Copyright is owned by the Author of the thesis. Permission is given for a copy to be downloaded by an individual for the purpose of research and private study only. The thesis may not be reproduced elsewhere without the permission of the Author.

EVALUATING A NOVEL UV DEVICE FOR WASTEWATER DISINFECTION

A thesis presented in partial fulfilment of the requirements for the degree of

Master of Engineering

In

Environmental Technology and Sustainable Energy

At

Massey University,

Manawatu Campus, Palmerston North, New Zealand.

Confidential

Huijian Huang

2014

Abstract

UV disinfection is the most common method used in wastewater disinfection. However, some types of wastewater effluent have a low UV transmittance (UVT), which cannot be disinfected efficiently by a commercial UV reactor. A novel UV reactor (called the *project prototype*) was developed, which has a different type of reactor hydraulics than a typical commercial UV reactor. This change in hydraulics is believed to be an innovative method of improving the low UVT fluid disinfection. The main purpose of this project is to evaluate the feasibility the project prototype.

The settings of the project prototype were first refined, and then compared to a control reactor, which was used to mimic a commercial UV reactor (called the commercial unit) at a range of UV doses. The UV dose was manipulated by changing the number of operated UV lamps and operated flow rate of the reactors. The disinfection performance of the reactors was not only compared at conventional wastewater treatment plants, but also at stabilization ponds. Within the conventional wastewater treatment plants, the reactors were tested using the effluent from the primary, secondary and tertiary treatment stages. In total, the reactors were compared twelve times at seven different wastewater treatment sites.

The results show that the project prototype was, on average, 1.4 times worse than the commercial unit at treating tertiary wastewater, where the wastewater had a high UVT (55 to 65%). This high UVT value favours the use of the commercial unit, as it is designed for this UVT range. However, at a low UVT range, the project prototype performed, on average, 1.4 times better than the commercial unit, at treating secondary wastewater, where the wastewater had UVT of 22 to 55 %. In the stabilization pond tests, where the UVT was 11 to 25%, the project prototype performed 2.1 times better than the commercial unit on average, and up to 8 times better at one location. In the primary treatment test, where the UVT of the wastewater was extremely low (5%), the project prototype, on average, performed 4.5 times better than the commercial unit, and in one case up to 13 times better than the commercial unit.

The research found that the project prototype has an advantage when treating low UVT fluid and great potential in the commercial market. The project prototype performs better

than the commercial unit at stabilization ponds. This suggests that the project prototype would be a viable option for pond treated wastewater disinfection. In addition, the project prototype offers superior performance on primary treated wastewater. This indicates the potential application at marine outfalls (primary treated wastewater), and the possibility of primary wastewater disinfection for irrigation. Overall, this research confirms the feasibility of the novel reactor in wastewater disinfection.

Acknowledgements

I cannot express my profound gratitude and deep regards enough to my supervisors for their continued support and professional guidance. Firstly, Professor Andy Shilton (Massey University, New Zealand) who did not only provide valuable advice, but also technical and financial support throughout the project. Also, Doctor Nicola Brown (Massey University, New Zealand) who provided many constructive suggestions and helped me in many other ways throughout.

In addition to my supervisors, I was fortunate enough to conduct experiments in different wastewater treatment plants. I would like to acknowledge the Mike Monaghan at the Palmerston North wastewater treatment plant, Steve Nind at the Manawatu district council, Marcus Coley and Joel Dykstra at the Levin wastewater treatment plant and Grant Stuart and Dave Bassett at the Paraparaumu wastewater treatment plant. Without their help, I would not have such a valuable experimental data.

I would also like to thank Mr Aidan Crimp, who helped me a lot in the experiments and also gave me a lot of useful information and ideas. Also, I would like to acknowledge the many members of the technical staff from Massey University, who gave me a lot of help.

Last but not less, I would like to acknowledge my God. I believe that I would not be able to finish my master thesis without His help, as Proverbs 1:7 “The fear of the Lord is the beginning of knowledge, but fools despise wisdom and instruction”.

This thesis is dedicated to my father Zhaoguang Huang and mother Qiaosheng Lu who always support me.

Table of Contents

Abstract ii

Acknowledgements iv

List of Figure ix

List of Table xiii

1. Introduction 1

1.1. Background 1

1.2. Research needs 1

1.3. The potential market 2

1.4. Project aim and objectives 2

2. Literature review 3

2.1. What UV light is 3

2.1.1. UV light propagation behaviours 4

2.1.2. Beer Lambert's Law 4

2.2. UV disinfection mechanisms 5

2.2.1. Wavelength and UV disinfection 6

2.2.2. Repair mechanism 8

2.3. UV emission & the technology 9

2.3.1. Low pressure mercury lamp 10

2.3.2. Medium pressure mercury lamp 11

2.3.3. Other light technologies 11

2.4. Effect of wastewater characteristics on UV disinfection 12

2.4.1. UV transmittance (UVT) 13

2.4.2. Total suspended solid (TSS) 14

2.4.3. Microorganism concentration 15

2.5. UV dose 15

2.6. The effect of hydraulics on UV disinfection 17
2.6.1. Plug flow hydraulics vs. complete mix hydraulics 17
2.6.2. The effect of lamp spacing on UV disinfection 19
2.6.3. The effect of reactor configuration on UV disinfection 20
2.6.4. A concept of supercritical flow UV disinfection 21
2.7. Prior art 25
2.7.1. Common design in wastewater treatment 26
2.7.2. Review of thin film UV reactors 27
2.7.3. Reactors comparisons 39
2.8. Literature review summary 42
3. Method and materials 43
3.1. Reactors 43
3.1.1. The 2nd generation 43
3.1.2. The project prototype 44
3.1.3. The Commercial unit 48
3.2. Reactor components and instrument 50
3.2.1. UV lamps 50
3.2.2. Ballast 50
3.2.3. UV intensity meter 50
3.2.4. Flow rate control device 50
3.3. Experimental procedure 51
3.3.1. Comparison of the project prototype and the 2nd generation 51
3.3.2. Project prototype variable test 52
3.3.3. Comparison of the project prototype and the commercial unit 52
3.4. Methods of analysis 61
3.4.1. Pathogen indicator for wastewater test 61

3.4.2. Bacteria enumeration 61
3.4.3. UV Transmittance 62
3.4.4. Total suspended solid 63
3.4.5. Quality control 63
4. Results and discussion 65
4.1. Comparison of the project prototype and the 2nd generation 65
4.2. Project prototype variable test 67
4.2.1. The effect of sluice gate gap thickness on UV disinfection 68
4.2.2. The effect of reaction chamber slope on UV disinfection 69
4.2.3. The effect of reflector shape on UV disinfection 70
4.3. Comparisons of the project prototype and commercial unit 71
4.3.1. Primary treated wastewater test 72
4.3.2. Secondary treated wastewater test 77
4.3.3. Tertiary treated wastewater test 82
4.3.4. Stabilization pond treated wastewater test 86
4.3.5. Summary of the project prototype and commercial unit comparison 95
4.4. Effect of flow rate on UV disinfection 96
4.5. Wastewater characteristics that affect the UV disinfection 97
4.5.1. The desirable wastewater for the project prototype 98
5. Conclusions and recommendations 103
6. Reference 105
7. Appendix 110
Appendix 1, Raw data 111
Pre-experimental data (no used in the discussion) 111
Project prototype vs. second generation 113
Project prototype variation test 116

Comparison of project prototype and commercial unit 120
Appendix 2, Patent review note 169
Scopus patent search 169
Google patent search results 176
Appendix 3, Froude number calculations 190
Appendix 4, Reflector designs 191
Appendix 5, Commercial unit design 192
Appendix 6, UV lamp- GPH840N2/S 196
Appendix 7, Ballast Information Sheet 197
Appendix 8, Flow meter information 198
Appendix 9, Wastewater consistency check 199
Appendix 10, Reliability of the sample analysis 200
Appendix 11, Statistical analysis of the results 202
P-value of 2nd generation prototype vs. project prototype 202
P-value for the project prototype variable test 203
Regression analyses of the project prototype vs. commercial unit 204
Wastewater characteristics that affect the UV disinfection 207

List of Figure

Figure 2-1, Range of electromagnetic waves 3
Figure 2-2, Irradiation profile of a single lamp in fluid (adapted from Masschelein & Rice, 2002, p. 86) 4
Figure 2-3, Chemical reaction of thymine dimer (Bolton & Cotton, 2008, p. page 28) 6
Figure 2-4, Disrupted DNA (Bolton & Cotton, 2008, p. 28) 6
Figure 2-5, UV absorbance of DNA or RNA bases (Masschelein & Rice, 2002, p. 63) 7
Figure 2-6, Relative UV absorbance of some microorganism and DNA (Bolton & Cotton, 2008, p. 29) 7
Figure 2-7, Spontaneous emission illustration (Masschelein & Rice, 2002, p. 10) 10
Figure 2-8, Comparison of low pressure mercury lamp (LP) and medium pressure mercury lamp (MP) emission spectrum with DNA absorptivity (USEPA *et al.*, 2006, pp. 2-21) 10
Figure 2-9, Lifetime of low pressure mercury lamp (LightTech) 11
Figure 2-10, Dose response curve of microorganisms (Chang *et al.*, 1985) 16
Figure 2-11, Two types of hypothetical dose distribution, adapted from USEPA *et al.* (2006, pp. 2-10) 18
Figure 2-12, Hypothetical Reactor A and Reactor B 19
Figure 2-13, illustration of hydraulic boundary layer 20
Figure 2-14, Different UV reactors that were assessed in Wols *et al.* (2011) study 21
Figure 2-15, The supercritical flow UV reactor (Shilton & Sykes, 2009) 23
Figure 2-16, Steriflo 900 (Shilton & Sykes, 2009) 24
Figure 2-17, Steriflo Channel reactor (Shilton & Sykes, 2009) 24
Figure 2-18, Typical open channel system, (a) horizontal lamps position; (b) vertical lamp position (Metcalf & Eddy, 2003, p. 1302) 26
Figure 2-19, Typical close channel system, (a) perpendicular lamp position; (b) parallel lamp position (Metcalf & Eddy, 2003, pp. 1304-1305) 27
Figure 2-20, UV reactor in Lu *et al.* (2010) study 28
Figure 2-21, Typical thin film UV reactor for juice/cider (Koutchma, 2008) 29
Figure 2-22, UV reactor configuration in Oppenheimer *et al.* (1959) 31
Figure 2-23, Special valve design for the reactor (Shama *et al.*, 1996) 32
Figure 2-24, UV reactor designed by Shama *et al.* (1996) 32

Figure 2-25, Open channel, low head UV reactor (Mamane *et al.*, 2010) 33
Figure 2-26, UV source component, (a) Top view of the reactor UV source; (b) Side view of reactor UV source (Mamane *et al.*, 2010) 33
Figure 2-27, UV dose measurement of the open channel, low head UV reactor (Mamane *et al.*, 2010) 34
Figure 2-28, UV liquid steriliser (Snowball, 2012) 35
Figure 2-29, Fluid disinfection apparatus from Snowball (2009) 36
Figure 2-30, Fluid disinfection apparatus and system from Snowball (2007) 37
Figure 2-31, Ultraviolet fluid disinfection system from Horton *et al.* (2002) 38
Figure 2-32, Ultraviolet wastewater disinfection system and method from Horton (2002) .. 39
Figure 3-1, Pictures of the reactors in the project (A: the 2nd generation; B: the project prototype; C: the commercial unit) 43
Figure 3-2, Sketch of the 2nd generation 44
Figure 3-3, Adjustable gap of the 2nd generation 44
Figure 3-4, Sketch of the project prototype; A: 3D sketch, B: 2 D sketch 45
Figure 3-5, The adjustable sluice gate of the project prototype 46
Figure 3-6, Demonstration of flow slope adjustable of the project prototype 47
Figure 3-7, Parabola reflector (A: top of reflector; B: underside of the reflector; C: reflector on the project prototype) 47
Figure 3-8, Square reflector (A: top of reflector; B: underside of the reflector; C: reflector on the project prototype) 48
Figure 3-9, Sketch of the commercial unit 49
Figure 3-10, Relationship between watt per flow and UV dose in a reactor, data from Nieuwstad *et al.* (1991) 53
Figure 3-11, PNWWTP process 56
Figure 3-12, Levin WWTP treatment process 56
Figure 3-13, Experimental set in the aerated lagoon pond 57
Figure 3-14, Paraparaumu WWTP process 58
Figure 3-15, Fielding WWTP process 58
Figure 3-16, Experimental set up in Rongotea stabilization pond 59
Figure 3-17, Shannon pond system and the experimental set up 60
Figure 3-18, Foxton beach pond system and the experimental set up 60

Figure 3-19, Colilert test procedure (adapted from IDEXX Laboratories, 2013) 62
Figure 4-1, Box plot of the project prototype performance vs. 2nd generation performance, at the sluice gate gaps of 2, 4 and 6 mm, treating low UVT wastewater 66
Figure 4-2, Box plot of the project prototype performance vs. 2nd generation performance, at the sluice gate gap of 2 mm, treating high UVT wastewater 67
Figure 4-3, Box plot of the project prototype performance at the sluice gate gaps of 2, 4, and 6 mm, treating high and low UVT wastewater 68
Figure 4-4, Box plot of the project prototype performance at the reaction chamber slopes of 0, 30 and 60 degree, treating high and low UVT wastewater 69
Figure 4-5, Box plot of the project prototype performance using the parabola and square shaped reflectors, treating both high and low UVT wastewater 71
Figure 4-6, *E. coli* log reduction of the reactors in the PNWWTP primary treated test; Commercial unit: *E. coli* log reduction of the commercial unit; prototype at 500 L/min: *E. coli* log reduction of the project prototype at flow rate of 500 L/min; likewise for the rest of the figures 72
Figure 4-7, *E. coli* log reduction of the reactors in the Levin WWTP primary treated test 74
Figure 4-8, p/c of the project prototype and commercial unit in the primary treated wastewater test 76
Figure 4-9, *E. coli* log reduction of the reactors in the PNWWTP secondary treated wastewater test 78
Figure 4-10, *E. coli* log reduction of the reactors in the Levin WWTP secondary treated wastewater test 79
Figure 4-11, *E. coli* log reduction of the reactors in the Paraparaumu WWTP secondary treated wastewater test 80
Figure 4-12, p/c of the project prototype and commercial unit in the secondary treated wastewater test 81
Figure 4-13, *E. coli* log reduction of the reactors in the PNWWTP tertiary treated wastewater test 83
Figure 4-14, *E. coli* log reduction of the reactors in the Fielding WWTP tertiary treated wastewater test 85
Figure 4-15, p/c of the project prototype and commercial unit in the tertiary treated wastewater test 86

Figure 4-16, *E. coli* log reduction of the reactors in the first Rongotea stabilization pond test 88
Figure 4-17, *E. coli* log reduction of the reactors in the second Rongotea stabilization pond test 89
Figure 4-18, *E. coli* log reduction of the reactors in the first Shannon stabilization pond test 90
Figure 4-19, *E. coli* log reduction of the reactors in the second Shannon stabilization pond test 91
Figure 4-20, *E. coli* log reduction of the reactors in the Foxton Beach stabilization pond test 93
Figure 4-21, p/c of the project prototype and commercial unit in the stabilization pond treated wastewater test 94
Figure 4-22, summary of the reactor comparison in different type of wastewaters 95
Figure 4-23, performances of the reactors at PNWWTP 98
Figure 4-24, p/c vs. UVT 99
Figure 4-25, p/c vs. TSS 100
Figure 4-26, p/c vs. initial *E. coli* concentration 101
Figure A-7-1, design of parabola shaped reflector 191
Figure A-7-2, design of square shaped reflector 191
Figure A-7-3, commercial unit design (a) 192
Figure A-7-4, commercial unit design (b) 193
Figure A-7-5, weir design of the commercial unit 194
Figure A-7-6, lamp positions of the commercial unit 195
Figure A-7-7, information of the UV lamps used in the project 196
Figure A-7-8, information of the ballast used in the project 197
Figure A-7-9, information of the flow meter used in the project 198
Figure A-7-10, *E. coli* concentration of the secondary treated wastewater from PNWWTP in a period of 45 minute 199
Figure A-7-11, CEL vs experimental results 200
Figure A-7-12, comparison of CEL, second comparison 201

List of Table

Table 2-1, Wastewater characteristic that effect on UV disinfection (Metcalf & Eddy, 2003, p. 1309) 13
Table 2-2, Lu *et al.* (2010) experimental data 29
Table 2-3, comparison of prior art with project prototype 40
Table 3-1, Reactors operational conditions in the early stage 54
Table 3-2, Modified reactors operational conditions 54
Table 3-3, Summary of the UV trials 55
Table 4-1, summary of the effect of flow rate on the project prototype 96
Table A-1, summary of key words search 169
Table A-2, Scopus patent search summary 170
Table A-3, google patent search summary 177
Table A-4, Found number at each setting 190
Table A-5, p-value of Figure A-7-12 results 201
Table A-6, P-values of 2nd generation vs. project prototype at different sluice gate gaps at low UVT wastewater condition (Figure 4-1) 202
Table A-7, p-values of reactors performance at different sluice gate gaps at low UVT wastewater conditions (Figure 4-1) 202
Table A-8, p-values of 2nd generation vs. project prototype at different UVT wastewater conditions (Figure 4-2) 202
Table A-9, p-values of reactors performance at different UVT wastewater conditions 202
Table A-10, p-values of the project prototype performance at different sluice gate gaps at both UVT wastewater conditions (Figure 4-3) 203
Table A-11, p-values of the project prototype performance at different UVT wastewater conditions (Figure 4-3) 203
Table A-12, p-values of the project prototype performance at different reaction chamber slopes at both UVT wastewater conditions (Figure 4-4) 203
Table A-13, p-value of the project prototype performance at different UVT wastewater conditions (Figure 4-4) 203
Table A-14, p-values of the project prototype with different reflector at both UVT wastewater conditions (Figure 4-5) 203

Table A-15, p-values of the project prototype performance at different UVT wastewater conditions (Figure 4-5) 203
Table A-16, Regression analyses of PNWWTP primary treated wastewater test (Figure 4-6) 204
Table A-17, Regression analyses of Levin primary treated wastewater test (Figure 4-7) 204
Table A-18, Regression analyses of PNWWTP secondary treated wastewater test (Figure 4-9) 204
Table A-19, Regression analyses of Levin WWTP secondary treated wastewater test (Figure 4-10) 204
Table A-20, Regression analyses of Paraparaumu WWTP secondary treated wastewater test (Figure 4-11) 205
Table A-21, Regression analyses of PNWWTP tertiary treated wastewater test (Figure 4-13) 205
Table A-22, Regression analyses of Fielding WWTP tertiary treated wastewater test (Figure 4-14) 205
Table A-23, Regression analyses of the first Rongotea stabilization pond treated wastewater test (Figure 4-16) 205
Table A-24, Regression analyses of the second Rongotea stabilization pond treated wastewater test (Figure 4-17) 206
Table A-25, Regression analyses of the first Shannon stabilization pond treated wastewater test (Figure 4-18) 206
Table A-26, Regression analyses of the first Shannon stabilization pond treated wastewater test (Figure 4-19) 206
Table A-27, Regression analyses of the first Shannon stabilization pond treated wastewater test (Figure 4-20) 206
Table A-28, p-values of the tests comparison for the commercial unit 207
Table A-29, p-values of the tests comparison for the project prototype 207