Fluid Dynamics Mechanism of Microbubble Generators and Their Simulations and Applications

微泡发生器流体动力学机理及其仿真与应用

李浙昆 著

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前 言

随着经济的增长、人口的增加、工业化和城市化的发展，矿物资源消耗越来越多，人类将面临资源枯竭的危险。由于矿物资源的不断被开发利用，品位低、嵌布粒度细、共生矿、组成复杂的难选矿所占比例日益增大，资源高效综合利用、微细粒矿物选别、再生资源利用、尾矿再选等，已经成为21世纪人类面临的重要任务。

微泡浮选对微细粒矿物选别、废纸脱墨、处理工业废水等有着特殊的功效，急待对其进行深入的研究。新的微泡浮选方法、新型微泡浮选柱以及微泡浮选的工业应用等的研究正在进行，而气泡发生装置作为微泡浮选最重要的关键技术，一直是研究和关注的重点。微泡的生成与控制一直是影响微泡浮选推广应用的瓶颈，对微泡浮选中微泡生成的理论与应用的研究还有待于不断深入。

在多种新型的气泡发生器中，流体型微泡发生器具有产生的气泡直径较小、空气保有量较高、气泡分散度较好以及可以产生湍动旋流（以利于气泡与矿粒之间的相互作用，促进物料性别）等特点。本专著选择了具有典型性的流体型微泡发生器作为研究对象，研究了射流式、旋流式、混流式、自吸式剪切流微孔等微泡发生器，研究了微泡发生器性能分析评价的方法、电导法检测液位高度、泡沫层厚度的方法，并进行了该检测装置的设计。

在流体型微泡发生器中，微泡生成时的流动是复杂的气、固、液三相流流动。三相流的性质、流量、流态等的变化，对微泡生成以及微泡浮选效果有着重要的影响，故对微泡生成的三相流力学机理进行研究是很有必要的。

本专著的主要研究内容如下：

一是对微泡生成机理及流体型微泡发生器进行了研究。本专著分析和研究了微泡浮选的作用及其关键技术、流体型微泡发生器工作原理、微泡形成的理论、微泡生成力学机理、气核的作用、微泡析出机理、流体型微泡发生器的微泡生成机理。分析和研究了气泡在流体中可能受到的各种力及其对微泡生成的

影响作用、流体型微泡生成中可能产生的力。分析了微泡发生器的结构、各部件在微泡生成中的作用以及对微泡生成的影响。对气泡尺寸和气泡行为、气泡的聚并与破碎规律、气泡的分散与结群、气泡与矿浆间的相互作用、气泡尺寸大小和稳定性的影响因素等进行了研究和分析，建立了单颗粒气泡与单颗粒矿粒因碰撞粉碎成微泡的力学机理模型。

二是研究了微泡生成三相流力学机理。在流体力学、多相流理论、湍流理论研究的基础上，分析和总结了多相流的模型研究以及典型的应用，分析和研究了微泡浮选中的气、固、液三相流力学，分析了微泡形成、运动、变化的规律以及影响微泡生成的主要因素，将气泡颗粒相视为拟流体，根据双流体模型的基本思想，建立了描述微泡发生器内流体流动的气、固、液三相流混合模型。在 $k-\varepsilon-k_p$ 湍流模型的基础上，提出了 $k-\varepsilon-k_p-k_g$ 多相湍流封闭模型，为进行微泡生成的三相流力学机理研究建立了相关的理论。

三是进行了基于 CFD 的数值模拟分析。本专著简要介绍了计算流体动力学（CFD）的发展概况、CFD 数值模拟方法及主要流程、FLUENT 软件及其主要功能。设计了流体型微泡发生器的数字样机，利用计算机仿真技术，对微泡浮选的关键技术及装置——微泡发生器进行数值模拟仿真分析，根据 CFD 的理论和计算机仿真技术，从两相流、三相流两个方面进行了数值模拟计算研究，定性、定量地分析了流体型微泡发生器内流场各处的速度、压力和各相耦合强度等重要参数。结合建立的三相流混合模型，对微泡发生器卷吸中的气、固、液三相流力学特性进行了数值模拟计算，模拟计算结果验证了三相流混合模型的合理性，得出了一些有价值的结论，为流体型微泡发生器的设计和改进提供了依据和有价值的参考。

四是在实验研究中，基于建立的三相流理论和流体型微泡发生器的设计理论，自主设计、制造、安装、调试了微泡发生器物理样机以及微泡发生器的实验装置。进行了一系列不同操作参数及结构参数对微泡生成的影响的实验研究，对不同工作压力、不同充气量、不同背压、不同喉嘴距、不同喉管长径比、孔板（或筛网）的作用、扩散管接入柱体形式等因素对微泡发生器产生微泡的性能的有效性进行了实验研究。分别对射流式、旋流式、混流式、自吸式剪切流微孔等微泡发生器进行了实验及应用研究。实验结果论证了三相流理论和流体型微泡发生器的设计理论的正确性，验证了数值模拟计算的正确性，为流体型微泡发生器的设计与实验提供了有效的方法，为微泡浮选研究提供了有价值的参考。

五是建立了微泡发生器性能分析评价系统。对微泡发生器的性能分析和评价进行了相关研究，明确了建立分析评价系统的目的和意义，为优化微泡发生

器性能，提供了帮助。分析了系统的功能要求、组成结构和总体实现方法，并将其分成了结构参数化建模、解算与操作参数离散、数据分析和数据查询与管理四大模块。对每个模块进行了功能分析、实现方法和程序开发三个方面的研究，分析了影响微泡发生器性能的结构参数，实现了对微泡发生器进行多结构参数组合、多操作参数组合、批量化、自动化和有序化的分析，根据相关的指标能够对性能进行评价，同时能够对大量的数据进行有效的管理。

六是采用电导法对液位高度、泡沫层厚度进行检测。研究了矿浆和矿化泡沫层之间物理特性的差异，根据矿浆、矿化泡沫层以及空气层之间的电导率差异实现液位高度和矿化泡沫层厚度的检测。设计了一种以介质电导率差异为基础的电导率液位传感器及整个检测装置，同时完成了对矿浆液位（工作背压）和矿化泡沫层厚度的测量。

总之，本专著以微细粒矿物选别问题为实际应用背景，从解决微粒浮选问题出发，研究流体型微泡发生器中的微泡生成三相流力学机理，为微粒的微泡浮选设备的设计、微泡浮选技术的实际应用提供了理论依据。在研究过程中建立了三相流力学模型，研究了数值模拟计算，借助计算机以及计算流体动力学（CFD）理论对微泡生成中的三相流力学问题进行了数值模拟计算，分析了微泡发生器的性能。本专著在理论研究、数值仿真分析的基础上，研发了微泡发生器及其实验装置，并对微泡发生器的性能进行了理论及实验研究。在不同工况条件下，研究和分析了微泡发生器的充气性能、微泡生成情况等。结合实验结果，分析总结出了微泡生成理论研究、计算机数值模拟以及实际开发设计理论和方法。本专著探索建立了一套较为完整的开发流体机械的设计与实验的有效方法，为流体型微泡发生器的开发应用、微泡浮选的研究应用提供了有价值的参考。

关键词：微泡浮选　微泡发生器　三相流力学理论　计算机仿真　实验分析

Preface

More and more mineral resources are consumed with the increase of population, the development of economy, industrialization and urbanization. Human being will meet the danger of resources exhausted. Because the mineral resources are continuously used by man, there are more and more mines that are bad quality, little grains embed together, accrete, and component complicated, and that are very difficult to select. Synthesized and efficient utilization of mineral resources, selection of micro-grains of mine, utilization of recycle resources, reselection of gangues, and so on are important tasks with which human will be confronted in the 21st century.

Microbubble flotation is a very efficient method for the selection of micro-grains of mine, the division printing ink from waste paper, cleaning industrial waste water, etc., so it is an urgent research direction. New microbubble flotation methods, new microbubble flotation columns and applications of microbubble flotation are being studied. The bubble generator, which is the most important key technique, is a researching key point. On account of that there is not a long time for the development and application of microbubble flotation, the research about principle, structure and operating parameters is not very good. It is needed continuously to solve the problems about easy log-jam and inconvenient operation of microbubble generators. The generation and control of microbubbles is a bottle-neck problem of wider applications of microbubble flotation. It is needed to study thoroughly about the theory and application of generation of microbubbles in microbubble flotation.

In various new microbubble generators, the fluid microbubble generator has good characteristics in: the generated bubble's diameter is small, there is more air in the flow, there is a good dispersion of bubbles and it can produce turbulent vortex that are useful for mutual actions between bubbles and mine grains, and useful for material selection. The dissertation selects the fluid microbubble generator as a typical research object. The microbubble generators such as jetting, swirling, mixed flowing, self-absorption shear flow micropores were studied. The method of analysis evaluating the performance of microbubble generators was studied. The method of detecting the height of liquid level and the thickness of foam layer was studied too. And the design of the detection device was carried out.

In the fluid microbubble generator while it produces microbubbles the flow is an intricate three phase flow of air, solid and liquid. Because a little change in property, flux, and flow states etc. of three phase flow will influence the result of microbubble generation and microbubble flotation, it is necessary to study the three phase flow mechanics mechanism of microbubble generation.

Followings are the main research contents in the dissertation:

First, the mechanism of microbubble generation and a fluid microbubble generator has been studied. The dissertation has studied and analyzed the function and key technologies of microbubble flotation, the working principle of fluid microbubble generator, the theory of microbubble generation, the mechanism of microbubble generation, the effects of gas bells, the mechanism of microbubble separation and the mechanism of microbubble generation in the fluid microbubble generator. It has studied and analyzed several of mechanics that would act on a bubble in the fluid, the influence actions of these mechanics for microbubble generation and the mechanics that will exist in the fluid microbubble generation process. It has analyzed the structure of the fluid microbubble generator, the functions and influences of every component for microbubble generation. And it has also studied and analyzed bubble's size and bubble's characteristics, bubble's integrating gather and bubble's crashing law, bubble's dispersion and thronging together, the mutual action between bubble and mine plasma, the influence factors that will decide the stability and size of bubble, and so on. The mechanics mechanism model, which expresses bubble's division through the collision between a bubble and a single mine grain, was proposed.

Second, the dissertation has studied the mechanism of three phase flow mechanics for microbubble generation. Based on the hydrodynamics, the theories of multiphase flow and turbulence, the multiphase flow models and typical applications have been summarized. It has studied and analyzed the mechanics theory of air, solid, and liquid three phase flow in microbubble flotation, the law of microbubble generation, bubble's movement and change, the key influence factors for producing microbubble. The granules of bubble were taken as a kind of virtual fluid. According to the basic idea of two flow model, a mechanics mixed model of air, solid, and liquid three phase flow has been set up. This mixed model will describe the flow running in the microbubble generator. Based on the $k-\varepsilon-k_p$ turbulent flow model, the $k-\varepsilon-k_p-k_g$ multiphase turbulent flow model has been proposed. Relative theories were built up for studying mechanism of three phase flow in microbubble generation.

Third, the numerical simulation analysis, based on CFD (Computational Fluid Dynamics), has been done. The dissertation has introduced briefly the development of CFD, the main processes, CFD numerical simulation methods, FLUENT software and its main functions. It built a numerical prototype of fluid microbubble generator that is a key technology and device in microbubble flotation. And then the numerical simulation analyses have been done by computer simulation technology. Using CDF theory and computer simulation technology, the numerical simulation computations have been done from two phase flow to three phase flow. The important parameters, such as velocities at different parts, pressures, coupling actions intensity, etc. of the flow in the fluid microbubble generator, have been analyzed qualitatively and quantificationally. Combined with the created mixed model of three phase flow, mechanics features of air, solid, and liquid three phase flow as jetting flow in the microbubble generator have been numerically simulated. The results showed that the mixed model of three phase flow is reasonable. Some valuable conclusions have been obtained. And they are good valuable references and a fundamental theory for designing and improving fluid microbubble generators.

Fourth, in the experimental research, based on the proposed theory of three phase flow and the design theory of fluid microbubble generators, the physical prototype and experimental device of microbubble generator have been designed, fabricated, fixed and adjusted by myself. A series of different operational and structural parameters, which would influence the microbubble generation, were studied experimentally. It means that different factors, such as different working pressures, different air charges, different output pressures, different distances of throat and nozzle, different proportions of throat pipe lengths and diameters, aperture boards and griddles, different forms of diffuse pipes connected with a column, which will influence the microbubble's generation, have been studied experimentally. The experiments and applied researches of the microbubble generators such as jetting, swirling, mixed flowing, self-absorption shear flow micropores were carried out. The experimental results shows that the proposed theory of three phase flow and the design theory of fluid microbubble generators are correct. The validity of numerical simulation computations was validated. This dissertation affords valuable means for designing and testing fluid microbubble generators, and affords valuable references for researching microbubble flotation.

Fifth, the analysis and evaluation system of microbubble generators' performance was established. It studies the performance analysis and evaluation of the microbubble generators, and clarifies the purpose and significance of establishing the analysis and evaluation system, which is helpful to optimize the performance of the microbubble generators. The functional requirements, composition structures and overall implementation methods of the system were analyzed, and the four modules are divided into structural parameterization modeling, solution and operation parameters discretization, data analysis and data query and management. The functional analysis, implementation method and program development of each module are studied. The functional parameters of the performance of the microbubble generators are analyzed, and the multi-structure parameters combination and the multi-operation parameters combination of the microbubble generators, batching, automated and orderly analysis are analyzed. According to the relevant indicators the performances can be evaluated, while a large number of data can be effectively managed.

Sixth, conductivity method is used to detect the liquid level, the thickness of the mineralized foam layer. The differences in the physical properties between the slurry and the mineralized foam are studied. The liquid level and the thickness of the mineralized foam are measured according to the differences in conductivity within the slurry, the mineralized foam and air layers. A conductivity level sensor based on the dielectric conductivity difference and the whole detection device were designed, and the measurement of the slurry level (working back pressure) and the thickness of the mineralized foam layer was completed at the same time.

In conclusion, this dissertation takes the selection of micro-grains of mine as real application background. In order to solve the problem of micro-grains flotation, the mechanics mechanism of three phase flow in a fluid microbubble generator was studied. It provided the theory for designing devices of microbubble flotation and applying the technology of microbubble flotation to reality. For founding the mechanics models of three phase flow, numerical simulation arithmetic was studied, the mechanics problems of three phase flow were solved in numerical simulation calculation by the theory of Computational Fluid Dynamics (CFD). The capability of the microbubble generator was analyzed. Based on the results of theoretic research and numerical simulation analysis, the microbubble generator and its experimental device were developed. And the capability of the microbubble generator was analyzed theoretically and experimentally. Under the different working conditions the capability of the microbubble generator and the microbubble generation were studied. According to the experimental results, the useful references, which included the theoretic research of microbubble generation, computer numerical simulation, and real development and design, were summarized. The dissertation sets up a whole set of efficient methods for designing and testing hydro-mechanisms and provides valuable reference for developing and applying fluid microbubble generators and microbubble flotation.

Key Words: microbubble flotation; microbubble generator; mechanics theory of three phase flow; computer simulation, analysis

目　录

第一部分　微泡发生器流体动力学机理研究
——以射流式微泡发生器为例

第一章　绪论 / 3

1.1　资源问题 / 3

1.1.1　资源危机 / 3

1.1.2　我国的资源消耗 / 5

1.1.3　我国矿产资源的特点及面临的任务 / 7

1.2　浮选概述 / 8

1.2.1　浮选发展简况 / 8

1.2.2　微泡浮选的发展应用简况 / 9

1.3　微泡浮选关键技术分析 / 12

1.3.1　微泡发生器 / 12

1.3.2　微泡发生器研究近况 / 13

1.4　选题及研究内容 / 15

1.4.1　选题背景 / 15

1.4.2　研究意义 / 17

1.4.3　研究内容／　17

第二章　微泡生成机理及射流微泡发生器的研究／　19

2.1　射流式微泡发生器工作原理／　19

2.2　微泡生成力学机理研究／　21

2.2.1　气核作用／　21

2.2.2　机理分析／　22

2.2.2.1　微泡析出机理／　22

2.2.2.2　吸气生成微泡机理／　24

2.2.2.3　孔板及扩散管的作用／　28

2.3　微泡生成的尺寸与分散／　29

2.3.1　微泡的尺寸／　29

2.3.1.1　析出微泡的尺寸／　30

2.3.1.2　孔板对微泡尺寸的影响／　31

2.3.1.3　射流生成微泡的尺寸／　31

2.3.2　气泡的分散／　32

2.4　微泡生成过程及力学分析／　33

2.4.1　力学分析／　33

2.4.2　微泡生成过程分析／　38

2.4.2.1　气泡破碎机理分析／　38

2.4.2.2　气泡兼并作用分析／　44

2.4.2.3　气泡的结群／45

2.4.2.4　气泡在矿浆中的运动／　46

2.4.3　矿粒对微泡生成的作用／　46

2.5　微泡发生器结构分析／　47

2.5.1 喷嘴 / 48
2.5.2 吸气室及进气管 / 49
2.5.3 混合室 / 49
2.5.4 孔板 / 50
2.5.5 喉管 / 50
2.5.6 扩散管 / 51
2.6 微泡发生器充气性能分析 / 52
2.6.1 充气量 / 52
2.6.1.1 射流速度对充气量的影响 / 52
2.6.1.2 微泡发生器的结构对充气量的影响 / 53
2.6.2 气泡分散度 / 54
2.6.3 气泡分布 / 55
2.6.4 含气率 / 55
2.7 本章总结 / 57

第三章 微泡生成三相流力学机理研究 / 58
3.1 流体力学发展概述 / 58
3.2 多相流研究概述 / 59
3.2.1 研究概况 / 60
3.2.2 颗粒轨道模型 / 62
3.2.3 欧拉多相模型 / 64
3.2.4 双流体模型 / 64
3.2.4.1 双流体模型及其发展 / 64
3.2.4.2 欧拉及拉格朗日观点比较和双流体模型通式 / 66
3.2.5 气、固、液三流体模型 / 67

3.2.6 紊流模型 / 68

3.3 微泡发生器内三相流流动分析 / 69

3.3.1 紊流流动 / 69

3.3.2 射流传质 / 70

3.3.3 相间耦合 / 70

3.3.3.1 气液相间的动量传递 / 71

3.3.3.2 气固、液固相间的动量传递 / 73

3.3.3.3 相间湍流相互作用 / 73

3.3.3.4 相内作用 / 73

3.3.4 物理模型分析 / 74

3.4 三相流混合模型的建立 / 75

3.4.1 瞬态方程组 / 76

3.4.2 时均方程组 / 78

3.4.3 湍流封闭模型 / 80

3.5 常数及符号 / 84

3.6 本章小结 / 85

第四章 基于 CFD 的数值模拟分析 / 87

4.1 CFD 概述及 FLUENT 软件 / 88

4.1.1 CFD 的发展概况 / 88

4.1.2 CFD 数值模拟方法及主要流程 / 88

4.1.3 FLUENT 软件简述 / 90

4.2 微泡发生器中的两相流数值模拟 / 91

4.2.1 计算域及数值计算模型 / 91

4.2.2 边界条件及基本参数 / 92

4.2.3　数值模拟结果分析 / 93

4.3　微泡发生器中的三相流数值模拟 / 98

4.3.1　微泡发生器总体结构 / 98

4.3.2　数值计算边界条件 / 99

4.3.3　三相流的基本参数 / 99

4.3.4　计算域、控制方程和计算方法 / 99

4.3.5　仿真模拟与计算分析 / 100

4.3.5.1　喷嘴处矿浆喷射速度的仿真模拟与计算分析 / 100

4.3.5.2　速度分布 / 101

4.3.5.3　压力分布 / 107

4.3.5.4　湍动能分布 / 110

4.3.5.5　各相份额及分布 / 111

4.4　本章总结 / 113

第五章　浮选柱数学模型及微泡矿化机理研究 / 114

5.1　浮选速率方程 / 114

5.2　浮选柱内矿粒的滞留时间 / 115

5.3　微泡矿化力学机理研究 / 115

5.3.1　单个矿粒与单微泡的附着 / 116

5.3.2　矿粒群与单微泡的附着 / 118

5.3.3　单层附着 / 118

5.3.4　多层附着 / 120

5.4　矿化微泡的特性 / 123

5.4.1　矿化微泡等速方程 / 123

5.4.2　空气与矿浆的流速比 / 123

5.4.3 矿化微泡密度 / 124
5.4.4 矿化微泡直径 / 125
5.5 微泡矿化的影响因素 / 126
5.5.1 矿粒疏水性对微泡矿化的影响 / 126
5.5.2 微泡直径对微泡矿化的影响 / 126
5.5.3 矿粒粒度对微泡矿化的影响 / 127
5.6 本章小结 / 127

第二部分 应用实例

第六章 射流式微泡发生器性能实验研究 / 131
6.1 实验装置 / 131
6.2 设计特点 / 133
6.3 实验结果分析 / 133
6.3.1 工艺参数的实验研究 / 133
6.3.1.1 介质流量及其压力的影响 / 134
6.3.1.2 背压的影响 / 136
6.3.1.3 进气量的影响 / 137
6.3.1.4 充气压力的影响 / 138
6.3.2 结构参数的实验研究 / 139
6.3.2.1 喷嘴到喉管入口间距的影响 / 139
6.3.2.2 喉管结构形式及长径比的影响 / 142
6.3.2.3 孔板（或筛网）的影响 / 143
6.3.2.4 扩散管接入方式的影响 / 144
6.4 本章总结 / 146