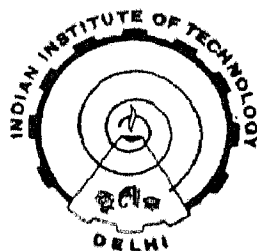


STUDIES ON HYDRODYNAMICS AND MIXING IN BUBBLE COLUMNS EMPLOYING NON-NEWTONIAN FLUIDS

By
MD. WASIFUL HAQUE

THESIS SUBMITTED
IN FULFILMENT OF THE REQUIREMENT
OF THE DEGREE OF
DOCTOR OF PHILOSOPHY



Department of Chemical Engineering
INDIAN INSTITUTE OF TECHNOLOGY, DELHI

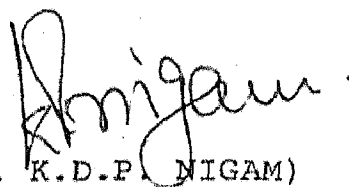
1986

CERTIFICATE

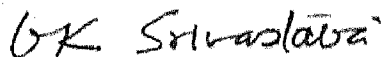
This is to certify that the thesis entitled, "STUDIES ON HYDRODYNAMICS AND MIXING IN BUBBLE COLUMNS EMPLOYING NON-NEWTONIAN FLUIDS" being submitted by Mr. Md. Wasiful Haque to the Indian Institute of Technology, Delhi for the award of the degree of 'DOCTOR OF PHILOSOPHY' is a record of the bonafied research work carried out by him. Mr. Md. Wasiful Haque worked under our guidance for the submission of this thesis which to our knowledge has reached to requisite standard.

The thesis or any part thereof has not been submitted to any other University or Insitution for the award of any degree or diploma.

September, 1986.



(Dr. K.D.P. NIGAM)
Assistant Professor,
Department of Chemical Engg.,
I.I.T. New Delhi-110016, INDIA.



(Dr. V.K. SRIVASTAVA)
Assistant Professor,
Department of Chemical Engg.,
I.I.T., New Delhi-110016, INDIA.

ACKNOWLEDGEMENTS

The author owes many thanks to Professor K.D.P. Nigam, Department of Chemical Engineering, Indian Institute of Technology, Delhi, for his valuable advice and guidance, throughout the course of this work.

I am deeply indebted to Professor M.M. Sharma for permitting me and providing the necessary facilities for carrying out experimental work in large diameter columns at University Department of Chemical Technology, University of Bombay, and to Dr. J.B. Joshi for his valuable advice and guidance during experimental work and research.

A debt of gratitude is also due to Dr. V.K. Srivastava and Dr. K. Viswanathan for their help to overcome difficulties during the experimental and theoretical work on this thesis.

Advice given by Dr. A.B. Pandit, U.D.C.T., University of Bombay and Dr. S.S. Sambi, Chemical Engineering Department, I.I.T. Delhi, during the experimental set-up and while carrying out the experiments are also gratefully acknowledged.

I wish to express my thanks to Indian Council for Cultural Relations, Department of Education, Ministry of Education and Culture, Government of India and Ministry of Education, Government of Bangladesh for awarding me a fellowship and financial support which made this assignment possible.

I am thankful to the Head of the Department, Teachers and Staff of Chemical Engineering Department, I.I.T. Delhi, for providing the necessary facilities for carrying out this research. I am also thankful to Mr. V.P. Gulati for typing this thesis.

I wish to express my thanks particularly to my wife for her cooperation at every stage.

September, 1986.

MD. WASIFUL HAQUE

ABSTRACT

Experimental data are reported on the gas holdup in 0.10m, 0.20 m, 0.38 m and 1.0 m diameter bubble columns employing water and highly viscous pseudoplastic CMC solutions. Transient conductivity or pH measurements were carried out to measure mixing time. Nine different gas sparger designs were employed to study the possibility of optimum sparger design in a 1.0 m diameter bubble column. Single bubble size and its rise velocity through a pseudoplastic non-Newtonian (CMC) liquid pool were studied by a cine photographic technique with a 16 mm high speed camera. The major results from the above studies are :

- A flow transition chart has been developed to predict the flow regime for highly viscous pseudo-plastic non-newtonian systems in bubble columns for a wide range of operating parameters. Effective critical viscosity at the transition from churn-turbulent to slug flow regime for different column diameters is also predicted.
- A correlation for the gas holdup in the churn turbulent regime has been presented covering a wide range of operating parameters as

$$\epsilon = 0.171 U_G^{0.6} \mu_{\text{eff}}^{-0.22} D^{-0.15}$$

with a standard deviation of 0.01 for $U_G \geq 0.03 \text{ ms}^{-1}$

and $0.10 \text{ m} \leq D \leq 1.0 \text{ m}$. This will be useful to design industrial size bubble columns treating viscous pseudo-plastic non-Newtonian solutions.

- The inviscid liquid circulation model has been found to be applicable for non-Newtonian systems as well in large diameter bubble columns. Although the liquid employed is viscous, it is shown that the inviscid circulation model explains the data extremely well.
- A new method has been developed to obtain the volume-to-surface mean bubble diameters using the estimated isolated bubble rise velocities from bubble column experiments.
- The drag coefficient relation of Hirose and Moo-Young is found to be valid for single rising bubbles in CMC solutions. The isolated bubble rise velocity reaches a constant value of about 0.30 m/s for a bubble size range of 10-18 mm for CMC concentrations studied here.
- Experimental mixing time data have been reported in bubble columns employing CMC solutions with different ratios of clear liquid height to diameter. An expression has been developed to predict the liquid circulation time required for complete mixing. The liquid mixing behavior is explained in terms of the average liquid circulation velocity. The equivalent path lengths for lag time, bulk mixing time and diffusion time are found to be $(0.5D+H)$, $(0.5D+H)$ and $5D$ respectively. A mathematical expression has been derived to predict the mixing time.

- Optimization of gas sparger design with respect to gas holdup and mixing time data is possible.
- Standard graphs and design equations have been developed which enable quick design and evaluation/ optimization of continuous or semi-batch bubble columns treating Newtonian and non-Newtonian liquids.

CONTENTS

	Page No.
LIST OF FIGURES	x
LIST OF TABLES	xiv
NOMENCLATURE	xvi
CHAPTER-1 INTRODUCTION	1
CHAPTER-2 LITERATURE REVIEW	6
2.1 GAS-LIQUID SYSTEMS IN BUBBLE COLUMNS	6
2.2 FLOW REGIMES	9
2.3 GAS HOLDUP	14
2.4 BUBBLE DYNAMICS IN BUBBLE COLUMNS	20
2.5 SINGLE BUBBLE DYNAMICS	23
2.5.1 Newtonian Liquids	23
2.5.2 Non-Newtonian Liquids	25
2.6 GAS-LIQUID INTERFACIAL AREA	27
2.7 MASS TRANSFER COEFFICIENTS	30
2.8 MIXING TIME	32
CHAPTER-3 THEORETICAL CONCEPTS	37
3.1 GAS HOLDUP AND LIQUID CIRCULATION VELOCITY	37
3.2 BUBBLE PARAMETERS	38
3.2.1 Newtonian Systems	38
3.2.2 Power-Law Fluids	40
3.3 AVERAGE LIQUID CIRCULATION AND MIXING TIME	42

		Page No.
CHAPTER-4	EXPERIMENTAL	43
4.1	SETUP TO STUDY GAS HOLDUP AND MIXING TIME	43
4.1.1	Measurement Procedure	46
4.1.2	System Studied	49
4.2	SETUP OF SINGLE BUBBLES RISING IN NON-NEWTONIAN LIQUIDS	51
4.2.1	Column Assembly	51
4.2.2	Bubble Injection Nozzle	54
4.2.3	Photographic Technique	54
4.2.4	Lighting Arrangements	56
4.2.5	Experimental Procedure	56
CHAPTER-5	RESULTS AND DISCUSSION	59
5.1	FLOW REGIMES	59
5.2	GAS HOLDUP	62
5.2.1	Effect of Sparger Design	62
5.2.2	Effect of H_c/D Ratio	62
5.2.3	Effect of Liquid Phase Viscosity	65
5.2.4	Effect of Column Diameter	65
5.2.5	Correlation and Comparison With the Literature Data	69
5.2.6	Mean Bubble Rise Velocity	69
5.2.7	The Appropriate Model - Inviscid Theory	73
5.3	LIQUID CIRCULATION VELOCITY	81
5.4	TERMINAL BUBBLE RISE VELOCITY AND MEAN BUBBLE DIAMETER	84

5.5	MIXING TIME	..	87
5.5.1	Mixing Time Model	..	87
5.5.2	Test of the Mixing Time Model for Smaller Columns	..	97
5.6	SINGLE BUBBLE MOTION IN NON- NEWTONIAN FLUIDS	..	106
5.6.1	Analysis of Single Bubble Rise Velocity	..	107
5.7	ESTIMATION OF d_{vs} IN INDUSTRIAL BUBBLE COLUMNS CONSIDERING NON-NEWTONIAN BEHAVIOR	..	113
5.8	OPTIMUM GAS SPARGER DESIGN WITH A LOW H_c/D RATIO	..	116
CHAPTER-6	DESIGN EVALUATION AND OPTIMIZATION OF BUBBLE COLUMNS	..	126
6.1	CONTINUOUS BUBBLE COLUMNS-EXAMPLES	..	126
6.1.1	Validity of Inviscid Model	..	135
6.1.2	Design of a Continuous Bubble Column Absorber	..	137
6.1.3	Evaluation of a Bubble Column	..	141
6.2	SEMI-BATCH BUBBLE COLUMNS	..	143
6.2.1	Liquid Phase-Solute Con- centration	..	143
6.2.2	Murphree Efficiency	..	144
6.3	SEMI-BATCH BUBBLE COLUMNS-EXAMPLES	..	146
6.3.1	Evaluation of a Semi-Batch Column Absorber	..	146
6.3.2	Design of a Semi-Batch Bubble Column Absorber	..	151
6.3.3	Fixing Minimum Liquid Depth	..	155

	Page No.
CHAPTER-7	
CONCLUSIONS	.. 157
RECOMMENDATIONS FOR FUTURE WORK	.. 160
REFERENCES	.. 162
 AUTHOR'S BIO-DATA	 ... 170