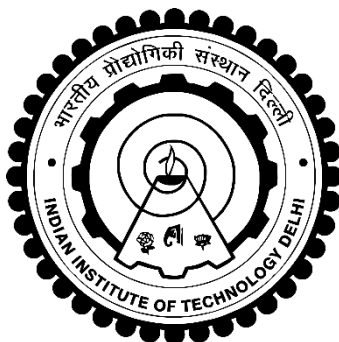


EXPERIMENTAL AND NUMERICAL INVESTIGATIONS OF DISPERSED GAS- LIQUID FLOW AND MIXING IN A SCALED-DOWN COLD FLOW MODEL OF BASIC OXYGEN FURNACE

ABDUL QUIYOOM



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

JULY 2018

©Indian Institute of Technology Delhi (IITD), New Delhi, 2018

EXPERIMENTAL AND NUMERICAL INVESTIGATIONS OF DISPERSED GAS- LIQUID FLOW AND MIXING IN A SCALED-DOWN COLD FLOW MODEL OF BASIC OXYGEN FURNACE

by

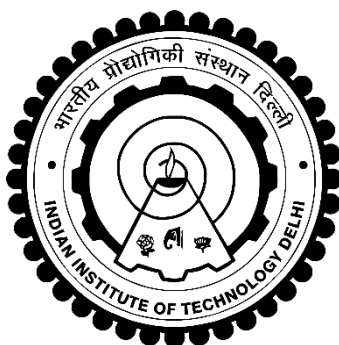
ABDUL QUIYOOM

Department of Chemical Engineering

Submitted

In fulfilment of the requirements of the degree of *Doctor of Philosophy*

to the



INDIAN INSTITUTE OF TECHNOLOGY DELHI

JULY 2018

Certificate

This is to certify that the thesis entitled “**Experimental and Numerical Investigations of Dispersed Gas-Liquid Flow and Mixing in a Scaled-down Cold Flow Model of Basic Oxygen Furnace**” being submitted by **Mr. Abdul Quiyoom** to the Indian Institute of Technology Delhi for the award of the degree of **Doctor of Philosophy** is a bonafide record of original research work carried out by him under my supervision in conformity with rules and regulations of the institute. The results contained in this thesis have not been submitted, in part or in full, to any other University or Institute for the award of any Degree or Diploma.

Date:

Dr. Vivek V. Buwa

Professor

Department of Chemical Engineering

Indian Institute of Technology Delhi

New Delhi–110016, India

Acknowledgements

The five years of the doctoral studies have been an exciting journey. I owe my gratitude to all those people who in different ways, academically, professionally and psychologically contributed to my journey and made this dissertation possible.

My profound gratitude goes to my supervisor, Prof. Vivek V. Buwa, for his caring, patience, encouragement and providing me with an excellent atmosphere for doing research. I have been amazingly fortunate to have an advisor who not only guided me on this thesis but also gave me much needed moral support when my steps faltered. On the more technical side, special thanks to him, for insightful discussions and constructive feedback throughout the gestation of my work.

I would like to express my sincere gratitude to my research committee members, Prof. Shantanu Roy, Dr. Sudip Patnayak and Murali R. Cholemari for their valuable suggestions and insight evaluation that helped me to complete the dissertation in more efficient way. I must acknowledge the support from the Tata Steel Reseach and Development division Jamshedpur and Foundation for Innovation and Technology Transfer (FIIT) IIT Delhi for the financial support. I would like to extend my gratitude to the Industrial Research & Development Unit (IRD) in support of Conference trips and Computer Service Centre IIT Delhi for providing computing resources at its Hybrid High-Performance Computing Facility.

I am thankful to Dr. S. K. Ajmani, Dr. M. K. Singh, Mr. Vikas Singh and Mr. Raghavendra from Tata Steel R&D Jamshedpur for their valuable suggestions and discussions throughout the project. My sincere thanks to Mr. Ravi Golani for showing me the actual BOF

vessel in Tata Steel and giving me some valuable insight into practical limitations regarding the BOF operations.

I am deeply thankful to all faculty members of the Chemical Engineering Department, and in particular the former and current head of the department Prof. Suddhasatwa Basu and Prof. Rajesh Khanna, for providing all necessary facilities during my stay at IITD. Thanks to all my colleagues of Multiphase Research Group: Parul, Saroj, Brajesh, Ekta, Abhijeet, Sayantani, David, Hasam and Sirisha for their support, discussions and use full advice. Specially, I would like to thank, V.M. Rajesh, G.M. Karthik, Vishal, Ritubhan and Arpit for wonderful discussions and sharing knowledge throughout their stay at IIT. My special thanks to Mr. Anil Kumar for his helping hands during experiments. Thanks are too little for the help and support I received from my good friend Saroj Kumar Panda since last four and half years.

My special thanks to my friends: Jarrar Ahmad, Viqar Baig, Mohd. Rashid, Danish Iqbal, Mehnaz Rasool Aamir Hayat, Dilshad Khan, Abdul Rahman, Salahuddin Ahmad, Khalid Muzaffar, Ejaz Ahmad, Aasif Mujtafa and Gyanendra Sharma for their enormous support and motivations during my stay at IIT Delhi. Most importantly, none of this would have been possible without the love and patience of my family. I can never fully emphasize the role played by Abba, Amma in bringing me up to whatever I am today. I will always be indebted to my brothers for their support at every stage of my life. This will be incomplete if I do not appreciate my dearly beloved wife, who has been a good companion for me.

Finally, All praise to great ALLAH, for making this world so beautiful and giving me all the tools necessary to enjoy it fully.

Abdul Quiyoom

Abstract

The present thesis focuses on the characterization of dynamics of dispersed gas-liquid flow and liquid-phase mixing generated by multiple meandering bubble plumes in a scaled-down cold flow model of Basic Oxygen Furnace (BOF) through measurements and CFD simulations. The role of complex interactions among meandering bubble plumes in the primary (in r -direction) and secondary (in θ -direction) flow, that governs the local mixing inside the vessel BOF vessel, was quantified. Cold flow experiments were performed to measure the instantaneous and time-averaged gas volume fraction, and local mixing time at different gas mass flow rates using in-house developed voidage and conductivity probes, respectively. 3D transient Euler-Lagrange (EL) simulations of dispersed gas-liquid flow were performed under cold flow conditions. The predicted instantaneous and time-averaged gas volume fraction and local as well as spatially-averaged mixing time were found in a satisfactory agreement with the measurements. The effect of oscillatory behavior of multiple bubble plumes on the dynamics of gas-liquid flow and mixing was studied. In the case of uniform flow scheme (conventional flow scheme used in industry), the liquid-phase flow field was found to be asymmetric and it led to asymmetric mixing inside the vessel. In this case, the local mixing time varied considerably from one location to the other location in the vessel.

3D/transient Euler-Lagrange (EL) without/with Volume-of-Fluid (VOF) simulations of dispersed gas-liquid flow were performed to investigate the effect of the free gas-liquid interface on the dynamics of gas-liquid flow and mixing at different H/D ratios. For lower H/D ratios, EL simulations performed with no-slip and free-slip boundary conditions led to oscillatory plume behaviour and higher liquid velocity regions which in turn led to lesser mixing time. In contrast, EL+VOF simulations led to reduced meandering motion of bubble

plumes and lower liquid velocities resulting in higher mixing times. Interestingly, the mixing time predicted using the EL+VOF approach was found to be in a good agreement with the measurements

The effect of PCD (pitch-to circle-diameter ratio), which provide the flow variation in the radial direction, on dynamics of gas-liquid flow and mixing was studied. It was found that the flow was symmetric when eight bottom tuyeres were placed at PCD of 0.5 and it led to efficient mixing than that the configurations in which tuyeres were placed at the PCD of 0.7 and 0.59. The contributions of different mixing mechanism and the role of primary and secondary flow in determining the dynamics of gas-liquid flow and local mixing were studied. The modified bottom tuyere arrangements (referred as STAR-configurations) that create the flow variation in r-direction (primary flow) and also in θ -direction (secondary flow) were proposed. The flow rate variation along the radial and circumferential direction in an alternating arrangement generated re-circulatory cells in the circumferential direction (in addition to the re-circulatory cells in the radial direction) and this led to fast mixing inside the vessel. The mixing time was found to be reduced by 40-45 % than that of the conventional flow scheme. The experimentally verified computational model and the proposed STAR-type configuration will be useful to improve mixing efficiency, hence steel quality in BOF vessels.

सार

वर्तमान थीसिस फैलाने वाले गैस-तरल प्रवाह के मापने और सीएफडी सिमुलेशन के माध्यम से बेसिक ऑक्सीजन फर्नेस (बीओएफ) के स्केल किए गए ठंडे प्रवाह मॉडल में कई घूमने वाले बबल प्लूम द्वारा उत्पन्न तरल चरण मिश्रण की गतिशीलता की विशेषता पर केंद्रित है। प्राथमिक (r -दिशा में) और द्वितीयक (θ - दिशा में) प्रवाह में घूमने वाले बबल प्लुम बीच जटिल इंटरैक्शन की भूमिका, जो बीओएफ वेसेल के अंदर स्थानीय मिश्रण को नियंत्रित करती है, को प्रमाणित किया गया था। तत्काल और समय-औसत गैस वॉल्यूम अंश और स्थानीय मिश्रण समय को मापने के लिए इन-हाउस विकसित प्रोब्स का उपयोग किया गया है। यूलर-लैंग्रेज (ईएल) अप्रोच का प्रयोग फैलाने वाले गैस-तरल के ठंडे प्रवाह का 3 डी क्षणिक सिमुलेशन के लिए किया गया था। अनुमानित तात्कालिक और समय-औसत गैस वॉल्यूम अंश और स्थानीय के साथ-साथ स्थानिक रूप से औसत मिश्रण समय माप के सात संतोषजनक पाए गए थे। गैस-तरल प्रवाह और मिश्रण की गतिशीलता पर बबल प्लुम के असंतुलित व्यवहार का प्रभाव अध्ययन किया गया था। डिफ़ॉल्ट प्रवाह योजना (उद्योग में उपयोग की जाने वाली पारंपरिक प्रवाह योजना) के मामले में, तरल चरण प्रवाह क्षेत्र असममित पाया गया था और इससे वेसेल के अंदर विषम मिश्रण होता है। इस मामले में, स्थानीय मिश्रण समय एक स्थान से दूसरे स्थान पर काफी भिन्न था।

गैस-तरल प्रवाह और मिश्रण की गतिशीलता पर मुक्त गैस-तरल इंटरफेस के प्रभाव की जांच के लिए फैले हुए गैस-तरल प्रवाह को वॉल्यूम-ऑफ-फ्लुइड (वीओएफ) + यूलर-लैंग्रेज (ईएल) सिमुलेशन और यूलर-लैंग्रेज (ईएल) के साथ विभिन्न एच / डी अनुपात में किया गया। निचले एच / डी अनुपात के लिए, ईएल सिमुलेशन ने नो-स्लिप और फ्री-स्लिप सीमा परिस्थितियों के साथ प्रदर्शन किया, जिससे ऑसीलेटरी बबल प्लूम व्यवहार, उच्च तरल वेग वाले क्षेत्रों का कारण बन गया जो बदले में कम मिश्रण समय का कारण बना। इसके विपरीत, ईएल + वीओएफ सिमुलेशन ने बबल प्लूम और कम तरल वेगों की घूमने वाली गति को कम कर दिया जिसके परिणामस्वरूप मिश्रण समय बढ़ गया। दिलचस्प बात यह

है कि ईएल + वीओएफ दृष्टिकोण का उपयोग करके अनुमानित मिश्रण समय माप के साथ एक अच्छे समझौते में पाया गया था

पीसीडी (पिच-टू सर्कल-व्यास अनुपात) का प्रभाव, जो रेडियल दिशा में प्रवाह भिन्नता प्रदान करता है का गैस-तरल प्रवाह और मिश्रण की गतिशीलता पर अध्ययन किया गया था। यह पाया गया कि प्रवाह सममित था जब आठ गॅस ईलेट 0.5 के पीसीडी पर रखे गए थे और इससे कॉन्फ़िगरेशन में उनीफ़ोर्म मिश्रण हुआ, 0.7 और 0.59 के पीसीडी की तुलना में। गैस-तरल प्रवाह और स्थानीय मिश्रण की गतिशीलता को निर्धारित करने में विभिन्न मिश्रण तंत्र और प्राथमिक और माध्यमिक प्रवाह की भूमिका का अध्ययन किया गया। संशोधित टायर व्यवस्था (स्टार-कॉन्फ़िगरेशन के रूप में संदर्भित) जो आर-दिशा (प्राथमिक प्रवाह) में प्रवाह भिन्नता और θ -दिशा (माध्यमिक प्रवाह) में भी प्रवाह भिन्नता का प्रस्ताव दिया गया था। इस वैकल्पिक व्यवस्था में रेडियल और परिधीय दिशा के साथ प्रवाह दर भिन्नता परिधीय दिशा में पुनः परिसंचरण उत्पन्न होता है (रेडियल दिशा में पुनः परिसंचरण के अतिरिक्त) और इससे वेसेल के अंदर तेजी से मिश्रण होता है। परंपरागत प्रवाह योजना की तुलना में मिश्रण समय 40-45% कम पाया गया। प्रयोगात्मक सत्यापित कम्प्यूटेशनल मॉडल और प्रस्तावित स्टार-प्रकार कॉन्फ़िगरेशन मिश्रण दक्षता में सुधार के लिए उपयोगी होगा।

Table of contents

Certificate	i
Acknowledgements	ii
Abstract	iv
Table of contents.....	vi
List of figures	xi
List of tables	xx
Nomenclature.....	xxii
Chapter 1: Introduction.....	1
1.1 Overview of BOF steelmaking process	2
1.2 The scope of the present work	7
1.3 Present state of art	9
1.3.1 Gas-liquid flow and mixing in bubble columns and shallow vessels	9
1.3.2 Optimization of bottom tuyere configuration in BOF vessel	13
1.4 Motivation of the present work	15
1.5 Specific objectives.....	16
1.6 Organization of thesis.....	17
Chapter 2: Experimental set-up and Measurement Techniques.	21
2.1 Scaled-down geometry and operating conditions	22

2.1.1	BOF geometry	22
2.1.2	Calculation of scale-down flow rate.....	27
2.2	Experimental set-up	32
2.2.1	Measurements of gas volume fraction distribution in the BOF vessel 34	
2.2.2	Bubble size distribution measurements	39
2.3	Mixing time measurements	44
2.4	Summary and Conclusions.....	45
Chapter 3: Computational Model.....		47
3.1	Euler–Lagrange model for dispersed gas–liquid flow in BOF vessel ..	48
3.1.1	Governing equations	50
3.1.2	Simulation of free gas–liquid interface (VOF method)	54
3.1.3	Simulation of liquid phase mixing.....	57
3.2	Solution domain, boundary conditions and numerics.....	58
3.3	Mixing time simulations	61
3.4	Summary and conclusions.....	63
Chapter 4: Modelling and Numerical Issues and Experimental Verification.....		65
4.1	Effect of grid resolutions on key flow variables	66
4.2	Effect of numerical parameters on time-averaged gas volume fraction and vertical liquid velocity profiles	69
4.2.1	Effect of bubble injection time step	69

4.2.2	Effect of step length factor.....	69
4.3	Effect of tuyere orientation on time–averaged gas volume fraction and vertical liquid velocity	70
4.4	Effect of gas-liquid drag, shear-induced lift and virtual mass forces ...	73
4.5	Effect of bubble size distribution on time–averaged gas volume fraction and vertical liquid velocity	81
4.6	Effect of mass flow rate on instantaneous and time–averaged gas volume fraction and experimental verification.....	82
4.7	Summary and conclusions.....	92
Chapter 5: Mixing Time Simulations and Experimental Verification.....		94
5.1	Preliminary mixing time simulations	95
5.1.1	Effect of grid size on mixing time	95
5.1.2	Effect of locations (single plane vs. multiple planes) on mixing time	96
5.2	Role of unsteady flow structure on liquid phase mixing	99
5.3	Effect of bubble size distribution on mixing time	102
5.4	Effect of mass flow rate on mixing time and experimental verification	103
5.5	Summary and conclusions.....	108
Chapter 6: Role of Free Surface in Liquid Phase Mixing.....		109
6.1	Role of free surface on dynamics of gas–liquid flow	110

6.2	Effect of mass flow rate on free surface and liquid phase mixing.....	120
6.3	Effect of H/D ratio on role of free surface in liquid phase mixing	123
6.4	Effect of surface tension on free surface and liquid phase mixing	134
6.5	Summary and conclusions.....	140

Chapter 7: Effect of Tuyere Configurations and Flow Schemes on Gas–Liquid Flow and Mixing142

7.1	Effect of PCD on dynamics of gas–liquid flow and Mixing	143
7.1.1	Effect of PCD on dynamic of gas–liquid flow	143
7.2	Effect of differential flow schemes on gas–liquid flow and liquid phase mixing	152
7.2.1	Effect of differential flow schemes on dynamics of gas–liquid flow	154
7.2.2	Effect of differential flow schemes on liquid phase mixing.....	162
7.3	Effect of STAR–configurations on dynamics of gas–liquid flow and liquid phase mixing.....	169
7.3.1	Effect of STAR–configurations on dynamics of gas–liquid flow .	170
7.3.2	Effect of STAR–configurations on liquid phase mixing	178
7.4.	Summary and conclusions.....	182

Chapter 8: Summary, Conclusions and Suggestions for Future Work184

8.1	Summary and conclusions.....	185
8.2	Suggestions for the future work	192

References	193
List of publications	200
Bio-Data	202

List of figures

Figure 1.1: Annual steel production in the world and in India (World Steel Association, 2015).	2
Figure 1.2: Schematic overview of steel making process.....	4
Figure 1.3: Methods of oxygen injection in BOF steelmaking process (a) top blowing, (b) bottom blowing and (c) combined blowing.	5
Figure 1.4: Schematic of Basic Oxygen Furnace (BOF) (Corus, 2008).	7
Figure 2.1: Schematic of actual BOF vessel used in industry.	23
Figure 2.2: Dimensions of (a) actual vessel and (b) scaled-down model.	24
Figure 2.3: Schematic of fabricated 6:1 scaled-down BOF vessel geometry with bottom tuyere (all dimensions in m).	26
Figure 2.4: Photograph of scaled-down BOF vessel (a) complete set-up, (b) frustum and dish part and (c) bottom tuyere configuration (top view).	32
Figure 2.5: Schematic of the experimental set-up with the scaled-down model of BOF	33
Figure 2.6: In-house developed single voidage probe (a) photograph and (b) schematic.	34
Figure 2.7: (a) Typical raw signal acquired by the probe, (b) signal after noise removal and base correction and (c) normalized and phase discriminated signal.	37
Figure 2.8: Measured time-averaged gas volume fraction profiles at vessel heights of (a) 0.153 m and (b) 0.238 m from the bottom of the vessel ($\dot{m}_G = 1.3 \times 10^{-3}$ kg/s).	38
Figure 2.9: (a) Photograph of dual tip voidage probe and (b) schematic of bubble crossing the probe tips.	40
Figure 2.10. The typical raw signal acquired by dual tip voidage probe, (b) signal after noise removal and base correction, (c) normalize signal and (d) phase discriminated signal.	41

Figure 2.11. Comparison of bubble size distribution obtained using photography and voidage probes (calculated by different methods) at gas flow rate of $1.2 \text{ m}^3/\text{hr}$	42
Figure 2.12: Measured bubble size distributions in the BOF vessel at $\dot{m}_G$ of (a) 3.72×10^{-4} (low) and (b) $1.30 \times 10^{-3} \text{ kg/s}$ (high).	43
Figure 2.13: Photographs of (a) miniaturized conductivity probe and (b) conductivity measurement system.	44
Figure 2.14: Typically processed time–evolution of conductivity recorded at different locations in the vessel ($\dot{m}_G = 1.3 \times 10^{-3} \text{ kg/s}$).	45
Figure 3.1. Flowchart of working principle of EL and VOF approach	57
Figure 3.2: (a) Solution domain and (b) computational mesh in case of (i) EL and (ii) EL+VOF simulations.	60
Figure 3.3: Comparison of time-evolution of measured conductivity signal and simulated tracer mass fraction at eight different locations in the vessel ($\dot{m}_G = 1.3 \times 10^{-3} \text{ kg/s}$).....	62
Figure 3.4: A typical graph showing the fraction of the vessel volume having simulated tracer concentration within $\pm 10\%$ of the final (equilibrium) tracer concentration ($\dot{m}_G = 1.30 \times 10^{-3} \text{ kg/s}$).	63
Figure 4.1. Simulated instantaneous liquid velocity distributions (a) vector plot, (b) contour and (c) stream lines in XY–plane at $t = 20 \text{ s}$ for grid sizes of (i) 43k, (ii) 130k (iii) 215k ($\dot{m}_G = 1.30 \times 10^{-3} \text{ kg/s}$).	67
Figure 4.2: Effect of grid sizes on time–averaged (a) gas volume fraction, (b) vertical liquid velocity, (c) turbulent kinetic energy and (d) turbulent dissipation rate at vessel height of 0.204 m ($\theta = 0^\circ\text{-}180^\circ$) ($\dot{m}_G = 1.30 \times 10^{-3} \text{ kg/s}$).	68
Figure 4.3: Effect of step length factor on time–averaged (a) gas volume fraction and (b) vertical liquid velocity at vessel height of 0.204 m ($\theta = 0^\circ\text{-}180^\circ$) at $\dot{m}_G = 1.30 \times 10^{-3} \text{ kg/s}$	71

Figure 4.4: Effect of bubble injection orientation on time–averaged (a) gas volume fraction and (b) vertical liquid velocity at vessel height of 0.153 m ($\theta = 0^\circ$ - 180°) at $\dot{m}_G = 1.30 \times 10^{-3}$ kg/s.	72
Figure 4.5: Comparison of C_D (estimated using different drag correlations) as a function of Eö number	76
Figure 4.6: Effect of lift force on simulated particles positions (coloured by liquid velocity magnitude) with lift coefficient (C_L) of (a) 0.5, (b) 0.26 (Tomiyama’s correlation), (c) without lift force and (d) snapshot of bubble plumes from an experiment.	78
Figure 4.7: Comparison of measured and predicted (with and without lift force) time–averaged gas volume fraction profiles at vessel height of 0.204 m ($\theta = 0^\circ$) ($\dot{m}_G = 1.3 \times 10^{-3}$ kg/s).	79
Figure 4.8: Simulated DPM concentration distribution (a) with virtual mass force (virtual mass coefficient $C_{vm} = 0.5$) and (b) without virtual mass force ($\dot{m}_G = 1.3 \times 10^{-3}$ kg/s).	80
Figure 4.9: Comparison of measured and predicted (with and without virtual mass force) time–averaged gas volume fraction profiles at vessel height of 0.204 m ($\theta = 0^\circ$) from the bottom at a mass flow rate of 1.3×10^{-3} kg/s.	80
Figure 4.10. A comparison of predicted time–averaged gas volume fraction profiles simulated using poly–dispersed and mono–dispersed bubbles at vessel height of 0.204 m ($\theta = 0^\circ$ - 180°) ($\dot{m}_G = 1.30 \times 10^{-3}$ kg/s).	81
Figure 4.11. A comparison of predicted time–averaged vertical liquid velocity profiles simulated using poly–dispersed and mono–dispersed bubbles at vessel height of 0.204 m ($\dot{m}_G = 1.30 \times 10^{-3}$ kg/s).	82
Figure 4.12: Simulated instantaneous (a) particle positions, (b) stream lines (colored by liquid velocity magnitude) and (c) turbulent kinetic energy in rz –plane at mass flow rates of (i) 3.73×10^{-4} (low), (ii) 7.44×10^{-4} (medium) and (iii) 1.30×10^{-3} kg/s (high).	85
Figure 4.13: Comparison measured and simulated local gas volume fraction fluctuations at point P1 ($\theta = 0^\circ$ - 180°) (shown in Figure 4.12 (i) (b)) at mass flow rates of (a) 3.73×10^{-4} (low) and (b) 1.30×10^{-3} kg/s (high).	86

Figure 4.14: Comparison of power spectra of gas volume fraction fluctuations (a) measured by voidage probe and (ii) predicted at $\dot{m}_G$ of 3.73×10^{-4} kg/s (low).....	87
Figure 4.15: Comparison of power spectra of gas volume fraction fluctuations (a) measured by voidage probe and (ii) predicted at $\dot{m}_G = 1.3 \times 10^{-3}$ kg/s (high).	88
Figure 4.16: Predicted time-averaged gas volume fraction profiles at different θ planes at vessel heights of (a) 0.104 m and (b) 0.280 m ($\theta = 0^\circ$ - 180°) ($\dot{m}_G = 1.30 \times 10^{-3}$ kg/s).	90
Figure 4.17: Comparison of experimental and simulated time- and θ -averaged gas volume fraction at vessel heights of (a) 0.153 m and (b) 0.280 m ($\theta = 0^\circ$ - 180°) at mass flow rates of 3.73×10^{-4} (low), 7.45×10^{-4} (medium), and 1.30×10^{-3} kg/s (high).	91
Figure 5.1: Effect of grid size on predicted mixing time calculated using definition 2 (fraction of the vessel having tracer mass fraction within $\pm 10\%$ of equilibrium concentration ($\dot{m}_G = 1.3 \times 10^{-3}$ kg/s).	95
Figure 5.2: Predicted snapshots of contours of tracer mass fraction distribution at (a) $t = 0$ s, (b) $t = 2$ s, (c) $t = 6$ s, (d) $t = 10$ s, (e) $t = 30$ s and (f) $t = 40$ s ($\dot{m}_G = 1.30 \times 10^{-3}$ kg/s).	97
Figure 5.3: Comparison of snapshots of simulated tracer mass fraction distribution at (a) $t = 2$ s, (b) $t = 6$ s, (c) $t = 20$ s and (d) $t = 40$ s at grid sizes of (i) 43k, (ii) 130k, and (iii) 215k at vessel heights of 0.0638 and 0.270 m from bottom ($\dot{m}_G = 1.30 \times 10^{-3}$ kg/s).	98
Figure 5.4: Probe location and tracer injection point.....	99
Figure 5.5: Comparison of predicted (using EL approach) and measured mixing time at different mass flow rates.	100
Figure 5.6: Predicted liquid velocity distribution in the vessel at a mass flow rate of 3.73×10^{-4} kg/s at (a) 20 s and (b) 40 s.	101
Figure 5.7. A comparison of predicted mixing time (fraction of the vessel volume having the tracer concentration within $\pm 10\%$ of the final (equilibrium) tracer concentration) simulated using poly-dispersed and mono-dispersed bubbles ($\dot{m}_G = 1.30 \times 10^{-3}$ kg/s).....	102

Figure 5.8: Comparison of snapshots of experimental and predicted tracer mass fraction distributions at $t =$ (a) 0 s, (b) 2 s, (c) 6 s and (d) 30 s at ($\dot{m}_G = 1.30 \times 10^{-3}$ kg/s).	104
Figure 5.9: Comparison of snapshots of simulated tracer mass fraction distribution at (a) $t = 2$ s, (b) $t = 6$ s, (c) $t = 20$ s and (d) $t = 40$ s at $\dot{m}_G$ of (i) 3.73×10^{-4} (low) , (ii) 7.45×10^{-4} (medium) and (iii) 1.30×10^{-3} kg/s (high) at vessel heights of 0.0638 and 0.270 m from bottom.....	105
Figure 5.10: Comparison of measured and predicted mixing time at different of mass flow rates (definition–1: $\pm 5\%$, and definition–2: $\pm 10\%$ criteria).	107
Figure 6.1: Instantaneous (a) bubble positions (colored by bubble velocity magnitude), (b) liquid velocity distribution (vector plot) and (c) streamlines (colored by liquid velocity magnitude) in rz –plane at $t = 20$ s for simulations performed with (i) no slip, (ii) free slip and (iii) free surface conditions at the top surface ($\dot{m}_G = 1.30 \times 10^{-3}$ kg/s, $H/D = 0.44$).	113
Figure 6.2: Comparison of liquid velocity fluctuation time series of (a) V_x , (b) V_z and (c) V_y components predicted using the EL and EL + VOF simulations ($\dot{m}_G = 1.30 \times 10^{-3}$ kg/s, $H/D = 0.44$). The locations of points P1 ($x = 0$ m, $y = 0.153$ m, $\theta = 0^\circ$) P2 ($x = 0.190$ m, $y = 0.153$ m, $\theta = 0^\circ$) and P3 ($x = 0.280$ m, $y = 0.153$ m, $\theta = 0^\circ$) are shown in Figure 6.1(i) (c).	115
Figure 6.3: Comparison of time–averaged vertical liquid velocity at vessel heights of (a) 0.150 m and (b) 0.288 m ($\theta = 0^\circ$ – 180°) for the cases of no slip, free slip, and free surface boundary conditions at the top surface ($\dot{m}_G = 1.30 \times 10^{-3}$ kg/s, $H/D = 0.44$).	116
Figure 6.4: Snapshots of iso–surface of DPM concentration at (a) $t = 10$ s, (b) $t = 11$ s and (c) $t = 12$ s for (i) no slip, (ii) free slip and (iii) free surface conditions at the top surface ($\dot{m}_G = 1.30 \times 10^{-3}$ kg/s, $H/D = 0.44$).	117
Figure 6.5: Contours of (i) turbulent kinetic energy and (ii) turbulent kinetic energy dissipation rate on rz –plane for the simulations performed with (a) no slip and (b) free surface conditions at the top surface ($\dot{m}_G = 1.3 \times 10^{-3}$ kg/s, $H/D = 0.44$).	118
Figure 6.6: Comparison of kinetic energy distributions in the entire vessel predicted using the EL and EL+VOF approaches ($\dot{m}_G = 1.3 \times 10^{-3}$ kg/s, $H/D = 0.44$).	119

Figure 6.7: Snapshots of simulated tracer mass fraction distribution at (a) 0 s, (b) 2 s, (c) 6 s, (d) 10 s, and (e) 40 s for (i) no slip, (ii) free slip and (iii) free surface conditions at the top surface ($\dot{m}_G = 1.30 \times 10^{-3}$ kg/s, $H/D = 0.44$).	122
Figure 6.8: Comparison of measured and predicted mixing time by EL (no slip), EL (free slip) and EL+VOF (free surface) approaches (definition 1: $\pm 5\%$ criteria), $H/D = 0.44$).	123
Figure 6.9: Instantaneous (a) liquid velocity distribution (vector plot), (b) stream lines (colored by liquid velocity magnitude) and (c) rate of turbulent energy dissipation in rz-plane at $t = 20$ s for (i) no-slip, and (ii) free surface conditions at $H/D = 0.22$ ($\dot{m}_G = 1.30 \times 10^{-3}$ kg/s).	125
Figure 6.10: Instantaneous (a) liquid velocity distribution (vector plot), (b) stream lines (colored by liquid velocity magnitude) and (c) rate of turbulent energy dissipation in rz-plane at $t = 20$ s for (i) no-slip, and (ii) free surface boundary conditions at $H/D = 0.88$ ($\dot{m}_G = 1.30 \times 10^{-3}$ kg/s).	126
Figure 6.11: Comparison of vertical liquid velocity fluctuation time series at H/D of (a) 0.22, (b) 0.44 and (c) 0.88 for no-slip (EL) and free surface (EL+VOF) conditions at top surface ($\dot{m}_G = 1.30 \times 10^{-3}$ kg/s). The location of points P1 ($x = 0.1$ m, $y = 0.153$ m, $\theta = 0^\circ$) P2 ($x = 0.195$ m, $y = 0.153$ m, $\theta = 0^\circ$) and P3 ($x = 0.380$ m, $y = 0.153$ m, $\theta = 0^\circ$) are shown in Figure 6.1 (ii) (b)), Figure 6.9 (i) (c) and Figure 6.10 (ii) (b).	128
Figure 6.12: Snapshots of simulated tracer mass fraction distribution at (a) $t = 0$ s, (b) $t = 2$ s, (c) $t = 6$ s, and (d) $t = 26$ s for (i) no-slip, and (ii) free surface conditions at top surface at $H/D = 0.22$ ($\dot{m}_G = 1.30 \times 10^{-3}$ kg/s).	130
Figure 6.13. Snapshots of simulated tracer mass fraction distribution at (a) $t = 0$ s, (b) $t = 2$ s, (c) $t = 6$ s (d) $t = 30$ s and (e) $t = 60$ s for (i) no-slip, and (ii) free surface conditions at top surface at $H/D = 0.88$ ($\dot{m}_G = 1.30 \times 10^{-3}$ kg/s) (color code: blue-0, red-equilibrium and above).	131
Figure 6.14: Comparison of histograms of liquid velocity magnitude in the entire vessel at H/D of (a) 0.22, (b) 0.44 and (c) 0.88 for no-slip (EL) and free surface (EL+VOF) conditions at top surface ($\dot{m}_G = 1.30 \times 10^{-3}$ kg/s).	133

Figure 6.15: Instantaneous (a) liquid velocity distribution (vector plot) (b) stream lines (colored by liquid velocity magnitude) and (c) rate of kinetic energy dissipation in rz-plane at $t = 20$ s for free surface approach with (i) $\sigma = 0.2\sigma^*$ (ii) $\sigma = \sigma^*$ (iii) $\sigma = 5\sigma^*$ and (iv) no slip boundary condition at top ($\dot{m}_G = 1.30 \times 10^{-3}$ kg/s, $H/D = 0.22$).....	136
Figure 6.16: Comparison of instantaneous vertical liquid velocity at point (a) P1 ($x = -0.150$ m, $y = 0.153$ m, $\theta = 0^\circ$) (b) P2 ($x = 0$ m, $y = 0.153$ m, $\theta = 0^\circ$) and (c) P3 ($x = 0.150$ m, $y = 0.153$ m, $\theta = 0^\circ$) for free surface boundary condition at top with (i) $\sigma = 0.2\sigma^*$ (ii) $\sigma = \sigma^*$ (iii) $\sigma = 5 \times \sigma^*$ and (iv) no slip boundary conditions at top ($\dot{m}_G = 1.30 \times 10^{-3}$ kg/s, $H/D = 0.22$). The location of points P1, P2 and P3 are shown in Figure 6.15 (ii) (b).....	138
Figure 6.17: Snapshots of simulated tracer mass fraction distribution at (a) $t = 0$ s, (b) $t = 2$ s, (c) $t = 6$ s and (d) $t = 26$ s for free surface approach at top with (i) $\sigma = 0.2\sigma^*$ (ii) $\sigma = \sigma^*$ (iii) $\sigma = 5\sigma^*$ and (iv) no slip boundary condition at top ($\dot{m}_G = 1.30 \times 10^{-3}$ kg/s, $H/D = 0.22$).....	139
Figure 7.1: Bottom tuyere configurations (a) schematic and (b) photograph.....	144
Figure 7.2: Snapshots of instantaneous (a) vertical liquid velocity distribution surface plot, (b) liquid velocity distribution in horizontal planes, and (c) pathlines of particles injected from top central axis at $t=20$ s at PCDs of (i) 0.7, (ii) 0.59 and (iii) 0.5 ($\dot{m}_G = 1.30 \times 10^{-3}$ kg/s).....	145
Figure 7.3: Comparison of the simulated vertical liquid velocity fluctuation time series at points (a) P1 ($x = -0.3$ m, $y = 0.2$, $\theta = 0^\circ$), (b) P2 ($x = -0.2$ m, $y = 0.2$, $\theta = 0^\circ$) and (c) P3 ($x = 0.1$ m, $y = 0.2$, $\theta = 0^\circ$) at different PCDs (mass flow rate: 1.3×10^{-3} kg/s) (the locations are shown in Figure 7.2 (i)(b)).....	147
Figure 7.4: Comparison of liquid velocity distributions inside the vessel for bottom tuyeres placed at different PCDs ($\dot{m}_G = 1.30 \times 10^{-3}$ kg/s).	148
Figure 7.5: Comparison of turbulent kinetic energy distributions inside the vessel for bottom tuyeres placed at different PCDs ($\dot{m}_G = 1.30 \times 10^{-3}$ kg/s).....	149
Figure 7.6: Comparison of snapshots of simulated tracer mass fraction distribution at (a) 2 s, (b) 6 s, (c) 20 s and (d) 40 s for PCD of (i) 0.7, (ii) 0.59 and (iii) 0.50 at vessel heights of 0.0638 and 0.270 m from bottom ($\dot{m}_G = 1.30 \times 10^{-3}$ kg/s).....	150

Figure 7.7: Comparison of predicted and measured mixing times at different PCDs (definition–1, $\pm 5\%$ criteria)	151
Figure 7.8: Schematic of (a) Uniform ($F = \dot{m}_G/8$), (b) W–type ($F = \dot{m}_G/8$), (c) 4–4–type ($F = \dot{m}_G/8$), (d) V–type ($F = \dot{m}_G/10$), (e) M–type ($F = \dot{m}_G/10$), and (f) linear–type ($F = \dot{m}_G/5$) differential flow schemes (where, F is gas mass flowrate ethrough each tuyere ($F = \dot{m}_G / 8$) and T represent tuyeres).....	153
Figure 7.9: Snapshots of instantaneous (a) vertical liquid velocity distribution surface plot, (b) liquid velocity distribution in horizontal planes (colored by velocity magnitude), and (c) pathlines (colored by velocity magnitude) of particles injected from top central axis at $t = 20$ s for (i) uniform,, (ii) W–static, (iii) V–static, (iv) M–static, (v) linear–static, (vi) 4–4 dynamic and (vii) W–dynamic differential flow schemes ($\dot{m}_G = 1.30 \times 10^{-3}$ kg/s).....	157
Figure 7.10: Comparison of instantaneous vertical liquid velocity at point (a) P1, (b) P2 and (c) P3, for different differential flow schemes ($\dot{m}_G = 1.30 \times 10^{-3}$ kg/s). The location of points P1 ($x = -0.290$ m, $y = 0.2$ m, $\theta = 0^\circ$) P2 ($x = -0.20$ m, $y = 0.2$ m, $\theta = 0^\circ$) and P3 ($x = -0.05$ m, $y = 0.2$ m, $\theta = 0^\circ$) are shown in Figure 7.9 (i) (b).	160
Figure 7.11: Comparison of liquid velocity distributions inside the vessel for different differential flow schemes ($\dot{m}_G = 1.30 \times 10^{-3}$ kg/s).	161
Figure 7.12: Comparison of turbulent kinetic energy distributions inside the vessel for the different differential flow schemes ($\dot{m}_G = 1.30 \times 10^{-3}$ kg/s).	162
Figure 7.13: Snapshots of simulated tracer mass fraction distribution for (i) uniform, (ii) W–static (iii) V–static (iv) M–static, (v) linear– static, (vi) 4–4–dynamic and (vii) W–dynamic differential flow schemes at time (a) 6 s, (b) 20 s and (c) 30 s for ($\dot{m}_G = 1.30 \times 10^{-3}$ kg/s).	165
Figure 7.14: Comparisons of predicted mixing time for different differential flow schemes at $\dot{m}_G = 1.30 \times 10^{-3}$ kg/s.....	166
Figure 7.15. Schematic of the (a) STAR–A and (b) STAR–B bottom tuyere configurations.	170

Figure 7.16: Snapshots of instantaneous (a) vertical liquid velocity distribution surface plot, (b) liquid velocity distribution in horizontal planes, and (c) stream lines at $t=20$ s for (i) uniform, (ii) STAR–A and (iii) STAR–B bottom tuyere configurations ($\dot{m}_G = 1.30 \times 10^{-3}$ kg/s).....	173
Figure 7.17. Comparison of predicted profiles of (a) liquid velocity magnitude, (b) turbulent kinetic energy and (c) vorticity distribution in $r\theta$ -planes at PCDs of (i) 0.4 and (ii) 0.8 ($\dot{m}_G = 1.30 \times 10^{-3}$ kg/s, $Y = 0.153$ m)	174
Figure 7.18: Snapshots of instantaneous liquid velocity magnitude distribution at planes (a) PCD = 0.8 and (b) PCD = 0.4, and (c) streamlines at in $r-\theta$ plane ($z = 0.70$ mm) for the cases of (a) uniform, (b) STAR–A and (c) STAR–B bottom tuyere configurations ($\dot{m}_G = 1.30 \times 10^{-3}$ kg/s).....	175
Figure 7.19: Comparison of simulated liquid velocity fluctuation time series at (a) P1 ($x = -0.3$ m, $y = 0.2$, $\theta = 0^\circ$), (b) P2 ($x = -0.2$ m, $y = 0.2$, $\theta = 0^\circ$) and (c) P3 ($x = -0.1$ m, $y = 0.2$, $\theta = 0^\circ$) for uniform and different STAR configurations (mass flow rate 1.3×10^{-3} kg/s) (locations are shown in Figure 7.16).....	178
Figure 7.20: Comparison of snapshots of simulated tracer mass fraction distribution at (a) 2 s, (b) 6 s, (c) 20 s and (d) 40 s for (i) uniform, (ii) STAR–A, and (iii) STAR–B bottom tuyere configurations at vessel heights of 0.0638 and 0.270 m from bottom ($\dot{m}_G = 1.30 \times 10^{-3}$ kg/s).	180
Figure 7.21: Comparison of predicted and measured mixing times for different STAR configurations (definition–1, $\pm 5\%$ criteria).	181
Figure 7.22. Comparison of mixing time obtain in the present work with literature for a given specific energy input rate	182

List of tables

Table 2.1. Details of the geometry of full-scale vessel and scaled-down model.	24
Table 2.2. Calculation of modified Froude no. for actual BOF vessel with liquid metal and argon as working fluids at $T = 1600\text{ }^{\circ}\text{C}$	28
Table 2.3: Calculation of air flow rate for fabricated 6:1 scaled-down vessel with water and air as working fluids at $T = 25^{\circ}\text{C}$	29
Table 2.4: Calculation of modified Froude no. for actual vessel with liquid metal and air as working fluids.	30
Table 2.5: Calculation of air flow rate using modified Froude no. for fabricated 6:1 scaled-down vessel with water and air as working fluids.	31
Table 2.6: Details of the actual BOF vessel and the scaled-down model and process parameters.	32
Table 3.1. Mesh quality for different grid sizes used in the present study	60
Table 4.1. Summary of correlations available for estimation of C_D	74
Table 5.1: Effect of locations (single plane vs. multiple planes) on mixing time.	99
Table 5.2: Comparison of locally measured and predicted mixing time at various locations at different mass flowrates.	106
Table 6.1: Comparison of volume-averaged turbulent kinetic energy and its dissipation rate in different zones ($\dot{m}_G = 1.3 \times 10^{-3}\text{ kg/s}$, $H/D = 0.44$).	119
Table 6.2 Effect of H/D ratio on average liquid phase mixing time at mass flow rate of $1.3 \times 10^{-3}\text{ kg/s}$	133
Table 6.3: Comparison of locally measured and predicted mixing time at different probe locations at $H/D = 0.44$ ($\dot{m}_G = 1.30 \times 10^{-3}\text{ kg/s}$).	134

Table 6.4. Comparison of locally measured and predicted mixing time at different probe locations at $H/D = 0.22$ ($\dot{m}_G = 1.30 \times 10^{-3}$ kg/s).	134
Table 6.5. Effect of surface tension coefficient on average liquid mixing at $\dot{m}_G = 1.3 \times 10^{-3}$ kg/s.	140
Table 7.1: Comparison of measured and predicted average mixing time for different differential flow schemes at different mass flow rates.	167
Table 7.2: Comparison of locally measured and predicted mixing time at various locations for different differential schemes at $\dot{m}_G = 3.73 \times 10^{-4}$ kg/s.....	168
Table 7.3 Comparison of locally measured and predicted mixing time at different locations of the various differential schemes at $\dot{m}_G = 1.3 \times 10^{-3}$ kg/s.....	169

Nomenclature

C_1, C_2, C_m	turbulent model parameters, -
C_D	drag force coefficient, -
C_L	lift force coefficient, -
C_{VM}	virtual mass coefficient, -
d_B	bubble diameter, m
$Eö$	Eotvos number,-
F'	Modified Froude number,-
$\overline{F}_G, \overline{F}_D, \overline{F}_L, \overline{F}_{VM}, \overline{F}_P$	gravitational force, drag force, lifts force, virtual mass force and pressure force, respectively, $\text{kg/m}^2 \cdot \text{s}^2$
$\overline{F}$	surface tension force, $\text{kg/m}^2 \cdot \text{s}^2$
g	gravitational acceleration, m/s^2
H	liquid height in the vessel, m
M	interphase momentum exchange term, $\text{kg/m}^3 \cdot \text{s}$
P	pressure, Pa
R_{e_B}	bubble Reynolds number,
U	means velocity, m/s
x, y, z	spatial coordinates (along width, depth and height, respectively) , m

Greek Symbols

α	volume fraction,-
θ	azimuthal direction,-
ε	energy dissipation rate, m ² /s ³
κ	energy dissipation rate, m ² /s ²
μ	viscosity, Pa.s
μ_{eff}	effective viscosity, Pa.s
$\bar{\bar{\tau}}$	viscous stress tensor
ν_t	kinematic turbulent viscosity, m ² /s
σ	surface tension, N/m
ρ	density, kg/m ³

Subscripts and superscripts

k	surface curvature
G	gas
L	liquid
lam,t, eff	laminar, turbulent, effective

Acronyms list

BOF	basic oxygen furnace
CFD	computational fluid dynamics
EL	Euler–Lagrange
EE	Euler–Euler
VOF	volume of fluid