

# **HYDRODYNAMIC INVESTIGATIONS IN FORCED CONVECTIVE BOILING FLOWS**

**ASHUTOSH YADAV**



**DEPARTMENT OF CHEMICAL ENGINEERING  
INDIAN INSTITUTE OF TECHNOLOGY DELHI**

**MAY 2018**



# **HYDRODYNAMIC INVESTIGATIONS IN FORCED CONVECTIVE BOILING FLOWS**

*by*

**ASHUTOSH YADAV**

**Department of Chemical Engineering**

*Submitted*

*in fulfillment of the requirements of the degree of Doctor of Philosophy*

*to the*



**Indian Institute of Technology Delhi**

**MAY 2018**

## THESIS CERTIFICATE

This is to certify that the thesis entitled '**Hydrodynamic investigations in forced convective boiling flows**' submitted by **Mr. Ashutosh Yadav** to the Indian Institute of Technology-Delhi for the award of degree of **Doctor of Philosophy** is a bona fide record of research work carried out by him under my supervision. The contents of this thesis have not been submitted to any other Institute or University for the award of any degree or diploma.

Date:

IIT Delhi

**Professor Shantanu Roy**

Department of Chemical Engineering

Indian Institute of Technology Delhi

New Delhi 110016, India

## ACKNOWLEDGEMENTS

I wish to express my deep sense of gratitude to my advisor Prof. Shantanu Roy for his guidance, extensive support and effective criticism throughout my research. I have learned to gain perception and manage research problems systematically from him and gained invaluable experience working under his supervision. It was a pleasure to work with him, and he taught me a lot, much more than what is written in this thesis.

I would like to thank my SRC members: Prof. V. V. Buwa, Prof. Anjan Ray, and Dr. Jyoti Phirani, for their encouragement and useful comments. I take this opportunity to thank Dr. Manojkumar Ramteke for his valuable suggestions on implementation of the Genetic Algorithm, Prof. J. B. Joshi for his valuable discussion on Advanced Heavy Water Reactor (AHWR) and Dr. H. J. Pant for his assistance and guidance in tracer particle making and residence time distribution studies. I would also thank Dr. Markus Schubert, Dr. Dinesh V. Kalaga and Salar Azizi for critical discussions on bubble columns.

I acknowledge our industrial partner Bhabha Atomic Research Centre (BARC) and Ministry of Human Resource Development (MHRD) for their financial support during my research period.

My time in IIT Delhi would not have been same without the inspiring exchanges and laughs provided by my friends and colleagues, including Tahmeed, Loveleen, Deepali, Meenakshi, Ravinder, Indranil, and Aakarsha. Special thanks to Puneet and Sangram for our regular fruitful discussions and all the fun memories. I am extremely grateful to Mr. Brahm Prakash for his assistance in setting up the experimental setups. Also, I would like to thank Naresh and Girish for their excellent assistance in the lab. I want to acknowledge my friends Pankaj, Rohit, Rachit, Avinash, and specially Dharmansh for weekend parties.

Above all, I express my very profound gratitude to my parents and sister for their support, courage, and love throughout my years of study. Thank you for your blessings and providing me a solid foundation to build my life on.

Ashutosh Yadav

## ABSTRACT

The design, performance and safety analysis of nuclear reactors, in particular, Boiling Water Reactors (BWRs), require accurate and extensive information about the vapor-liquid water flow dynamics. Computational fluid dynamics (CFD) has evolved over the last several decades as an important tool for improving the safety and performance of the nuclear reactors. However, CFD results must be validated and verified by reliable experimental data (at multiple scales) to guarantee, with adequate confidence, the reliability and worth of the model predictions. Most of the experimental data available in the literature suffer from the limitations posed by conventional invasive techniques, which interfere with the flow itself. Their limitations are magnified in the context of flow boiling wherein bubble nucleation and vapor evolution is known to be a complex and multi-scale problem. Additionally, the experiments performed in the past are predominantly based on test sections which are single rod annular geometry or rectangular geometry. Also, most of the experimental data available in the past are based on systems operating at a very high pressure and high flow rates.

The present thesis focuses on investigating multiphase flow dynamics of convective boiling flows on two test sections. In this process, two non-invasive techniques i.e.  $\gamma$ -ray densitometry and Radioactive Particle Tracking (RPT) has been developed for performing experiments pertaining to boiling flows. The first test section is a vertical annular channel of single heater rod whereas the second experimental test section has the provision of holding different heater rods arrangements. For both experimental test sections, experiments were performed at the different inlet flow conditions, i.e., inlet flow rates and inlet liquid temperatures. In the case of the second experimental test section, experiments were also performed at various heater rods configuration. Radial and axial void fraction measurements were performed on these experimental test section using non-invasive  $\gamma$ -ray densitometry and Radioactive Particle Tracking (RPT), respectively. Non-invasive Radioactive Particle Tracking

(RPT) has been used for measuring liquid velocity field, mean flow patterns and “turbulent” kinetic energy. The unique aspect of this thesis lies in the fact that non-invasive radiation based techniques have been used for all experimental measurements.

Another aspect of the present thesis was to make RPT suitable for systems having large interrogation volumes and possessing internals such as in the present case. Two new reconstruction algorithms were developed in this thesis. First was the extension of classical Monte-Carlo (MC) technique known as “MC-RGA” technique, whereby the convergence and computational speed of the algorithm are enhanced using Real Coded Genetic Algorithm (RGA). This modification results in drastic reduction in computational time required for detector parameter estimation and altogether eliminates the need for the “distance-count map,” which was earlier inherent to RPT experimentation. RPT application was limited to convective boiling flow experiments owing to the “shadow effect” caused by the solid heater rods. The “shadow effect” makes classical position reconstruction algorithm based on Monte Carlo (MC) technique futile. A novel tracer particle reconstruction algorithm based Support Vector Regression (SVR) and Relevance Vector Machine (RVM) has been applied in this study. The machine learning based reconstruction algorithms were very fast and accurate in terms of position reconstruction.

Apart from providing mean phase velocities and other “turbulence” quantities, RPT also provides the actual Lagrangian trajectory of the tracer particle mimicking liquid phase in the present study. Hence, it is an appropriate method for the detailed characterization of the complex liquid dynamics observed in boiling two-phase flows. The position time series of the radioactive tracer particle conveying information on the liquid motion were examined by Recurrence Plots (RP) and Recurrence Quantification Analysis (RQA). The Lagrangian trajectories were also quantified using mean displacement model. Eddy diffusivity was calculated in axial and radial direction for different experimental conditions.

## सार

परमाणु रिएक्टरों के डिजाइन, प्रदर्शन और सुरक्षा विश्लेषण, विशेष रूप से, उबलते जल रिएक्टरों (बीडब्लूआर), को वाष्प-तरल जल प्रवाह गतिशीलता के बारे में सटीक और व्यापक जानकारी की आवश्यकता होती है। परमाणु रिएक्टरों की सुरक्षा और प्रदर्शन में सुधार के लिए पिछले कई दशकों में कम्प्यूटेशनल तरल गतिशीलता (सीएफडी) विकसित हुआ है। हालांकि, सीएफडी परिणामों को विश्वसनीय प्रयोगात्मक डेटा (एकाधिक पैमाने पर) द्वारा पर्याप्त आत्मविश्वास, विश्वसनीयता और मॉडल भविष्यवाणियों के मूल्य के साथ गारंटी के लिए सत्यापित और सत्यापित किया जाना चाहिए। साहित्य में उपलब्ध अधिकांश प्रयोगात्मक डेटा परंपरागत आक्रामक तकनीकों द्वारा उत्पन्न सीमाओं से ग्रस्त हैं, जो प्रवाह के साथ हस्तक्षेप करते हैं। उनकी सीमाओं को प्रवाह उबलते संदर्भ में बढ़ाया जाता है जिसमें बबल न्यूक्लियेशन और वाष्प विकास को जटिल और बहु-पैमाने की समस्या माना जाता है। इसके अतिरिक्त, अतीत में किए गए प्रयोग मुख्य रूप से परीक्षण खंडों पर आधारित होते हैं जो सिंगल रॉड क्युलर ज्यामिति या आयताकार ज्यामिति होते हैं। इसके अलावा, अतीत में उपलब्ध अधिकांश प्रयोगात्मक डेटा बहुत उच्च दबाव और उच्च प्रवाह दर पर चल रहे सिस्टम पर आधारित होते हैं।

वर्तमान थीसिस दो परीक्षण खंडों पर संवहनी उबलते प्रवाह की मल्टीफेस प्रवाह गतिशीलता की जांच पर केंद्रित है। इस प्रक्रिया में, दो गैर-आक्रामक तकनीकें यानी  $\gamma$ -ray densitometry और रेडियोधर्मी कण ट्रैकिंग (आरपीटी) उबलते प्रवाह से संबंधित प्रयोग करने के लिए विकसित की गई हैं। पहला परीक्षण खंड एकल हीटर रॉड का एक लंबवत कणिका चैनल है जबकि दूसरे प्रयोगात्मक परीक्षण खंड में विभिन्न हीटर रॉड व्यवस्था आयोजित करने का प्रावधान है। प्रयोगात्मक परीक्षण खंड दोनों के लिए, विभिन्न इनलेट प्रवाह स्थितियों, यानी इनलेट प्रवाह दर और इनलेट तरल तापमान पर प्रयोग किए जाते थे। दूसरे प्रयोगात्मक परीक्षण खंड के मामले में, विभिन्न हीटर रॉड विन्यास पर प्रयोग भी किए गए थे। क्रमशः गैर-आक्रामक  $\gamma$ -रे densitometry और रेडियोधर्मी कण ट्रैकिंग (आरपीटी) का उपयोग कर इन प्रयोगात्मक परीक्षण खंड पर रेडियल और अक्षीय शून्य अंश माप किया गया था। गैर-आक्रामक रेडियोधर्मी कण ट्रैकिंग (आरपीटी) का उपयोग तरल वेग क्षेत्र, माध्य प्रवाह पैटर्न और "अशांत" गतिशील ऊर्जा को मापने के लिए किया गया है। इस थीसिस का अनूठा पहलू इस तथ्य में निहित है कि सभी प्रयोगात्मक मापों के लिए गैर-आक्रामक विकिरण आधारित तकनीकों का उपयोग किया गया है।

वर्तमान थीसिस का एक अन्य पहलू आरपीटी को बड़े पृष्ठताछ वाले सिस्टमों के लिए उपयुक्त बनाना था और वर्तमान मामले में आंतरिक जैसे पास रखना था। इस थीसिस में दो नए पुनर्निर्माण एल्गोरिदम विकसित किए गए थे। सबसे पहले शास्त्रीय मोंटे-कार्लो (एमसी) तकनीक का विस्तार "एमसी-आरजीए" तकनीक के रूप में जाना जाता था, जिससे एल्गोरिदम की अभिसरण और कम्प्यूटेशनल गति को वास्तविक कोडित जेनेटिक एल्गोरिदम (आरजीए) का उपयोग करके बढ़ाया जाता है। इस संशोधन के परिणामस्वरूप डिटेक्टर पैरामीटर अनुमान के लिए आवश्यक कम्प्यूटेशनल समय में भारी कमी आई है और पूरी तरह से "दूरी-गणना मानचित्र" की आवश्यकता को समाप्त कर देता है, जो पहले आरपीटी प्रयोग के लिए निहित था। आरपीटी आवेदन ठोस हीटर रॉड के कारण "छाया प्रभाव" के कारण संवहनी उबलते प्रवाह प्रयोगों तक ही सीमित था। "छाया प्रभाव" मोंटे कार्लो (एमसी) तकनीक व्यर्थ पर आधारित शास्त्रीय स्थिति पुनर्निर्माण एल्गोरिदम बनाता है। इस अध्ययन में एक उपन्यास ट्रेसर कण पुनर्निर्माण एल्गोरिदम आधारित समर्थन वेक्टर रिग्रेशन (एसवीआर) और प्रासंगिकता वेक्टर

मशीन (आरबीएम) लागू किया गया है। मशीन पुनर्निर्माण आधारित पुनर्निर्माण एल्गोरिदम स्थिति पुनर्निर्माण के मामले में बहुत तेज़ और सटीक थे।

औसत चरण वेग और अन्य "अशांति" मात्रा प्रदान करने के अलावा, आरपीटी वर्तमान अध्ययन में तरल चरण की नकल करने वाले ट्रेसर कण के वास्तविक लगांगियन प्रक्षेपवक्र को भी प्रदान करता है। इसलिए, उबलते दो चरण प्रवाह में देखी गई जटिल तरल गतिशीलता के विस्तृत लक्षण के लिए यह एक उचित विधि है। रेडियोधर्मी ट्रेसर कण की स्थिति समय श्रृंखला तरल गति पर जानकारी संदेश देने की पुनरावृत्ति प्लॉट्स (आरपी) और पुनरावृत्ति मात्रा विश्लेषण (आरक्यूए) द्वारा जांच की गई थी।

# CONTENTS

|                                                               | Page       |
|---------------------------------------------------------------|------------|
| <b>ACKNOWLEDGEMENTS</b>                                       | <b>i</b>   |
| <b>ABSTRACT</b>                                               | <b>iii</b> |
| <b>CONTENTS</b>                                               | <b>v</b>   |
| <b>LIST OF FIGURES</b>                                        | <b>ix</b>  |
| <b>LIST OF TABLES</b>                                         | <b>xix</b> |
| <b>CHAPTER 1: Introduction</b>                                | <b>1</b>   |
| 1.1. General Introduction                                     | 1          |
| 1.2. Overview                                                 | 6          |
| 1.3. Background                                               | 9          |
| 1.4. Motivation for this Research                             | 10         |
| 1.5. Research Objectives                                      | 12         |
| 1.6. Organisation of the Thesis                               | 12         |
| References                                                    | 13         |
| <b>CHAPTER 2: Background</b>                                  | <b>17</b>  |
| 2.1. Scope                                                    | 17         |
| 2.2. Pool Boiling                                             | 17         |
| 2.3. Flow Boiling                                             | 19         |
| 2.3.1 Non-Isothermal Single-Phase Experiments                 | 23         |
| 2.3.2 Boiling Flow Experiments                                | 24         |
| 2.3.3 Numerical Simulations                                   | 33         |
| Nomenclature                                                  | 40         |
| References                                                    | 42         |
| <b>CHAPTER 3: Experimental Setups</b>                         | <b>47</b>  |
| 3.1. Scope                                                    | 47         |
| 3.2. Single Rod Experimental Setup                            | 48         |
| 3.3. Multiple Heater Rods Experimental Setup                  | 50         |
| <b>CHAPTER 4: Void Fraction Measurements in Boiling Flows</b> | <b>57</b>  |

|                                                                                                     |                                                                                  |            |
|-----------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------|------------|
| 4.1.                                                                                                | Scope                                                                            | 57         |
| 4.2                                                                                                 | Introduction                                                                     | 57         |
| 4.3                                                                                                 | Gamma-Ray Densitometry (GDT)                                                     | 58         |
| 4.4                                                                                                 | Adaptation of Drift Flux Model to Current Work                                   | 62         |
| 4.5                                                                                                 | Results and Discussion                                                           | 65         |
| 4.5.1                                                                                               | Single Heater Rod Setup                                                          | 66         |
| 4.5.2                                                                                               | Multiple Heater Rods Setups                                                      | 84         |
| 4.6                                                                                                 | Summary                                                                          | 98         |
|                                                                                                     | Nomenclature                                                                     | 100        |
|                                                                                                     | References                                                                       | 102        |
| <b>CHAPTER 5: Radioactive Particle Tracking (RPT): MC-RGA Technique for Position Reconstruction</b> |                                                                                  | <b>105</b> |
| 5.1.                                                                                                | Scope                                                                            | 105        |
| 5.2                                                                                                 | Introduction                                                                     | 106        |
| 5.3                                                                                                 | RPT: Background                                                                  | 108        |
| 5.4                                                                                                 | RPT Position Rendering                                                           | 110        |
| 5.5                                                                                                 | Genetic Algorithms: Summary of Relevant Points                                   | 114        |
| 5.6                                                                                                 | The “MC-RGA” Algorithm: This Work                                                | 121        |
| 5.7                                                                                                 | Experimental                                                                     | 123        |
| 5.8                                                                                                 | Results and Discussion                                                           | 128        |
| 5.8.1                                                                                               | MC-RGA application                                                               | 129        |
| 5.9                                                                                                 | Summary                                                                          | 142        |
|                                                                                                     | Nomenclature                                                                     | 143        |
|                                                                                                     | References                                                                       | 144        |
| <b>CHAPTER 6: Machine Learning based RPT Particle Position Reconstruction Algorithms</b>            |                                                                                  | <b>147</b> |
| 6.1                                                                                                 | Scope                                                                            | 147        |
| 6.2                                                                                                 | Introduction                                                                     | 147        |
| 6.3                                                                                                 | Artificial Neural Networks (ANN) based RPT Reconstruction                        | 151        |
| 6.4                                                                                                 | Implementation of Support Vector Regression (SVR) for RPT reconstruction         | 154        |
| 6.5                                                                                                 | Implementation of Relevance Vector Machine (RVM) for RPT Position Reconstruction | 160        |
| 6.6                                                                                                 | Experimental                                                                     | 165        |

|                                                                                                                                                        |                                             |            |
|--------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------|------------|
| 6.7                                                                                                                                                    | Results and Discussion                      | 170        |
| 6.8                                                                                                                                                    | Recommendations                             | 186        |
| 6.9                                                                                                                                                    | Summary                                     | 187        |
|                                                                                                                                                        | Nomenclature                                | 196        |
|                                                                                                                                                        | References                                  | 197        |
| <b>CHAPTER 7: Investigation of Liquid Hydrodynamics in Boiling Flows using<br/>Radioactive Particle Tracking (RPT) Technique</b>                       |                                             | <b>201</b> |
| 7.1                                                                                                                                                    | Scope                                       | 201        |
| 7.2                                                                                                                                                    | Introduction                                | 201        |
| 7.3                                                                                                                                                    | RPT Experimental Implementation             | 204        |
| 7.4                                                                                                                                                    | Eddy Diffusivity Calculation                | 213        |
| 7.5                                                                                                                                                    | Results and Discussion                      | 215        |
|                                                                                                                                                        | 7.5.1 Liquid Velocity Field Measurement     | 216        |
|                                                                                                                                                        | 7.5.2 Liquid Eddy Diffusivity               | 242        |
| 7.6                                                                                                                                                    | Summary                                     | 251        |
|                                                                                                                                                        | Nomenclature                                | 252        |
|                                                                                                                                                        | References                                  | 253        |
| <b>CHAPTER 8: Recurrence Plots and Recurrence Quantification Analysis of<br/>Radioactive Particle Tracking (RPT) Particle Position Time<br/>Series</b> |                                             | <b>257</b> |
| 8.1                                                                                                                                                    | Scope                                       | 257        |
| 8.2                                                                                                                                                    | Introduction                                | 257        |
| 8.3                                                                                                                                                    | Experimental                                | 259        |
| 8.4                                                                                                                                                    | Recurrence Plot (RP): Background            | 262        |
| 8.5                                                                                                                                                    | Recurrence Quantification Analysis (RQA)    | 270        |
| 8.6                                                                                                                                                    | Results and Discussion                      | 272        |
| 8.7                                                                                                                                                    | Summary                                     | 288        |
|                                                                                                                                                        | Nomenclature                                | 289        |
|                                                                                                                                                        | References                                  | 290        |
| <b>CHAPTER 9: Summary, Conclusions and Recommendations</b>                                                                                             |                                             | <b>293</b> |
| 9.1                                                                                                                                                    | Experimental                                | 293        |
| 9.2                                                                                                                                                    | Void Fraction Measurements in Boiling Flows | 293        |

|                   |                                                                                                                                               |            |
|-------------------|-----------------------------------------------------------------------------------------------------------------------------------------------|------------|
| 9.3               | Radioactive Particle Tracking (RPT): MC-RGA Technique for Position Reconstruction                                                             | 295        |
| 9.4               | Machine learning based RPT particle position reconstruction algorithms                                                                        | 296        |
| 9.5               | Investigation of Liquid Hydrodynamics in Boiling Flows using RPT Technique                                                                    | 297        |
| 9.6               | Recurrence Plots and Recurrence Quantification Analysis of RPT Particle Position Time Series                                                  | 298        |
| 9.7               | Thesis Accomplishments                                                                                                                        | 299        |
| 9.8               | Recommendations for Future Work                                                                                                               | 302        |
| <b>Appendix A</b> | <b>Conversion of Chordal Void Fraction to Radial Void Fraction using Modified Fourier-Hankel (MFH) Method</b>                                 | <b>305</b> |
| <b>Appendix B</b> | <b>Comparative Analysis of Liquid Hydrodynamics in a Co-current Flow-Through Bubble Column with Densely Packed Internals via Radiotracing</b> | <b>311</b> |
| <b>Appendix C</b> | <b>Details of Computed Tomography for Boiling Flows</b>                                                                                       | <b>327</b> |
| <b>Appendix D</b> | <b>An Algorithm for Estimating Radial Gas Holdup Profiles in Bubble Columns from Chordal Densitometry Measurements</b>                        | <b>347</b> |
| <b>Appendix E</b> | <b>Online RPT Position Reconstruction: Development and Presentation of Graphic User Interface (GUI)</b>                                       | <b>367</b> |
| <b>VITA .....</b> |                                                                                                                                               | <b>379</b> |

## LIST OF FIGURES

| Figure | Title                                                                                                                                                                                                                               | Page  |
|--------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------|
| 1.1    | Evolution of nuclear reactors (image taken from U.S. Department of Energy <a href="http://www.gen-4.org">http://www.gen-4.org</a> ).                                                                                                | 2     |
| 1.2    | Fuel cluster in the AHWR pressure tube (Sinha and Kakodkar, 2006).                                                                                                                                                                  | 5     |
| 1.3    | Simplified schematic of AHWR (Sinha and Kakodkar, 2006).                                                                                                                                                                            | 5     |
| 2.1    | Nukiyama's boiling curve (Collier and Thome, 1994).                                                                                                                                                                                 | 18    |
| 2.2    | Commonly encountered flow regimes of flow boiling inside a vertical tube.                                                                                                                                                           | 20    |
| 2.3    | The pyramid of the boiling flow phenomena (Dinh, 2012).                                                                                                                                                                             | 35    |
| 3.1    | Schematic diagram of single rod experimental flow setup.                                                                                                                                                                            | 49    |
| 3.2    | Photograph of the test section for single rod experimental setup.                                                                                                                                                                   | 50    |
| 3.3    | (a) Schematic diagram of the multiple heater rods experimental setup, (b) Photograph of bottom flange for holding test section. and (c) Photograph of top flange for holding test section.                                          | 51-52 |
| 3.4    | Schematic representation of the heater rods arrangements: a) arrangement A (single rod), b) arrangement B (two rods), c) arrangement C (three rods) and d) arrangement D (four rods).                                               | 54    |
| 3.5    | Photograph of the test section for multiple heater rods experimental setup.                                                                                                                                                         | 55    |
| 4.1    | Schematic diagram of gamma-ray densitometry.                                                                                                                                                                                        | 59    |
| 4.2    | 3D schematic diagram of the gamma-ray densitometry.                                                                                                                                                                                 | 61    |
| 4.3    | Schematic representation of the drift flux model.                                                                                                                                                                                   | 62    |
| 4.4    | Photograph of boiling in experimental setup for inlet mass flux of (a) $G = 2.89 \text{ kg m}^{-2} \text{ s}^{-1}$ ; (b) $G = 8.67 \text{ kg m}^{-2} \text{ s}^{-1}$ ; (c) $G = 12.1 \text{ kg m}^{-2} \text{ s}^{-1}$ .            | 68    |
| 4.5    | Time-averaged (a) chordal and (b) radial void fraction profile for $q'' = 22.7 \text{ kW m}^{-2}$ , $G = 8.67 \text{ kg m}^{-2} \text{ s}^{-1}$ and inlet liquid temperature $60 \text{ }^{\circ}\text{C}$ (Annular gap = 17.5 mm). | 69    |
| 4.6    | (a) Variation of radial void fraction for $q'' = 22.7 \text{ kW m}^{-2}$ as a parameter of inlet liquid temperatures for $G = 8.67 \text{ kg m}^{-2} \text{ s}^{-1}$ and at measurement height = 64 cm (Annular gap = 17.5 mm).     | 70    |

|      |                                                                                                                                                                                                                                                           |    |
|------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----|
|      | (b) Variation of radial void fraction for $q'' = 22.7 \text{ kW m}^{-2}$ as a parameter of inlet liquid mass flux for inlet liquid temperature of $60^\circ\text{C}$ and at measurement height = 64 cm (Annular gap = 17.5 mm).                           | 71 |
| 4.7  | (a) Axial development of void fraction for $q'' = 22.7 \text{ kW m}^{-2}$ as function of different inlet liquid temperatures and inlet liquid mass flux of $G = 2.89 \text{ kg m}^{-2} \text{ s}^{-1}$ .                                                  | 72 |
|      | Axial development of void fraction for $q'' = 22.7 \text{ kW m}^{-2}$ as function of different inlet liquid temperatures and inlet liquid mass flux of: (b) $G = 6.94 \text{ kg m}^{-2} \text{ s}^{-1}$ (c) $G = 8.67 \text{ kg m}^{-2} \text{ s}^{-1}$ . | 73 |
|      | (d) Axial development of void fraction for $q'' = 22.7 \text{ kW m}^{-2}$ as function of different inlet liquid temperatures and inlet liquid mass flux of $G = 12.1 \text{ kg m}^{-2} \text{ s}^{-1}$ .                                                  | 74 |
| 4.8  | Variation of an area-averaged void fraction with thermal equilibrium quality for $q'' = 22.7 \text{ kW m}^{-2}$ .                                                                                                                                         | 76 |
| 4.9  | Comparison of drift flux model with experimental data for $q'' = 22.7 \text{ kW m}^{-2}$ , $G = 2.89 \text{ kg m}^{-2} \text{ s}^{-1}$ and inlet liquid temperature of (a) $45^\circ\text{C}$ (b) $60^\circ\text{C}$ .                                    | 77 |
| 4.10 | (a) Comparison of drift flux model with experimental data for $q'' = 22.7 \text{ kW m}^{-2}$ , $G = 6.94 \text{ kg m}^{-2} \text{ s}^{-1}$ and inlet liquid temperature of $45^\circ\text{C}$ .                                                           | 78 |
|      | (b) Comparison of drift flux model with experimental data for $q'' = 22.7 \text{ kW m}^{-2}$ , $G = 6.94 \text{ kg m}^{-2} \text{ s}^{-1}$ and inlet liquid temperature of $60^\circ\text{C}$ .                                                           | 79 |
|      | Comparison of drift flux model (Hibiki et. al. 2003) with experimental data for $q'' = 22.7 \text{ kW m}^{-2}$ , $G = 6.94 \text{ kg m}^{-2} \text{ s}^{-1}$ and inlet liquid temperature of (c) $45^\circ\text{C}$ and (d) $60^\circ\text{C}$ .          | 81 |
| 4.11 | Schematic diagram showing the location of the chordal scans done for heater rod arrangement A.                                                                                                                                                            | 83 |
| 4.12 | Schematic diagram showing the location of the chordal scans done for heater rod arrangement B at (a) $0^\circ$ and (b) $90^\circ$ plane.                                                                                                                  | 84 |
| 4.13 | Schematic diagram showing the location of the chordal scans done for three heater rods arrangement at (a) $0^\circ$ and (b) $90^\circ$ plane.                                                                                                             | 84 |
| 4.14 | (a) Chordal average void fraction distribution at axial height of 82 cm for an inlet liquid flow rate of 5 LPH for heater rod arrangement A (Total radius of column = 12 cm).                                                                             | 85 |

|      |                                                                                                                                                                                                                        |     |
|------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----|
|      | (b) Chordal average void fraction distribution at axial height of 82 cm for an inlet liquid flow rate of 10 LPH for heater rod arrangement A (Total radius of column = 12 cm).                                         | 86  |
| 4.15 | Variation of the void fraction for single rod arrangement at various axial locations for heater rod arrangement A (Total radius of column = 12 cm).                                                                    | 87  |
| 4.16 | Chordal void fraction distribution at axial height of 82 cm for inlet flow rate of (a) 5 LPH and (b) 10 LPH for heater rod arrangement B (0° plane) (Total radius of column = 12 cm).                                  | 88  |
| 4.17 | Chordal void fraction distribution at axial height of 82 cm for inlet liquid flow rate of (a) 5 LPH and (b) 10 LPH for heater rod arrangement B (90° plane) (Total radius of column = 12 cm).                          | 89  |
| 4.18 | (a) Axial variation of the void fraction for heater rod arrangement B for 0° plane at an inlet liquid flow rate of 10 LPH and 70 °C (Total radius of column = 12 cm).                                                  | 90  |
|      | (b) Axial variation of the void fraction for heater rod arrangement B for 90° plane at an inlet liquid flow rate of 10 LPH and 70 °C (Total radius of column = 12 cm).                                                 | 91  |
| 4.19 | (a) Chordal average void fraction distribution for heater rod arrangement C at the axial height of 82 cm (0° plane) for inlet liquid flow rate of 5 LPH (Total radius of column = 12 cm).                              | 92  |
|      | (b) Chordal average void fraction distribution for heater rod arrangement C at the axial height of 82 cm (0° plane) for inlet liquid flow rate of 10 LPH (Total radius of column = 12 cm).                             | 92  |
| 4.20 | (a) Chordal void fraction distribution for heater rod configuration D at axial height of 82 cm (90° plane) for inlet liquid flow rate of 5 LPH (Total radius of column = 12 cm).                                       | 93  |
|      | (b) Chordal void fraction distribution for heater rod configuration D at axial height of 82 cm (90° plane) for inlet liquid flow rate of 10 LPH (Total radius of column = 12 cm).                                      | 93  |
| 4.21 | Variation of the chordal average void fraction distribution at different axial heights for 10 LPH and 70°C for (a) 0° and (b) 90° plane (Total radius of column = 12 cm).                                              | 95  |
| 5.1  | Flow chart of Radioactive Particle Tracking technique.                                                                                                                                                                 | 107 |
| 5.2  | Geometrical interpretation for determining the effective distance $d(\alpha, \theta)$ traveled by photons in detector and path length $e(\alpha, \theta)$ traveled in the reactor (adapted from Larachi et al., 1994). | 110 |
| 5.3  | Schematic representation of the genetic algorithm.                                                                                                                                                                     | 115 |

|      |                                                                                                                                                                                                                                                  |     |
|------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----|
| 5.4  | Flow chart of MC-RGA used in the present work.                                                                                                                                                                                                   | 118 |
| 5.5  | “Virtual bubble column”: (a) Schematic, and calibration locations: (b) $r-\theta$ plane.                                                                                                                                                         | 122 |
|      | (c) “Virtual bubble column”: $r-z$ plane.                                                                                                                                                                                                        | 123 |
| 5.6  | (a) Schematic diagram of the actual bubble column experimental setup.                                                                                                                                                                            | 125 |
|      | (b) Schematic diagram of the detector arrangement for the RPT experiment on actual bubble column.                                                                                                                                                | 125 |
| 5.7  | Variation of average fitness function value with the number of generations for Eq. 5.7 at varying (a) population size (b) mutation probability.                                                                                                  | 128 |
|      | (c) Variation of average fitness function value with the number of generations for Eq. 5.7 at varying crossover probability.                                                                                                                     | 129 |
| 5.8  | Variation of average fitness function value with the number of generations for Eq. 5.19 at varying (a) population size and (b) mutation probability.                                                                                             | 130 |
|      | (c) Variation of average fitness function value with the number of generations for Eq. 5.19 at varying crossover probability.                                                                                                                    | 131 |
| 5.9  | Variation of average fitness function (Eq. 5.7) for Detector 2 (typical) with the number of generations.                                                                                                                                         | 133 |
| 5.10 | The parity plot of measured counts and calculated counts (using constants found by MC-RGA model) for Detector 1 (typical).                                                                                                                       | 134 |
| 5.11 | The histogram plots of absolute error in mm against the percentage of number of calibration points for (a) X direction (b) Y direction (c) Z direction and (d) Mean Euclidean distance error.                                                    | 135 |
| 5.12 | (a) Comparison of the typical axial liquid velocity plot at different axial heights obtained using MC technique and MC-RGA method and (b) the mean Eulerian velocity field plot for liquid in a 2-D frame for bubble column using MC-RGA method. | 139 |
| 6.1  | The illustration of the multilayer neural network used in this work (Hagan et al., 2006).                                                                                                                                                        | 151 |
| 6.2  | Schematic illustration of the SVR reconstruction model using $\varepsilon$ -sensitive loss function.                                                                                                                                             | 156 |
| 6.3  | Flow chart of the SVR position reconstruction model.                                                                                                                                                                                             | 159 |
| 6.4  | Schematic illustration of the RVM position reconstruction model.                                                                                                                                                                                 | 161 |
| 6.5  | Flow chart of the RVM position reconstruction model.                                                                                                                                                                                             | 162 |

|      |                                                                                                                                                                                                                                  |     |
|------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----|
| 6.6  | (a) Schematic diagram of experimental setup and (b) Radial calibration location for the actual column with centrally located internal tube RPT experiments.                                                                      | 165 |
| 6.7  | Schematic diagram illustrating the shadow region effect.                                                                                                                                                                         | 167 |
| 6.8  | (a) Comparison of MEDE (mm) for different reconstruction algorithms for actual bubble column and (b) Comparison of mean error (mm) in X, Y and Z direction for different reconstruction algorithms for actual bubble column.     | 172 |
|      | (c) Illustration of the total number of the axial calibration data, relevance vectors and support vectors.                                                                                                                       | 173 |
| 6.9  | (a) Typical axial liquid velocity plot obtained using SVR based reconstruction at different axial heights for actual bubble column and (b) vector plot of the time-averaged liquid phase velocity.                               | 175 |
| 6.10 | (a) The MEDE (mm) plot for the different reconstruction algorithms in the form of histogram plot for case D and (b) Mean absolute error (mm) histogram plot of the X, Y and Z direction for different reconstruction algorithms. | 179 |
| 6.11 | Comparison of MEDE (mm) of different cases for the actual column with the centrally located internal tube.                                                                                                                       | 179 |
| 6.12 | Comparison of SVR and RVM model in terms of RVs and SVs for Case D.                                                                                                                                                              | 180 |
| 7.1  | (a) Schematic diagram of the test loop.                                                                                                                                                                                          | 202 |
|      | (b) Schematic diagram of the test section with an arrangement of detectors around the column.                                                                                                                                    | 202 |
|      | (c) Schematic diagram of the detectors arrangement around the column.                                                                                                                                                            | 202 |
|      | (d) Schematic representation of the heater rods arrangements: a) single heater rod and b) three heater rods.                                                                                                                     | 204 |
| 7.2  | Schematic representation of the calibration rod with the tracer particle.                                                                                                                                                        | 206 |
| 7.3  | (a) Photograph of the calibration disk used for three heater rods arrangement.                                                                                                                                                   | 207 |
|      | (b) Schematic diagram of the calibrator used for the single heater rod arrangement.                                                                                                                                              | 207 |
|      | (c) Schematic diagram of the calibrator disk used for the three heater rods arrangement.                                                                                                                                         | 208 |
| 7.4  | Calibration curves for detector number (a) 8 and (b) 4.                                                                                                                                                                          | 209 |
| 7.5  | Flowchart for the calculation of the axial or radial diffusivity                                                                                                                                                                 | 212 |

|      |                                                                                                                                                                                                                         |     |
|------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----|
| 7.6  | Photograph of boiling experimental flow setup with RPT detector arrangement.                                                                                                                                            | 215 |
| 7.7  | Compartment division scheme in an $r$ - $\theta$ plane for three heater rods configuration.                                                                                                                             | 215 |
| 7.8  | (a) Velocity vectors arrangement at inlet flow rate of 0.01 cm/s and inlet liquid temperature 50 °C (for single heater rod (arrangement A)).                                                                            | 218 |
|      | (b) Velocity vectors arrangement at inlet flow rate of 0.01 cm/s and inlet liquid temperature 70 °C (for single heater rod (arrangement A)).                                                                            | 219 |
| 7.9  | (a) Time-averaged axial liquid velocity plot for single heater rod case (arrangement A) at inlet liquid flow velocity of 0.01 cm/s and inlet liquid temperature of 50 °C.                                               | 222 |
|      | (a) Time-averaged kinetic energy plot for single heater rod case (arrangement A) at inlet liquid flow velocity of 0.01 cm/s and inlet liquid temperature of 50 °C.                                                      | 222 |
| 7.10 | (a) Contour plot of the axial liquid velocity at axial height (a) 90 cm and (b) 75 cm (inlet liquid flowrate = 0.01 cm/s and inlet liquid temperature = 50 °C).                                                         | 223 |
| 7.11 | (a) Time-averaged axial liquid velocity (b) Liquid turbulence kinetic energy plot for single heater rod case (arrangement A) at inlet liquid flow velocity of 0.01 cm/s and inlet liquid temperature, $T_{in} = 70$ °C. | 224 |
| 7.12 | (a) Contour plot of the axial liquid velocity for single heater rod arrangement at axial height of 90 cm (inlet liquid flowrate = 0.01 cm/s and inlet liquid temperature = 70 °C).                                      | 225 |
|      | (b) Contour plot of the axial liquid velocity for single heater rod arrangement at axial height of 75 cm (inlet liquid flowrate = 0.01 cm/s and inlet liquid temperature = 70 °C).                                      | 226 |
| 7.13 | (a) Time-averaged axial liquid velocity (b) Liquid turbulence kinetic energy plot for single heater rod case (arrangement A) at inlet liquid flow velocity of 0.02 cm/s and inlet liquid temperature of 70 °C.          | 227 |
| 7.14 | (a) Time-averaged axial liquid velocity plot for three heater rods case (arrangement C) at inlet liquid flow velocity of 0.01 cm/s and inlet liquid temperature of 50 °C.                                               | 229 |
|      | (b) Liquid turbulence kinetic energy plot for three heater rods case (arrangement C) at inlet liquid flow velocity of 0.01 cm/s and inlet liquid temperature of 50 °C.                                                  | 230 |
| 7.15 | Contour plot of the axial liquid velocity for three heater rods arrangement at axial height of 75 cm (inlet liquid flow rate = 0.01 cm/s and inlet liquid temperature = 50 °C).                                         | 230 |

|      |                                                                                                                                                                                                                                              |     |
|------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----|
| 7.16 | (a) Contour plot of axial liquid velocity for three heater rods arrangement at axial height of 75 cm (inlet liquid flowrate = 0.01 cm/s and inlet liquid temperature = 70 °C).                                                               | 231 |
|      | (b) Contour plot of axial liquid velocity for three heater rods arrangement at axial height of 90 cm (inlet liquid flowrate = 0.01 cm/s and inlet liquid temperature = 70 °C).                                                               | 232 |
| 7.17 | (a) Time-averaged axial liquid velocity (b) Liquid turbulence kinetic energy plot for three heater rods case (arrangement C) at inlet liquid flow velocity of 0.01 cm/s and inlet liquid temperature of 70 °C.                               | 233 |
| 7.18 | (a) Time-averaged axial liquid velocity (b) Liquid turbulence kinetic energy plot for three heater rods case (arrangement C) at inlet liquid flow velocity of 0.02 cm/s and inlet liquid temperature of 50 °C.                               | 234 |
| 7.18 | Comparison of the (c) time averaged liquid velocity and (d) kinetic energy for single and three heater rods at different axial locations.                                                                                                    | 236 |
| 7.19 | (a) Schematic representation of the heater rods arrangements: a) arrangement A (single rod), b) arrangement B (two rods), c) arrangement C (three rods) and d) arrangement D (four rods).                                                    | 240 |
| 7.19 | (b) Self-diffusion of 5000 tracers virtually injected in the imaginary compartment with $0 < z < 200$ mm and $0 < r < 12$ mm.                                                                                                                | 241 |
| 7.20 | Mean square displacement of 500 tracer particles (virtually injected) for a compartment $0 \text{ mm} < z < 200 \text{ mm}$ , $0 \text{ mm} < r < 12 \text{ mm}$ (heater arrangement A): (a) axial displacement and (b) radial displacement. | 242 |
| 7.21 | (a) Axial eddy diffusivity and (b) Radial eddy diffusivity as a function of dimensionless radial position for heater rod arrangement A (inlet liquid temperature = 70 °C).                                                                   | 243 |
| 7.22 | (a) Axial eddy diffusivity and (b) Radial eddy diffusivity as a function of radial position for heater rods arrangement B (inlet liquid temperature = 70 °C).                                                                                | 244 |
| 7.23 | (a) Axial eddy diffusivity and (b) radial eddy diffusivity as a function of radial position for heater rod arrangement C (inlet liquid temperature = 70 °C).                                                                                 | 245 |
| 8.1  | Schematic diagram of the (a) test loop and (b) test section with an arrangement of detectors around the column.                                                                                                                              | 260 |
|      | (c) Schematic diagram of the planar arrangement of detectors arrangement around the test section.                                                                                                                                            | 261 |
| 8.2  | (a) Schematic representation of the construction of the recurrence plot (RP) (Savari et al., 2016).                                                                                                                                          | 265 |
|      | (b) Representation of the time series.                                                                                                                                                                                                       | 267 |

|     |                                                                                                                                                                                           |     |
|-----|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----|
| 8.3 | (a) RP of stochastic system (white noise).                                                                                                                                                | 268 |
|     | (b) RP of periodic system (sine function).                                                                                                                                                | 269 |
|     | (c) RP of chaotic system (Rössler system in chaotic regime).                                                                                                                              | 269 |
| 8.4 | Variation of (a) % Recurrence Ratio (RR) and (b) % Determinism (DET) with a number of data points (inlet condition: liquid flow rate = 5 LPH and liquid temperature = 70 °C).             | 274 |
| 8.5 | Variation (inlet condition: liquid flow rate = 5 LPH and liquid temperature = 75 °C) of Recurrence ratio (RR) with threshold radius, $\epsilon$ for axial direction position time series. | 276 |
|     | (b) Variation (inlet condition: liquid flow rate = 5 LPH and liquid temperature = 70 °C) of DET with threshold radius, $\epsilon$ for axial direction.                                    | 277 |
| 8.6 | Axial direction position time series and corresponding recurrence plot for inlet flow rate of 5 LPH and temperature of 70 °C for heater rod arrangement A.                                | 279 |
| 8.7 | RP in the axial direction for inlet flow rate of 5 LPH and temperature of 70 °C for (a) arrangement A (b) arrangement B (c) arrangement C and (d) arrangement D.                          | 281 |
| 8.8 | Variation of (a) % recurrence rate (RR) and (b) % determinism (DET) for different heater rods configuration at fixed liquid flow rate of 5 LPH.                                           | 283 |
|     | (c) Variation of entropy (ENT) for different heater rods configuration at fixed liquid flow rate of 5 LPH.                                                                                | 284 |
| 8.9 | (a) Variation of % RR for different heater rods configuration at fixed inlet liquid temperature of 70 °C.                                                                                 | 286 |
|     | Variation of (b) DET and (c) ENT for different heater rods configuration at fixed inlet liquid temperature of 70 °C.                                                                      | 287 |
| A.1 | (a) Comparison of Abel inversion using MFH method with known radial function 1 (Table A.1).                                                                                               | 308 |
|     | (b) Comparison of Abel inversion using MFH method with known radial function 2 (Table A.1).                                                                                               | 309 |
| B.1 | Schematic of the experimental set-up showing the installation of RPT and RTD (all dimensions are in mm).                                                                                  | 314 |
| B.2 | Configuration of the internals used for RPT experiments.                                                                                                                                  | 315 |
| B.3 | Typical experimental curve ( $E_\theta$ v/s $\theta$ ) with corresponding simulated ( $E_\theta$ v/s $\theta$ ) curve using axial dispersion model.                                       | 319 |

|      |                                                                                                                                                                                                                                                                                                                                |     |
|------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----|
| B.4  | Variation of liquid dispersion coefficient with gas flow rates at measurement plane of $H/D = 3.33$ for liquid flow rate of (a) 200 LPH and (b) 500 LPH respectively at various internals arrangement.                                                                                                                         | 320 |
| B.5  | Variation of dispersion coefficient with gas flow rate at measurement plane of $H/D = 4.16$ for liquid flow rate of (a) 200 LPH and (b) 500 LPH respectively at various internals arrangement.                                                                                                                                 | 321 |
| C.1  | Schematic of the phantom for which the data were generated by simulation. $D_{col} = 8$ inch (Varma et al., 2008).                                                                                                                                                                                                             | 331 |
| C.2  | (a) Exact phantom and (b) Reconstructed phantom with AM algorithm.                                                                                                                                                                                                                                                             | 332 |
|      | (c) Reconstructed phantom with VARD-AM algorithm.                                                                                                                                                                                                                                                                              | 333 |
| C.3  | (a) Reconstruction of Exact phantom.                                                                                                                                                                                                                                                                                           | 334 |
|      | (b) Reconstruction of Exact phantom with AM algorithm.                                                                                                                                                                                                                                                                         | 334 |
|      | (c) Reconstruction of Exact phantom with VARD-AM algorithm.                                                                                                                                                                                                                                                                    | 335 |
| C.4  | Parallel beam arrangement of source and detectors. A: The source and detector are simultaneously moved at different angular orientation to make parallel line measurements. B: Another arrangement where the source and detectors are fixed, and the domain is moved laterally at different angular orientation (Varma, 2008). | 336 |
| C.5  | (a) Schematic representation of the heater rods arrangement and (b) $0^\circ$ azimuthal plane.                                                                                                                                                                                                                                 | 337 |
| C.6  | Variation of the chordal intensity with a chordal number at (a) $0^\circ$ and (b) $45^\circ$ .                                                                                                                                                                                                                                 | 338 |
| C.7  | (a) Reconstruction of empty column using VARD-AM algorithm and                                                                                                                                                                                                                                                                 | 339 |
|      | (b) Reconstruction of column filled with water using VARD-AM algorithm.                                                                                                                                                                                                                                                        | 339 |
| C.8  | Reconstruction of the empty column with 3 rods using (a) AM algorithm and (b) VARD-AM algorithm.                                                                                                                                                                                                                               | 340 |
| C.9  | Reconstruction of a water filled column filled with 3 rods using (a) AM algorithm and (b) VARD-AM algorithm.                                                                                                                                                                                                                   | 341 |
| C.10 | (a) Chordal holdup for time of acquisition = 5 s (18 azimuthal locations and 33 chordal locations at each azimuthal position).                                                                                                                                                                                                 | 342 |
|      | (b) Chordal holdup for time of acquisition = 30 s (36 azimuthal locations and 33 chordal locations at each azimuthal position).                                                                                                                                                                                                | 343 |
| C.11 | (a) Tomographic reconstruction of water filled column ( $T_{in} = 25^\circ\text{C}$ and $V_l = 0.025$ cm/s).                                                                                                                                                                                                                   | 343 |

|     |                                                                                                                                                 |     |
|-----|-------------------------------------------------------------------------------------------------------------------------------------------------|-----|
|     | (b) Tomographic reconstruction of empty column ( $T_{in} = 25\text{ }^{\circ}\text{C}$ and $V_l = 0.025\text{ cm/s}$ ).                         | 344 |
|     | (c) Tomographic reconstruction of boiling two-phase flows ( $T_{in} = 25\text{ }^{\circ}\text{C}$ and $V_l = 0.025\text{ cm/s}$ ).              | 344 |
| D.1 | Schematic diagram of $\gamma$ -ray densitometry setup.                                                                                          | 349 |
| D.2 | (a) Schematic representation of Abel transform and (b) Schematic representation of movement detector and source assembly in a horizontal plane. | 350 |
| D.3 | Schematic diagram of experimental setup.                                                                                                        | 356 |
| D.4 | (a) Polynomial fitting of chordal averaged experiment data and (b) Radial gas holdup profiles of corresponding chordal averaged profiles.       | 357 |
| D.5 | (a) Time averaged chordal- averaged holdup profile and (b) Time averaged radial gas holdup profile.                                             | 359 |
| D.6 | Gas hold profiles for $V_g = 0.3\text{ m/s}$ and $H_D/D = 2$ at different axial locations.                                                      | 360 |
| D.7 | Gas holdup profiles for $H_D/D = 2$ and $h/D = 1.2$ at different air superficial velocities.                                                    | 361 |
| E.1 | Flowchart of the MATLAB GUI.                                                                                                                    | 368 |
| E.2 | Snapshot of the MATLAB GUI.                                                                                                                     | 369 |
| E.3 | Snapshot of the GUI window showing plot options                                                                                                 | 370 |
| E.4 | (a) Plot showing a variation of the tracer particle in Y direction with time for 50 s.                                                          | 371 |
|     | (b) Plot showing a variation of the tracer particle in Y direction with time for 100 s.                                                         | 372 |
| E.5 | (a) Plot showing a variation of the tracer particle in the X direction with time for 50 s.                                                      | 372 |
|     | (b) Plot showing a variation of the tracer particle in the X direction with time for 100 s.                                                     | 373 |
| E.6 | (a) Plot showing a variation of the tracer particle in Z direction with time for 50 s.                                                          | 373 |
|     | (b) Plot showing a variation of the tracer particle in Z direction with time for 100 s.                                                         | 374 |
| E.7 | Variation of the tracer positions in the X-Y plane (a) 5 s and (b) 10 s.                                                                        | 375 |
| E.8 | Variation of the tracer positions in the Y-Z plane (a) 5 s and (b) 10 s.                                                                        | 376 |
| E.9 | Variation of the tracer positions in X-Z plane (a) 5 s and (b) 10 s.                                                                            | 377 |

## LIST OF TABLES

| <b>Table</b> | <b>Title</b>                                                                                         | <b>Page</b> |
|--------------|------------------------------------------------------------------------------------------------------|-------------|
| 1.1          | AHWR design specifications (Sinha and Kakodkar, 2006).                                               | 4           |
| 2.1          | Key references from literature on non-isothermal single phase measurements.                          | 27          |
| 2.2          | Key references from literature on sub-cooled boiling flow experiments.                               | 29          |
| 2.3          | Selected references from literature review of CFD work on boiling flow.                              | 38          |
| 4.1          | Experimental conditions                                                                              | 67          |
| 5.1          | Detector positions for simulated “virtual” bubble column                                             | 125         |
| 5.2          | Constants used for generating counts for simulated virtual bubble column                             | 126         |
| 5.3          | Comparison of MC and MC-RGA algorithm                                                                | 139         |
| 6.1 (a)      | Definitions of variables used for machine learning based position reconstruction.                    | 156         |
| 6.1 (b)      | Calibration data ratios.                                                                             | 169         |
| 6.2          | MEDE for simulated bubble column for different ML reconstruction algorithms.                         | 173         |
| 6.3          | Reconstruction performance indices of actual bubble column.                                          | 174         |
| 6.4          | Computational time required by different algorithms.                                                 | 177         |
| 6.5          | Reconstruction performance indices of actual column with centrally located internal for case A.      | 179         |
| 6.6          | Reconstruction performance indices of actual column with centrally located internal tube for case B. | 179         |
| 6.7          | Reconstruction performance indices of actual column with centrally located internal tube for case C. | 180         |
| 6.8          | Reconstruction performance indices of actual column with centrally located internal tube for case D. | 180         |
| A.1          | Known chordal and corresponding radial functions.                                                    | 308         |
| B.1          | Set of experiments performed for RTD in bubble column mode.                                          | 315         |
| C.1          | Attenuation values of the materials used in the simulated phantom.                                   | 331         |
| D.1          | Values of constants for $V_g = 0.3$ m/s and $H_D/D = 2$ .                                            | 360         |