8 By-products Activation 175

5 Conclusion and Recommendations 179
5.1 Conclusions 179
5.2 Recommendations 180

REFERENCES 182
### LIST OF TABLES

<table>
<thead>
<tr>
<th>TABLE NO.</th>
<th>TITLE</th>
<th>PAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1</td>
<td>Technologies to produce the hydroxyl radicals</td>
<td>9</td>
</tr>
<tr>
<td>2.2</td>
<td>Rate constants the reaction of hydroxyl radicals with</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>organic compounds and hydrogen peroxide</td>
<td></td>
</tr>
<tr>
<td>2.3</td>
<td>Summary of hydrodynamic cavitation conducted in the</td>
<td>23</td>
</tr>
<tr>
<td></td>
<td>different field of studies</td>
<td></td>
</tr>
<tr>
<td>2.4</td>
<td>Characteristics of wastewater discharged from</td>
<td>37</td>
</tr>
<tr>
<td></td>
<td>steriliser condensate, separator sludge and</td>
<td></td>
</tr>
<tr>
<td></td>
<td>hydrocyclone</td>
<td></td>
</tr>
<tr>
<td>2.5</td>
<td>Characteristics of palm oil mill effluents</td>
<td>37</td>
</tr>
<tr>
<td>2.6</td>
<td>Summary of advanced POME treatment</td>
<td>46</td>
</tr>
<tr>
<td>3.1</td>
<td>Different number and size of orifice on the plates</td>
<td>56</td>
</tr>
<tr>
<td>3.2</td>
<td>List of chemicals used in the study</td>
<td>57</td>
</tr>
<tr>
<td>3.3</td>
<td>List of parameters and code of standard for this study</td>
<td>59</td>
</tr>
<tr>
<td>4.1</td>
<td>ANOVA table for different pressures asserted on HC</td>
<td>82</td>
</tr>
<tr>
<td>4.2</td>
<td>Flow characteristics of single-plate at 45 psi</td>
<td>85</td>
</tr>
<tr>
<td>4.3</td>
<td>ANOVA table for single-plate at 60 minutes</td>
<td>86</td>
</tr>
<tr>
<td>Section</td>
<td>Description</td>
<td>Page</td>
</tr>
<tr>
<td>---------</td>
<td>------------------------------------------------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>4.4</td>
<td>Flow characteristics of double-plate at 45 psi</td>
<td>88</td>
</tr>
<tr>
<td>4.5</td>
<td>ANOVA table for double-plate arrangement</td>
<td>89</td>
</tr>
<tr>
<td>4.6</td>
<td>Flow characteristics of triple-plate at 45 psi</td>
<td>91</td>
</tr>
<tr>
<td>4.7</td>
<td>ANOVA table for triple-plate arrangement</td>
<td>91</td>
</tr>
<tr>
<td>4.8</td>
<td>Flow characteristics of double-plate arrangement</td>
<td>93</td>
</tr>
<tr>
<td>4.9</td>
<td>ANOVA table for different double-plate arrangement</td>
<td>93</td>
</tr>
<tr>
<td>4.10</td>
<td>ANOVA table for different distances of orifice plates</td>
<td>95</td>
</tr>
<tr>
<td>4.11</td>
<td>Flow characteristics of different arrangements of plate at 45 psi</td>
<td>97</td>
</tr>
<tr>
<td>4.12</td>
<td>ANOVA table for different plate arrangements</td>
<td>97</td>
</tr>
<tr>
<td>4.13</td>
<td>Flow rate and cavitation number for single-plate</td>
<td>99</td>
</tr>
<tr>
<td>4.14</td>
<td>Flow rate and cavitation number for double-plate</td>
<td>101</td>
</tr>
<tr>
<td>4.15</td>
<td>Flow rate and cavitation number for triple-plate</td>
<td>103</td>
</tr>
<tr>
<td>4.16</td>
<td>ANOVA table for different pH runs</td>
<td>118</td>
</tr>
<tr>
<td>4.17</td>
<td>ANOVA table for different concentrations of hydrogen peroxide</td>
<td>120</td>
</tr>
<tr>
<td>4.18</td>
<td>ANOVA table for different air flow rate</td>
<td>122</td>
</tr>
<tr>
<td>4.19</td>
<td>Characterization of POME through series of ponds system at Felda Bukit Besar Palm Oil Refinery</td>
<td>124</td>
</tr>
<tr>
<td>4.20</td>
<td>Correlation between colour and other substances in treatment ponds</td>
<td>154</td>
</tr>
</tbody>
</table>
4.21 ANOVA table for COD removal at different \( \text{H}_2\text{O}_2 \) dosages 158

4.22 ANOVA table for COD removal at different aeration flow rates 162

4.23 ANOVA table for colour removal at different pH values 165

4.24 ANOVA table for colour removal at different \( \text{H}_2\text{O}_2 \) dosages 166

4.25 ANOVA table for colour removal in the stepwise addition of \( \text{H}_2\text{O}_2 \) 168

4.26 ANOVA table for colour removal at different aeration flow rates 170
## LIST OF FIGURES

<table>
<thead>
<tr>
<th>FIGURE NO.</th>
<th>TITLE</th>
<th>PAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1</td>
<td>Schematic diagrams of the sonochemical reactor to form acoustic cavitation. (a) Dual Frequency Flow Cell. (b) Ultrasonic bath with longitudinally vibrating horn. (c) Triple frequency hexagonal flow cell</td>
<td>13</td>
</tr>
<tr>
<td>2.2</td>
<td>Schematic diagrams of the reactor to form hydrodynamic cavitation. (a) High-Speed Homogenizer. (b) High-Pressure Homogenizer, Microfluidizer. (c) Orifice plate set-up</td>
<td>14</td>
</tr>
<tr>
<td>2.3</td>
<td>Profile of pressure recovery across an orifice</td>
<td>16</td>
</tr>
<tr>
<td>2.4</td>
<td>Theoretical scheme of hydrodynamic cavitation as AOPs</td>
<td>17</td>
</tr>
<tr>
<td>2.5</td>
<td>Schematic diagram of different phases of the cavity cluster downstream of the orifice. (a) Initial radius of nuclei of cavities. (b) Complete growth of the cavities cluster under the influence of pressure oscillation. (c) Collapsing cavities cluster under the action of far-field pressure. (d) Collapsing cavities cluster at the final stage</td>
<td>18</td>
</tr>
<tr>
<td>2.6</td>
<td>Schematic diagrams of orifice plate with different diameter and number of orifice</td>
<td>28</td>
</tr>
<tr>
<td>2.7</td>
<td>The oil palm fruit</td>
<td>36</td>
</tr>
<tr>
<td>Section</td>
<td>Title</td>
<td>Page</td>
</tr>
<tr>
<td>---------</td>
<td>-----------------------------------------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>3.1</td>
<td>Research framework of the study</td>
<td>52</td>
</tr>
<tr>
<td>3.2</td>
<td>Hydrodynamic cavitation reactor</td>
<td>54</td>
</tr>
<tr>
<td>3.3</td>
<td>Schematic diagram of hydrodynamic cavitation</td>
<td>54</td>
</tr>
<tr>
<td>3.4</td>
<td>Orifice plates arranged in the cavitation chamber</td>
<td>55</td>
</tr>
<tr>
<td>3.5</td>
<td>Configurations of the orifice plate</td>
<td>56</td>
</tr>
<tr>
<td>3.6</td>
<td>Calibration curve of iodine solutions at different concentrations</td>
<td>62</td>
</tr>
<tr>
<td>3.7</td>
<td>Calibration curve of β-carotene solutions at different concentrations</td>
<td>62</td>
</tr>
<tr>
<td>3.8</td>
<td>Calibration curve of phenolics solutions at different concentrations</td>
<td>63</td>
</tr>
<tr>
<td>3.9</td>
<td>Side view of cavitation chamber</td>
<td>65</td>
</tr>
<tr>
<td>3.10</td>
<td>Schematic diagram of pond treatment system and Felda Bukit Besar Palm Oil Refinery</td>
<td>67</td>
</tr>
<tr>
<td>3.11</td>
<td>Calibration curve of catechol solutions at different concentrations</td>
<td>70</td>
</tr>
<tr>
<td>3.12</td>
<td>Calibration curve of ρ-Benzquinone solutions at different concentrations</td>
<td>71</td>
</tr>
<tr>
<td>4.1</td>
<td>Flow characteristics of liquid for six orifice plates</td>
<td>76</td>
</tr>
<tr>
<td>4.2</td>
<td>$C_v$ for six orifice plates with different inlet pressure</td>
<td>77</td>
</tr>
<tr>
<td>4.3</td>
<td>Cavitation number of single-plate with respect to $\alpha$ at 45 psi inlet pressure</td>
<td>78</td>
</tr>
<tr>
<td>Section</td>
<td>Description</td>
<td></td>
</tr>
<tr>
<td>---------</td>
<td>-------------</td>
<td></td>
</tr>
<tr>
<td>4.4</td>
<td>Cavitation number of single-plate with respect to $\beta$ at 45 psi inlet pressure</td>
<td></td>
</tr>
<tr>
<td>4.5</td>
<td>Iodine liberation at different inlet pressure using Plate 3</td>
<td></td>
</tr>
<tr>
<td>4.6</td>
<td>Number of liquid recirculation passes through orifice plate, P3</td>
<td></td>
</tr>
<tr>
<td>4.7</td>
<td>Profile of iodine liberation for single-plate at 45 psi</td>
<td></td>
</tr>
<tr>
<td>4.8</td>
<td>Profile of iodine liberation for double-plate at 45 psi</td>
<td></td>
</tr>
<tr>
<td>4.9</td>
<td>Profile of iodine liberation with triple-plate at 45 psi</td>
<td></td>
</tr>
<tr>
<td>4.10</td>
<td>Profile of iodine liberation with double-plate orientation</td>
<td></td>
</tr>
<tr>
<td>4.11</td>
<td>Profile of iodine liberation with different length of orifice plates</td>
<td></td>
</tr>
<tr>
<td>4.12</td>
<td>Profile of iodine liberation with different arrangements</td>
<td></td>
</tr>
<tr>
<td>4.13</td>
<td>Iodine liberation for single-plate with respect cavitation number</td>
<td></td>
</tr>
<tr>
<td>4.14</td>
<td>Iodine liberation of single-plate with number of recirculation</td>
<td></td>
</tr>
<tr>
<td>4.15</td>
<td>Iodine liberation for double-plate with cavitation number</td>
<td></td>
</tr>
<tr>
<td>4.16</td>
<td>Iodine liberation of double-plate with number of recirculation</td>
<td></td>
</tr>
<tr>
<td>4.17</td>
<td>Iodine liberation for triple-plate with cavitation number</td>
<td></td>
</tr>
<tr>
<td>Section</td>
<td>Description</td>
<td></td>
</tr>
<tr>
<td>---------</td>
<td>-------------</td>
<td></td>
</tr>
<tr>
<td>4.18</td>
<td>Iodine liberation of triple-plate with number of recirculation</td>
<td></td>
</tr>
<tr>
<td>4.19</td>
<td>Profile of iodine liberation for single-plate with respects to $\alpha$</td>
<td></td>
</tr>
<tr>
<td>4.20</td>
<td>Profile of iodine liberation for double-plate with respect to $\alpha$</td>
<td></td>
</tr>
<tr>
<td>4.21</td>
<td>Profile of iodine liberation for triple-plate with respect to $\alpha$</td>
<td></td>
</tr>
<tr>
<td>4.22</td>
<td>Iodine liberation for single-plate with respect to $\beta$</td>
<td></td>
</tr>
<tr>
<td>4.23</td>
<td>Iodine liberation for double-plate with respect to $\beta$</td>
<td></td>
</tr>
<tr>
<td>4.24</td>
<td>Iodine liberation for triple-plate with respect to $\beta$</td>
<td></td>
</tr>
<tr>
<td>4.25</td>
<td>Cavitational yield with $\beta$ for single plate</td>
<td></td>
</tr>
<tr>
<td>4.26</td>
<td>Cavitational yield for different combinations</td>
<td></td>
</tr>
<tr>
<td>4.27</td>
<td>Profile of iodine liberation at different pH</td>
<td></td>
</tr>
<tr>
<td>4.28</td>
<td>Profile of iodine liberation at different concentrations of $\text{H}_2\text{O}_2$</td>
<td></td>
</tr>
<tr>
<td>4.29</td>
<td>Profile of iodine liberation at different air flow rate</td>
<td></td>
</tr>
<tr>
<td>4.30</td>
<td>Profile of pH performances of the ponds system</td>
<td></td>
</tr>
<tr>
<td>4.31</td>
<td>Profile of BOD removal performances of the ponds system</td>
<td></td>
</tr>
<tr>
<td>4.32</td>
<td>Profiles of BOD and TSS removal performance of the ponds system</td>
<td></td>
</tr>
<tr>
<td>Section</td>
<td>Description</td>
<td>Page</td>
</tr>
<tr>
<td>---------</td>
<td>------------------------------------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>4.33</td>
<td>Profile of COD removal performances of the ponds system</td>
<td>128</td>
</tr>
<tr>
<td>4.34</td>
<td>Profiles of COD and TSS removal performance of the ponds system</td>
<td>128</td>
</tr>
<tr>
<td>4.35</td>
<td>Profile of TOC removal performances of the ponds system</td>
<td>129</td>
</tr>
<tr>
<td>4.36</td>
<td>Profiles of TOC and TSS removal performance of the ponds system</td>
<td>130</td>
</tr>
<tr>
<td>4.37</td>
<td>Profiles of TOC and O&amp;G removal performance of the ponds system</td>
<td>131</td>
</tr>
<tr>
<td>4.38</td>
<td>Profile of TSS removal performances of the ponds system</td>
<td>132</td>
</tr>
<tr>
<td>4.39</td>
<td>Profiles of TSS and colour removal performance of the ponds system</td>
<td>133</td>
</tr>
<tr>
<td>4.40</td>
<td>Profile of VSS removal performances of the ponds system</td>
<td>134</td>
</tr>
<tr>
<td>4.41</td>
<td>Profiles of VSS and colour removal performance of the ponds system</td>
<td>135</td>
</tr>
<tr>
<td>4.42</td>
<td>Profile of TP removal performances of the ponds system</td>
<td>136</td>
</tr>
<tr>
<td>4.43</td>
<td>Profiles of TP and O&amp;G removal performance of the ponds system</td>
<td>137</td>
</tr>
<tr>
<td>4.44</td>
<td>Profiles of TP and TSS removal performance of the ponds system</td>
<td>138</td>
</tr>
<tr>
<td>Section</td>
<td>Description</td>
<td></td>
</tr>
<tr>
<td>---------</td>
<td>-------------</td>
<td></td>
</tr>
<tr>
<td>4.45</td>
<td>Profile of TN removal performances of the ponds system</td>
<td></td>
</tr>
<tr>
<td>4.46</td>
<td>Profiles of TN and TSS removal performance of the ponds system</td>
<td></td>
</tr>
<tr>
<td>4.47</td>
<td>Profile of AN removal performances of the ponds system</td>
<td></td>
</tr>
<tr>
<td>4.48</td>
<td>Profile of O&amp;G removal performances of the ponds system</td>
<td></td>
</tr>
<tr>
<td>4.49</td>
<td>Profiles of O&amp;G and TSS removal performance of the ponds system</td>
<td></td>
</tr>
<tr>
<td>4.50</td>
<td>Profile of carotene removal performances of the ponds system</td>
<td></td>
</tr>
<tr>
<td>4.51</td>
<td>Profiles of carotene and colour removal performance of the ponds system</td>
<td></td>
</tr>
<tr>
<td>4.52</td>
<td>Profile of phenolic removal performances of the ponds system</td>
<td></td>
</tr>
<tr>
<td>4.53</td>
<td>Profiles of phenolic and colour removal performance of the ponds system</td>
<td></td>
</tr>
<tr>
<td>4.54</td>
<td>Profile of tannin-lignin removal performances of the ponds system</td>
<td></td>
</tr>
<tr>
<td>4.55</td>
<td>Profiles of phenolic and colour removal performance of the ponds system</td>
<td></td>
</tr>
<tr>
<td>4.56</td>
<td>Profile of colour removal performances of the ponds system</td>
<td></td>
</tr>
</tbody>
</table>
4.57 Relationship between colour and tannin-lignin removal performance of the ponds system 151

4.58 Relationship between colour and phenolics removal performance of the ponds system 151

4.59 Relationship between colour and carotene removal performance of the ponds system 152

4.60 Relationship between colour and TSS removal performance of the ponds system 152

4.61 Relationship between colour and VSS removal performance of the ponds system 153

4.62 Profile of COD removal at different pH values 156

4.63 Profiles of COD removal with different H$_2$O$_2$ concentrations (at pH 8.6) 157

4.64 Profiles of COD removal in the stepwise addition of H$_2$O$_2$ 159

4.65 Profiles of COD removal at different aeration flow rates 161

4.66 Profile of colour removal at different pH values 164

4.67 Profiles of colour removal with different H$_2$O$_2$ concentrations 165

4.68 Profiles of colour removal in the stepwise addition of H$_2$O$_2$ 167

4.69 Profiles of colour removal at different aeration flow rates 169
<table>
<thead>
<tr>
<th></th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.70</td>
<td>Profiles of removal for different colouring constituents</td>
<td>171</td>
</tr>
<tr>
<td>4.71</td>
<td>Relationship between colour and phenolics</td>
<td>172</td>
</tr>
<tr>
<td>4.72</td>
<td>Relationship between colour and tannin/lignin</td>
<td>172</td>
</tr>
<tr>
<td>4.73</td>
<td>Relationship between colour and carotene</td>
<td>173</td>
</tr>
<tr>
<td>4.74</td>
<td>Relationship between tannin/lignin and phenolics</td>
<td>174</td>
</tr>
<tr>
<td>4.75</td>
<td>Formation of catechol and p-Benzooquinone with phenolic degradation as a function of time</td>
<td>176</td>
</tr>
<tr>
<td>4.76</td>
<td>Degradation pathways of phenolics compound</td>
<td>178</td>
</tr>
<tr>
<td>4.77</td>
<td>Concentration of tannin/lignin with respects to time</td>
<td>179</td>
</tr>
</tbody>
</table>
# LIST OF ABBREVIATIONS

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Full Form</th>
</tr>
</thead>
<tbody>
<tr>
<td>AOPs</td>
<td>Advanced oxidation processes</td>
</tr>
<tr>
<td>Ar</td>
<td>Argon</td>
</tr>
<tr>
<td>AC</td>
<td>Acoustic cavitation</td>
</tr>
<tr>
<td>AF</td>
<td>Anaerobic filter</td>
</tr>
<tr>
<td>AHR</td>
<td>Anaerobic hybrid reactor</td>
</tr>
<tr>
<td>ABF</td>
<td>Anaerobic baffled filter</td>
</tr>
<tr>
<td>ADF</td>
<td>Anaerobic downflow filter</td>
</tr>
<tr>
<td>ABSR</td>
<td>Anaerobic bench scale reactor</td>
</tr>
<tr>
<td>ADMI</td>
<td>American Dye Manufacturing Index</td>
</tr>
<tr>
<td>AN</td>
<td>Ammoniacal nitrogen</td>
</tr>
<tr>
<td>AC</td>
<td>Activated carbon</td>
</tr>
<tr>
<td>BOD</td>
<td>Biological oxygen demand</td>
</tr>
<tr>
<td>BT-POME</td>
<td>Biological treated palm oil mill effluent</td>
</tr>
<tr>
<td>COD</td>
<td>Chemical oxygen demand</td>
</tr>
<tr>
<td>FBR</td>
<td>Fluidised bed reactor</td>
</tr>
<tr>
<td>HC</td>
<td>Hydrodynamic cavitation</td>
</tr>
<tr>
<td>H$_2$O$_2$</td>
<td>Hydrogen peroxide</td>
</tr>
<tr>
<td>HRT</td>
<td>Hydraulic retention time</td>
</tr>
<tr>
<td>HCl</td>
<td>Hydrochloric acid</td>
</tr>
<tr>
<td>KI</td>
<td>Potassium iodide</td>
</tr>
<tr>
<td>MLSS</td>
<td>Mixed liquor suspended solids</td>
</tr>
<tr>
<td>MWCO</td>
<td>Molecular weight cut-off</td>
</tr>
<tr>
<td>MBR</td>
<td>Membrane bioreactor</td>
</tr>
<tr>
<td>MTBE</td>
<td>Methyl-tert-butyl ether</td>
</tr>
<tr>
<td>O&amp;G</td>
<td>Oil &amp; grease</td>
</tr>
<tr>
<td>OLR</td>
<td>Organic loading rate</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Description</td>
</tr>
<tr>
<td>--------------</td>
<td>-------------</td>
</tr>
<tr>
<td>POME</td>
<td>Palm oil mill effluent</td>
</tr>
<tr>
<td>P1</td>
<td>Plate 1</td>
</tr>
<tr>
<td>P2</td>
<td>Plate 2</td>
</tr>
<tr>
<td>P3</td>
<td>Plate 3</td>
</tr>
<tr>
<td>P4</td>
<td>Plate 4</td>
</tr>
<tr>
<td>P5</td>
<td>Plate 5</td>
</tr>
<tr>
<td>P6</td>
<td>Plate 6</td>
</tr>
<tr>
<td>RO4</td>
<td>Reactive orange 4</td>
</tr>
<tr>
<td>RBC</td>
<td>Rotating biological contactor</td>
</tr>
<tr>
<td>RR2</td>
<td>Reactive Red 2</td>
</tr>
<tr>
<td>TOC</td>
<td>Total organic carbon</td>
</tr>
<tr>
<td>TSS</td>
<td>Total suspended solids</td>
</tr>
<tr>
<td>TP</td>
<td>Total phosphorus</td>
</tr>
<tr>
<td>TN</td>
<td>Total nitrogen</td>
</tr>
<tr>
<td>UASB</td>
<td>Up-flow anaerobic sludge blanket</td>
</tr>
<tr>
<td>UF</td>
<td>Ultrafiltration</td>
</tr>
<tr>
<td>US</td>
<td>Ultrasound</td>
</tr>
<tr>
<td>VSS</td>
<td>Volatile suspended solids</td>
</tr>
</tbody>
</table>
LIST OF SYMBOLS

A - Total weight of flask
B - Tare weight of flask
Cv - Cavitation number
dh - Diameter of the orifice
g - Gravity acceleration
H - Pressure head
H - Hydrogen atoms
HO - Hydroxyl radical
I3 - Iodine molecules
Na2SO4 - Sodium sulphate
N2 - Nitrogen
NaOH - Sodium hydroxide
n - Number of holes of orifice plate
O2 - Oxygen
P2 - Downstream pressure of liquid
Pv - Vapour pressure of liquid
Q - Flow rate in the main line
R - Alkyl radical
RH - Organic substrate
ROH - Hydroxylated adduct-radical
ROO - Peroxyl radical
ROOH - Hydroperoxides
t - Time of operation
v - Velocity of liquid
vo - Velocity at the orifice
vp - Fluid velocity of inlet pipe
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha$</td>
<td>Total perimeter of orifices/total area of orifices</td>
</tr>
<tr>
<td>$\beta$</td>
<td>Total area of orifices/cross sectional area of pipe</td>
</tr>
<tr>
<td>$\rho$</td>
<td>Density of the liquid</td>
</tr>
</tbody>
</table>
CHAPTER 1

INTRODUCTION

1.1 Preamble

Advanced oxidation processes (AOPs) are treatment technologies that use free radicals, particularly hydroxyl radicals (HO•) as a medium to attack and degrade organic substances. The HO• can be formed in AOPs under photochemical and non-photochemical procedures (Quiroz et al., 2011). The photochemicals consist of photo-fenton, heterogeneous photocatalysis, UV/H₂O₂ and UV/O₃. The non-photochemicals consist of alkaline media ozonation, O₃/H₂O₂, fenton and fenton-like reactions, electrochemical oxidation, cavitation and sub/super critical water.

AOPs offer several advantages against other processes such as easy operation, high efficiency, less production of residuals and toxic intermediates in the wastewater treatment (Jawale et al., 2014). The formation of HO• and other free radicals such as H·, HO₂• and H₂O₂ contain powerful oxidizing potential which is able to degrade target contaminants in aqueous solutions (Zhang et al., 2014). However, among free radicals released, only hydroxyl radical (HO•) is of particular interest because of their high oxidation capability. Its oxidizing capacity is up to 10⁹ M⁻¹·s⁻¹ stronger than ozone with second order reaction rate constant in the range of 10⁶ – 10⁹ M⁻¹·s⁻¹ (Aris, 2008).

The formation of HO• oxidise target pollutant molecules and decompose them non-selectively to less harmful substances, leading to the ultimate mineralization products of carbon dioxide (CO₂) and water (H₂O) (Cheng et al.,
In these process, the HO· involves three possible mechanisms for pollutant decomposition in contaminated water which are electron transfer, radical addition and hydrogen abstraction (Mehrjouei et al., 2015).

One of techniques that can be utilised to generate HO· is cavitation. The collapse of microbubbles or cavities in cavitation can be violent enough to produce radicals. Cavitation consists of four techniques, namely acoustic, hydrodynamic, optic and particle cavitation (Gogate, 2010). Compared to other cavitation techniques, hydrodynamic cavitation (HC) is a better alternative technique to generate HO· (Parsa et al., 2013). In recent years, HC has gained considerable importance as it is a relatively benign technique with respect to economic and environmental considerations. The use of HC is preferred to generate HO· because of less energy consumption (Arrojo and Benito, 2008; Arrojo et al., 2007; Ambulgekar et al., 2004; Gogate, 2002; Kumar et al., 2000), simpler reaction device (Gogate and Kabadi, 2009; Ambulgekar et al., 2004; Gogate, 2002), lower maintenance cost and more convenient operation (Zhang et al., 2014).

The HC process involves the formation, growth and subsequent collapse of cavities that occur at small intervals of time and emit large amount of energy at several locations in a very small reactor. The HO· is produced from the cavitation activities as it is induced by the passage of liquid through simple mechanical constrictions (orifice plate) under controlled conditions (Jadhav et al., 2013). At the vena-contracta of the constriction, the pressure of the liquid is reduced lower than the vapour pressure of the liquid as it passes through the mechanical constriction at the operating temperature, hence producing a large amount of cavities. During system operation, the reduced pressure is recovered by the flow of liquid ending up at the downstream section of the constriction resulting in the subsequent collapse of the generation of cavities and the release of millions of radicals (Moholkar et al., 1999).

Hydrodynamic cavitation has offered considerable promise in wastewater treatment applications due to its ability to generate HO· in situ and the ease of operation. The successful degradation of organic pollutants using HC involved two
main mechanisms which are the reaction of \( \text{HO}^\cdot \) with the pollutants and thermal decomposition of the volatile pollutant molecule entrapped inside the cavity (Jawale et al., 2014). Wang et al. (2009) have studied on rhodamine B degradation using swirling jet-induced cavitation combined with \( \text{H}_2\text{O}_2 \). Zhang et al. (2009) have investigated the degradation of C.I. Acid Orange 7 using ultrasound enhanced heterogeneous Fenton-like process. Both techniques are acceptable with the performance of rhodamine B degradation is up to 99.2% removal, while 56% of COD removal and 90% of colour removal have been removed from C.I. Acid Orange 7.

The application of HC throughout the past few decades had never been reported on the treatment of biological treated palm oil mill effluent (BT-POME). The tertiary treatment of BT-POME, however, was reported in other techniques including ultrafiltration (UF) membrane (Idris et al., 2010), UV-responsive ZnO photocatalyst (Ng and Cheng, 2016) and fenton’s oxidation (Aris et al., 2008). The degradation of BT-POME is approximately in the ranged of 64% - 82.4% of COD removal and the colour removal is increased as high as 92.4% when using fenton’s oxidation. The performance of AOPs and other techniques responded to the pollutants of BT-POME, HC method therefore could be adopted as an alternative approach for tertiary treatment of BT-POME considering of its achievement in degrading pollutants in other wastewaters.

1.2 Problem Statement

The generation of \( \text{HO}^\cdot \) using cavitation technique has been conducted using HC reactor. The most preferred cavitation technique is the use of the orifice plate as constriction device, which operate individually in circulation closed loop reactor (Balasundaram and Harrison, 2006; Ambulgekar et al., 2004; Sivakumar and Pandit, 2002; Vichare et al., 2000). Several studies have been conducted to improve the capacity of HC in generating the radicals. Wang et al. (2015) and Ghayal et al. (2013) have studied the performance of multiple orifice in a single plate to generate
the radicals. Additional constriction of venturi within multi-hole orifice plates have been to extend the degradation of Rhodamine B has been reported by Mishra and Gogate (2010), while Chakinala et al. (2008) have used chloroalkanes as additives in improving the performance of HC. Similarly, Ambulgekar et al. (2004) and Wu et al. (2015) studied the effect of aqueous potassium permanganate and hydrogen peroxide, respectively in enhancing the efficacy of cavitation.

To date, study on the HO$^-$ production using multiple-plate combination considering the number and arrangement of plates has not yet been published. The use of multiple-plate using HC operational mode is expected to enhance the production of huge amounts of cavities as well as the possibility of collapsing cavities enabling the formation of more HO$^-$. In addition, although pH, aeration and hydrogen peroxide has proven to generate more HO$^-$ in cavitation process (Li et al., 2015; Gogate and Katekhaye, 2012; Gore et al., 2014) it has never been studied on multiple-plate combination. The formation of radicals is expected to sufficiently degrade organic pollutants in wastewater treatment.

The most common and conventional method to treat POME is ponding system. Its performance in treating POME was previously evaluated; however, the performance characteristics in relation to colour of the POME has never been reported.

Colour removal for POME treatment is still an unsolved problem. While the use of techniques such as membrane separation and carbon adsorption has been reported, their applications are still remote due to unattractive cost. HC could provide another alternative in dealing with the problem. Therefore, this study focuses on the production of HO$^-$ using HC reactor with the novel multiple-plate combinations that are anticipated to accelerate the formation of HO$^-$. This technique is then tested for further removal of COD and colour of BT-POME.
1.3 Objectives of the Study

The aim of this study is to generate HO· using HC reactor with multiple-plate combinations under appropriate conditions. The formation of HO· observed in potassium iodide solution (KI solution) is compared with their performance with BT-POME. Special attention is directed to the selected conditions for the formation of HO· based on iodine liberation in KI solution and the best conditions for the degradation of BT-POME especially on COD and colour removal are selected.

The detailed objectives of this study are as follows:

i. To evaluate the effect of HC plate configurations and arrangements in terms of orifice characteristics and number of plate on the generation of the HO·.

ii. To determine the effect of pH, H₂O₂ dosing and aeration on the performance of HC.

iii. To investigate the performance of the existing POME’s pond treatment system and to relate the performance characteristics in determining the colour causing compounds.

iv. To assess the performance of the HC process in treating BT-POME with respect to COD and colour removal, colour causing compounds, and by-products formation and degradation.

1.4 Scope of the Study

This study involves the design, fabrication and application of a 10-litre laboratory-scale of HC reactor. The design and operation of the reactor were based on the system developed by Vichare et al. (2000). In order to enhance the formation of HO·, the cavitation chamber was modified to suit multiple-plate combinations.
The experimental works were conducted separately for observing the generation of HO\(^\cdot\) and treatment of BT-POME. The performance in generating HO\(^\cdot\) was observed initially in KI solution and later implemented on BT-POME. The BT-POME sample was obtained from the discharge point of the treatment ponds at Felda Bukit Besar palm oil mill. The POME in previously analysed on its characteristics from six sources of raw POME and treatment ponds. The optimised HC was later tested for treating BT-POME. Six plates with different configurations were used in this study. The plates were arranged in sequence for single-, double- and triple-plate with the distance between plates were 10cm and 20 cm. The effects of pH, hydrogen peroxide (H\(_2\)O\(_2\)) and aeration in accelerating the formation of HO\(^\cdot\) was also investigated. The statistical approach using Excel (Microsoft), Minitab v17 (Minitab) and SPSS (IBM) for an in-depth study of the parameters involved.

1.5 Significance of the Study

The application of HC to generate HO\(^\cdot\) employing orifice plate have been extensively reported (Braeutigam et al., 2010; Balasundaram and Harrison, 2006; Kanthale et al., 2005; Gogate and Pandit, 2000; Moholkar and Pandit, 1997). In addition, HC has been studied extensively for the improvement in terms of the generation of HO\(^\cdot\) (Gogate and Patil, 2014; Gore et al., 2014; Wu et al., 2012; Franke et al., 2011; Pradhan and Gogate, 2010; Chakinala et al., 2009; Jyoti and Pandit, 2003). However, the use of multiple-plate combinations appears to be missing in the experimental study. The significance of this study are, therefore, listed as follows;

i. This study provides design and technical procedural inputs of a lab-scale HC system which was not covered in the literature. It was modified specifically for the multiple-plate combinations and to explore some other aspects of HC.
ii. The study verified the advantages of multiple-plate combinations as compared to single plate to enhance the formation of HO'. The generation of HO' was determined based on iodine liberation.

iii. The present study provides a better understanding of the factors that affect colour of the POME. It provides a statistical relationship describing how the colour is related with other factors.

iv. This study determines the viability of HC as tertiary treatment of BT-POME under the current conditions involved. In order to verify the performance of HO' generated, the reduction of COD and colour were quantified during the operation under similar conditions.
REFERENCES


Gogate, P.R. (2011). Hydrodynamic cavitation for food and water processing. *Food and Bioprocess Technology*, 4, 6, 996 - 1011.


Nazir, N.M. (2013). *Biodeolourisation of Palm Oil Mill Effluent (POME) by selected exogenous bacteria*. Masters, Universiti Teknologi Malaysia, Skudai.


