Analysis of Theoretical and Experimental Research on Bubble Parameters and Gas-liquid Interaction in Bubble Flow

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Abstract. Bubble flow is a phenomenon in which gas flows with liquid in the form of bubbles, which widely exists in production and life. As an important part of fluid mechanics, bubble flow also has a certain impact on the actual production process. This work briefly summarizes the development of research on bubble flow in recent years. Firstly, a brief introduction to the development process and current situation of bubble flow in chronological order is presented, and the main difficulties related to the research and development of bubble flow are also pointed out, including the complicated gas-liquid distribution pattern and the exchange of materials and energy between gas and liquid phases, which slow down scholars’ research progress. Then, several theoretical models for bubble flow research are introduced. These models take bubble parameters into account, including the ultimate velocity of bubble rising, the transfer of energy and matter in the coalescence, and rupture of the bubble, the phase distribution of the bubble in the tube, and the interaction between the bubble and the liquid (the shear stress produced by bubbles affecting the turbulence field). This work briefly explains the ideas of each model and the results obtained, compares and analyzes their advantages, disadvantages and limitations, and predicts the theoretical and technical means required for subsequent theoretical model construction. Finally, part of the experimental research is summarized, along with the process and technical means of each experiment as well as the relationship between the experimental results and the theoretical research. It is hoped that this work could help to have a preliminary understanding of the research process and research methods of bubble flow, and provide some perspectives for incorporating bubble flow hydrodynamic theory into industrial applications and real life.

1. Introduction
Multiphase flow is the simultaneous flow of materials with two or more thermodynamic phases, which is widely present in engineering processes, such as petrochemical, chemical, and nuclear engineering. In gas-liquid multiphase flow, the phenomenon that gas flows with the liquid in the form of bubbles is called bubble flow. In bubble flow, the distribution mode of each phase has a great effect on the fluid dynamic parameters and the exchange of mass, momentum and energy between the phases. Therefore, it is difficult to carry out in-depth research on bubble flow.

In the 1870s, workers found that the mixing of water, oil, and bubbles had an important effect on flow in the early oil industry [1]. With the development of related research, the term bubble flow was officially used in the 1940s. In order to better analyze and predict the flow of bubble flow, many early scholars tried to use different methods to establish semi-empirical formulas for the bubble flow process in the beginning, such as the combination of gas-liquid two-phase into a single phase with specific
physical properties, the use of radioactive technology to mark, etc. [2-3]. However, these methods can only simply analyze the influence of certain physical parameters in bubble flow.

In the 1970s, based on the fundamental conservation principle, Drew [4], Ishii [5] and other scholars successively derived the basic equations of two-phase flow by analyzing the pressure, velocity, temperature, apparent density, volume fraction, size and distribution of suspended solids of each phase, as well as the pressure drop, stability, critical state and inter-phase interaction of multiphase flow. Since then, more and more scholars began to try to establish the equations representing the flow process of bubble flow from the bubble flow equations (including the two-fluid model, the homogeneous model and statistical group model) and physical models, who are constantly making improvements from the bubble parameters, gas-liquid interaction, bubble interaction and other factors that may affect the bubble flow. However it is very difficult to theoretically calculate and predict the physical parameters of bubble flow due to the existence of multiphase and discontinuity of interface characteristics. At present, research on the flow process and prediction of flow trajectory are still complicated and limited. In order to further establish more accurate and applicable bubble flow equations and predict the flow of bubble flow, researchers have used different theoretical models and experimental methods to study the factors influencing bubble flow. However, since different models usually have different application scopes and limitations, it is difficult to obtain accurate and stable data from experiments because of the turbulence caused by bubbles and the unpredictability of bubble coalescence and rupture. This work summarizes the models and experiments that scholars have studied and developed in recent years, and then makes a comparative analysis. Firstly, the research development of different mechanisms influencing bubble flow will be introduced, and their research methods, application scope and limitations will also be summarized. Secondly, some specific experimental methods of bubble flow research and their conclusions will be introduced, along with the comparison and analysis of the limitations and possible future development direction. Finally, horizontal comparison among the existing experimental conclusions and theoretical models will be presented, and some conclusions will be summarized.

2. Theoretical Research on Bubble Flow

In traditional bubble flow, bubble parameters and the interaction between gas and liquid are the research focus. Bubbles will produce shear force on liquid, change the distribution of liquid flow field or transform laminar flow into turbulence. Similarly, the kinetic energy of fluid and the pressure on the bubble will cause the coalescence and rupture of the bubble, and the ultimate velocity of the bubble in the tube will also affect the fluid. Scholars mainly establish models to describe bubbles and turbulent liquid to predict the influence of these factors on bubble flow. This section mainly summarizes the mechanism, advantages and disadvantages of the models established by scholars considering macro and micro factors, and horizontally compares the practicability and limitations of these models.

| Bubble parameters                                      | Bubble size                        | Authors                  | Research results                                                                 | Time  |
|--------------------------------------------------------|------------------------------------|--------------------------|---------------------------------------------------------------------------------|-------|
| Influence of bubble sizes on terminal velocity (VT)    | Small sphere                       | Batchelor [6]            | Calculating VT with Hadamard–Rybczynski equation                                | 1967  |
|                                                        | Medium-sized sphere                | Tomiyama et al. [8]      | Deriving VT in consideration of surface tension and initial state of the bubble | 2002  |
|                                                        | Large sphere                       | Davies and Taylor [7]    | Proposing the spherical cap model in which VT is based on the potential solution flowing on the sphere | 1950  |
| Influence of bubble sizes on phase distribution        | Large bubbles (over 5mm) and small bubbles (smaller than 5mm) | Serizawa et al. [9]      | Large bubbles rose in the tube, while small bubbles were attracted to the wall. | 1975  |
|                                                        |                                    | Politano et al. [10]     | Using the dispersed two-phase flow model to show the distribution of bubble sizes | 2003  |
| Coalescence and break-up                               | Liao Y, Lucas D [11]               |                          | Summarizing the empirical model and physical model that can be used to analyze the bubble collision mechanism | 2010  |
2.1. Bubble parameters

Some studies on bubble parameters are summarized in Table 1.

The size of the bubble in the infinite stagnant liquid under the dominance of surface tension will affect the ultimate velocity of the rise of a single bubble, $V_T$. When the bubble is small enough, $V_T$ can be obtained by the use of Hadamard–Rybczynski formula (Batchelor, 1967) [6]. As for large spherical bubbles, in 1950, Davies and Taylor first proposed a spherical cap bubble model $V_T$ based on potential flow around a sphere [7]. As for medium-sized bubbles whose surface tension plays a major role, based on the method of Davies and Taylor, Tomiyama et al. [8] derived the ultimate velocity of medium-sized bubbles in the bubble flow by assuming that the bubbles were distorted oblate spheres and taking surface tension into account. This result was also consistent with the results of experiments conducted with air and water. This study made a very important conclusion that under the dominance of surface tension, the main reason for the difference in $V_T$ was the difference in initial shape deformation. Specifically, the deformation of a smaller initial shape leads to a lower $V_T$ and a higher length-width ratio, while the deformation of a larger initial shape results in a higher $V_T$ and a lower length-width ratio.

Sekoguchi et al. [9] first studied the influence of bubble size on the phase distribution in the vertical channel. They found that small bubbles were attracted to the wall, while bubbles larger than 5 mm in diameter rose in the center of the duct. The bubble size was also considered to be the reason for the large differences in many experimental data at that time. Politano et al. [10] established a polydisperse model of two-phase flow to express the bubble size distribution, and used the finite difference method to numerically solve the model and analyze the influence of bubble size on the radial phase distribution in the vertical upward channel. The turbulent flow near the wall and the accumulation of small bubbles cause the coalescence of high gas volume fraction to form larger bubbles; in the center of the channel, however, the larger bubbles will burst and the smaller bubbles produced will tend to migrate to the wall. Since this model ignores such process, it is only applicable for flows of gases and liquids with sufficiently low apparent velocities. In order to deal with this problem, it is necessary to further understand the turbulent viscosity near the wall in the future to predict the influence of bubble coalescence and rupture on the flow of multiphase flow. In addition, this model does not include the influence of wall on resistance, lift and other forces, thus having certain limitations.

Coalescence and rupture include energy transfer and mass transfer, which are the reasons for the evolution of bubble size in multiphase flow. Compared with rupture, coalescence is considered to be more complicated. In the development of complex multiphase flow models, description of the turbulence effect and interfacial transfer is essential to the research on the influence of bubble coalescence and rupture. Many scholars are conducting related studies [11]. However, in the simulation of polydisperse flow, the modeling of bubble coalescence and rupture is considered to be the weakest link, especially in the case of turbulent flow where a variety of mechanisms will affect the relative movement of bubbles and the collision of bubbles. Previous research results mainly relied on empirical relationships, and further research is needed.

2.2. Gas-liquid Interaction

The bubble can cause turbulence or change the structure of turbulent flow through shear stress, which can restrain or increase the turbulence under certain flow conditions. Drew and Lahey [12] modified the liquid turbulence model in 1981 to simulate the turbulence in multiphase flow. The equation obtained by linearly superimposing the turbulence caused by bubbles and shear was in line with some experimental data. However, multiphase turbulence was not only the linear superposition of bubble and single-phase flow turbulence, so the application of these models was greatly limited. Later, scholars were devoted to more rigorously deriving the turbulence model caused by bubbles. For example, Kataoka and Sherizawa [13] used the local instantaneous equation to derive a two-equation turbulence model of gas-liquid two-phase flow. The equations of their model explain the energy transfer on the interface through the properties of the interface area closure, introduce the drag source term for the turbulence caused by bubbles, and calculate the turbulence generation by the resistance and relative velocity between the phases. In 2003, Politano et al. [10] proposed a turbulence model that uses the law
of the wall suitable for two-phase flow to evaluate the boundary conditions near the wall to the buffer zone and the near-wall area based on the k-ε model. Rzehak et al. [14] compared several turbulence models caused by bubbles in 2013, and proposed a new method for describing the influence of bubbles on turbulence in the k-ε model to better predict the porosity near the wall turbulence. Further research in this field should improve the accuracy of void ratio prediction in the near wall area by improving the modeling of two-phase turbulence wall function and the closure of bubble force. In 2015, Marco et al. [15] extended the model of Roland et al. to a wider range of experiments with a large number of data, who proposed further optimization of the model and then added similar turbulence models caused by bubbles to the multiphase Reynolds stress equation model. This model includes the source terms of turbulent kinetic energy and turbulent energy dissipation rate, assuming that the bubble converts the work of resistance into turbulent kinetic energy inside the bubble wake. In the source of turbulent energy dissipation rate, the mixed scale is calculated according to water turbulence velocity scale and bubble length scale, making a more accurate model.

The existing models and corresponding experimental data have provided ideas and data support for the improvement of the models. However, due to the existence of multiphase in theory and the discontinuity of interface characteristics, it is very difficult to calculate and predict the complete physical parameters of bubble flow. The models introduced above were established by considering some important factors, which didn’t fully consider all the important aspects of turbulence, such as anisotropy and spatial dependence of bubble size distribution. In addition, most models are only applicable in a certain range, such as in the case of large pipes and low-speed flow, thus leading to the large difference between experimental data obtained by different models. In order to better explain and predict the flow of bubble flow and establish more accurate models, it is necessary to further study the mechanism of energy transfer and mass transfer at the gas-liquid interface, and consider the influence of wall and velocity so as to improve the applicability of the models.

3. Experimental Research on Bubble Flow
Bubble parameters can be directly and effectively obtained through experiments. However, bubble flow involves a large span of scales and a large number of deformable topological structures, which lead to the change of phase interface. Meanwhile, it is difficult to accurately measure the bubble distribution density and the continuous change of the physical parameters of a single bubble in the space. Therefore, most of the research on bubble flow is theoretical verification based on simulation, and specific experiments are few. At present, the main purpose of bubble flow experiments is to verify the existing models and establish a database so as to lay a solid foundation for further theoretical research.

Lucas et al. [16] used a high-resolution sensor developed by Prasser [17] to improve the measurement accuracy of bubble parameters. This sensor can analyze the parameters of a single bubble in the entire cross section of the pipeline, which uses the position and size of a single bubble to macroscopically evaluate the average time distribution of bubble flow. They measured and built an extensive database of air-water bubbles and slugs in a vertical tube with an inner diameter of 51.2 mm in the experiment, including radial gas volume fraction distribution, bubble size distribution, and distribution of gas decomposed by each bubble size. In the experiment, 10 kinds of different entrance lengths were measured at the same time, so the obtained data more accurately reflected the transient evolution of the flow along the pipeline. As for the case of polydisperse flow, this experiment confirmed the assumption that the sign of lift changed with respect to the bubble size, and verified the early discovery presented by Tomiyama [18] in the single bubble experiment that small bubbles were often found near the wall area, while large bubbles tended to concentrate in the core.

Carina et al. [19] studied the influence of bubble groups on the finely dispersed oil droplets in the separated liquid flow, who used the chamber to conduct visualization experiments. The visualization of the flow rate and the injection of oil droplets and bubbles helped determine the kinematic characteristics of the oil droplets and bubbles. The experimental instrument used could describe in detail the contours of the injected bubbles and oil droplets without errors caused by the observation of the curved surface. Then the kinematic behavior was quantified on this basis. This experiment revealed that in the presence
of bubble groups the movement of small droplets in the liquid flow had the hydrodynamic effect and the efficiency of droplet separation was highly dependent on the liquid induction velocity generated by the bubble flow. When there were no bubbles, the inertia exerted by the continuous fluid inhibited the gravity of the droplets, causing the droplets to be carried away by the liquid flow. This effect prevented effective gas-liquid separation. Moreover, this study proved that the instantaneous state of the bubble would affect the kinematic behavior in the chamber.

Hosokawa et al. [20] performed multiphase flow simulations to test the applicability of the interfacial momentum transfer and two-phase turbulence to the closed relationship of turbulent bubble flow, who used a water pump and an air compressor to mix gas and liquid phases into the pipe to flow. Besides, they also adopted a special image processing method (Hosokawa and Tomiyam) [21] and a laser Doppler velocimeter to measure the radial distribution of void fraction, bubble length and width as well as phase velocity and to calculate the turbulent kinetic energy of bubbles in a vertical tube. Finally, it was verified that the length-width ratio of bubbles and liquid velocity gradient would affect the resistance coefficient of bubbles. The experimental results showed that due to the existence of the wall, the length-width ratio of bubbles near the wall was greater than that of the free rising bubbles, and the change of the length-width ratio resulted in the decrease of the relative velocity between the bubbles and the liquid near the wall, which was also consistent with the conclusion of theoretical simulation.

4. Conclusion

This work briefly introduces the research on bubble flow in multiphase flow. The analysis of bubble flow is very difficult because the distribution mode of each phase in bubble flow will greatly affect the physical parameters by influencing the parameters of each phase and the exchange of mass, momentum and energy. Meanwhile, the calculation workload is huge due to the discontinuity of the gas-liquid interface parameters. This work introduces the development history of bubble flow research in chronological order, summarizes some bubble flow models and experiments, objectively analyzes the advantages, disadvantages and limitations of these models, and predicts the possible development trend of bubble flow in the future.

First of all, this work gives an introduction to the early studies and development of bubble flow. Due to the late understanding and development of bubble flow as well as the complexity of bubble flow studies, the progress of bubble flow research is relatively slow. However, with the development of technical means, scholars have shifted the research focus from establishing semi-empirical formulas with greater limitations to using numerical simulation and experimental methods to obtain models with a wider range of applications.

Secondly, this work summarizes some related bubble flow models. Most of these models were established by considering the factors affecting bubble flow, including but not limited to the size and distribution of the bubbles, the interaction between the bubbles (coalescence and rupture), and the shear stress of bubbles on the liquid. This article makes a horizontal analysis of these models, objectively points out their advantages, disadvantages, limitations, and directions for improvement, and predicts the possible development trend of subsequent models.

Finally, this work introduces some experimental studies of bubble flow. There are few related experiments because bubble parameters and their effects on turbulence are difficult to determine, most of which were carried out to establish a database and analyze the applicability of theoretical models in practical applications.

Based on the existing research methods and research content, there is still a lot of room for improvement in the research and development of bubble flow. Bubble flow is widely present in industrial processes, such as the petrochemical industry. In-depth research on bubble flow and its application to the actual production can effectively improve the production efficiency, and scholars are also conducting further research.
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