Comparative study on the flow and mass transfer characteristics of sub-millimeter bubbles and conventional bubbles in gas-liquid two-phase flow

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Highlights

- The differences between a sub-millimeter bubble column and a conventional bubble column are explored.
- A numerical simulation approach for the sub-millimeter bubbles gas-liquid bubbly flow is proposed.
- Focused on bubble column at two scales, laboratory scale and industrial scale
- The mechanism of mass transfer enhancement of submillimeter bubbles is discussed.

1. Introduction

Gas–liquid reactors containing bubbles are intensively used in the chemical industry. However, the gas–liquid mass transfer is usually the rate-limiting step. One possible way to intensify the mass transfer is the application of sub-millimeter bubbles (1–1000 μm) which efficiently increase interfacial area. The differences in flow and mass transfer characteristics between a sub-millimeter bubble column and a conventional bubble column were explored using experimental and numerical simulation methods. A specific numerical simulation approach was proposed for the flow and mass transfer processes of sub-millimeter bubbles in gas-liquid bubbly flow.

2. Methods

The main part of the apparatus is a cylindrical bubble column made of polymethyl methacrylate with an inner diameter of 50 mm and a height of 1.5 m. Air and CO_2 were used as gas-phase medium for flow and mass transfer experiments, respectively. The liquid-phase medium was tap water, and the temperature was controlled at 20 °C. The high-speed camera (Vision Research Inc., Phantom VEO 710L) was placed at 0.75 m to take images of the gas-liquid flows. A deep learning-based image processing method for bubble detection, segmentation, and shape reconstruction [1] was applied in the present work to obtain the bubble size distribution (BSD) and Sauter mean bubble diameter, d_{32}. The overall gas holdup of the bubble column was measured using a differential pressure transmitter. The radial and axial distributions of gas holdups were measured by the Electrical Resistance Tomography, ERT (ITS, p2+). The bubble column has 10 sampling points in different axial positions, and the liquid phase medium was taken at each sampling point during the mass transfer experiments, and the concentration of dissolved CO_2 in the liquid phase was determined using a titrator (Metrohm, ECO). The two-fluid model (TFM) was adopted to perform the CFD simulations. The drag model [2] and the mass transfer coefficient model [3] constructed specifically for sub-millimeter bubbles in our previous work was adopted in the present work.

3. Results and discussion

As shown in Fig.1, under comparable operating conditions, the size distribution of bubbles in sub-millimeter bubble columns is narrower, with an average size reduced to approximately 3% of that observed in conventional columns. Moreover, the gas holdup increases by over two-fold, and the interfacial area enhances by two orders of magnitude. Furthermore, the radial distribution of the gas-liquid phases in sub-millimeter bubble columns shows greater uniformity, contributing to a reduction in axial back-mixing. In Fig.2, due to the existence of a strong gas-liquid interface fragmentation as well as the generation of new gas-liquid interfaces within the sub-millimeter bubble generator, in which an extremely fast gas-liquid mass transfer occurs, although the gas-liquid phase has a short residence time within the generator, the liquid phase already contains a higher concentration of CO_2 when it leaves the sub-millimeter bubble generator. After entering the inlet of the bubble column, due to the strong mass transfer ability of sub-millimeter bubbles, the CO_2 in the liquid phase quickly reaches the saturation concentration under the corresponding pressure in a short axial height, and is maintained until the outlet of the bubble column. The mass transfer rate at the bottom of conventional bubble column is also very fast, and after a short axial height reaches a high concentration, but the CO_2 concentration rises more slowly along the axial height, resulting in significantly lower CO_2 concentrations in the conventional bubble column than in the sub-millimeter bubble column. Notably, the interfacial area within sub-millimeter bubble columns plays a pivotal role in intensifying mass transfer, even though their liquid-side mass transfer coefficient is lower compared to conventional columns. Leveraging the substantial interfacial area, the volumetric mass transfer coefficient within sub-millimeter bubble columns is approximately ten times that within conventional columns. In Fig.3, Simulation outcomes for large-scale bubble column reactors indicate that sub-millimeter bubbles have the potential to yield a more uniform gas holdup distribution, thereby exhibiting reduced sensitivity to initial gas-liquid distribution effects.

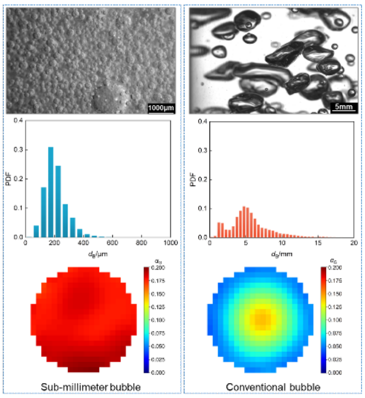

Figure 1. Comparison of bubble size distribution and gas holdup distribution.

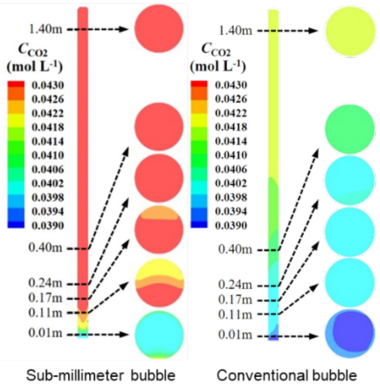

Figure 2. Comparison of CO_2 concentration distribution in Laboratory-scale bubble column.

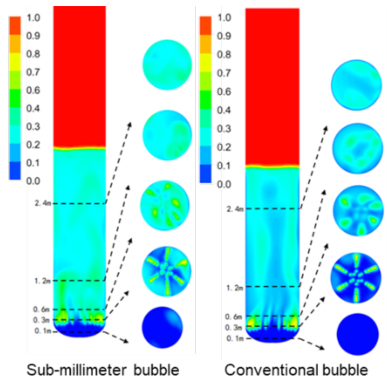

Figure 3. Comparison of gas holdup distribution in industrial-scale bubble column.

4. Conclusions

A comparative study of the flow and mass transfer characteristics of a sub-millimeter bubble column versus a conventional bubble column was carried out experimentally and by two-fluid numerical simulation. The sub-millimeter bubble gas-liquid two-phase flows have significantly higher gas holdup and narrower bubble size distributions, and although the liquid-side mass transfer coefficients are slightly lower than those of the conventional bubbles, the significantly larger specific surface area result in significantly higher mass transfer rates. Industrial-scale bubble column simulations have also demonstrated that sub-millimeter bubbles have a more uniform gas content distribution and larger surface area.

References

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Keywords

sub-millimeter bubble; bubble column; mass transfer; numerical simulation; process intensification