Table of contents

Vorwort **iii**

List of figures **xi**

List of tables **xvii**

Nomenclature **xix**

1 Introduction **1**

2 State of the art and basic knowledge **3**

2.1 Definition and fundamentals of fine bubbles 3

2.1.1 Classification of fine bubbles 3

2.1.2 Fields of application for fine bubbles 4

2.1.3 Characteristics and physical models describing ultrafine bubbles . . 5

2.2 Hydrodynamics and mass transfer in bubbly flows 11

2.2.1 Fundamentals of rising bubbles in stagnant liquid 11

2.2.2 Mass transfer in two-phase systems 14

2.2.3 Hydrodynamic and mass transfer characteristics of microbubbles . . 18

2.3 Suitable reactor systems and generation principles for fine bubble aeration . 22

2.3.1 Design and hydrodynamics of aerated stirred tank reactors 22

2.3.2 Fine bubble generation principles 30

3 Experimental setups and procedure **35**

3.1 Proof of stability for ultrafine bubbles in aqueous liquids 36

3.1.1 Ultrafine bubble generation by pressurized dissolution 36

3.1.2 Ultrafine bubble generation by ultrasonication 37

3.2 Three reactor setups to evaluate the performance using fine bubble aeration 38

3.2.1 Setup of fine bubble aerated bubble column reactor 39

3.2.2 Setup of jet reactor with injector nozzle fine bubble generator . . . 40
3.2.3 Setup of fine bubble aerated stirred tank reactor 43
3.2.4 Liquid systems for fine bubble aerated reactor setups 44
3.3 Setups for investigating local mass transfer effects at microscale bubbles . . 45
3.3.1 Setup for generating single microscale bubbles 45
3.3.2 Setup for measuring local concentration fields at a free rising microscale bubble 46
3.3.3 Setup for measuring local concentration gradients at a fixed microscale bubble 48

4 Measurement techniques 51
4.1 Nanoparticle Tracking Analysis 51
4.1.1 Principle and equipment 52
4.1.2 Application to ultrafine bubble liquids 53
4.2 Laser induced fluorescence 54
4.3 Confocal laser scanning microscopy 55
4.4 Determination of the gas hold-up from endoscopic measurements 57

5 Experimental results and discussion 59
5.1 Proof of stability for ultrafine bubbles in aqueous liquids 60
5.1.1 Evaluation of particle size distribution 60
5.1.2 Conclusion on the existence of ultrafine bubbles and their application to process industry 63
5.2 Evaluation and comparison of fine bubble aerated reactor concepts 64
5.2.1 Hydrodynamic characterization of fine bubble aerated bubble column reactor 64
5.2.2 Characterization of fine bubble aerated jet reactor systems 67
5.2.3 Comparison of fine bubble aerated jet and stirred tank reactor concepts 69
5.3 Characterization of the membrane aerated stirred tank reactor concept . . . 72
5.3.1 Hydrodynamics of membrane aerated stirred tank reactor 72
5.3.2 Mass transfer behavior of membrane aerated stirred tank reactor . . 82
5.4 Fundamental mass transfer characteristics of microscale bubbles 87
5.4.1 Visualization of local mass transfer effects at single microscale bubbles 87
5.4.2 Modeling of counterdiffusion effects at a single microscale bubble . 92
5.4.3 Evaluation of counterdiffusion effects in fine bubble swarms 94
5.4.4 Modeling of counterdiffusion effects in fine bubble swarms 100

6 Conclusion 103

References 105

Appendix A Technical data of the SOPAT probes 115

Appendix B Additional data for the fine bubble aerated jet reactor setup 117

Appendix C Additional data for the membrane aerated STR 119