Flow characteristics of a novel helical liquid-bridge flow at different scales

Liang Yuan[1], Haifeng Cong[1,2]*, Xingang Li[1,2]*

1 School of Chemical Engineering and Technology, National Engineering Research Center of Distillation Technology, Collaborative Innovation Center of Chemical Science and Engineering (Tianjin), Tianjin University, Tianjin 300072, China; 2 Zhejiang institute of Tianjin University, Ningbo, Zhejiang, 315201, China

**Corresponding author: conghaifeng@tju.edu.cn (H.F. Cong); lxg@tju.edu.cn (X.G. Li)*

Highlights

- The influence of multiple factors on the flow patterns of helical liquid-bridge at different scales is elucidated.
- A fluid flow model predicts the profile of the liquid-bridge and the liquid phase residence time.
- The flow mechanism provides an application guide for the intensive of gas-liquid reactions at different scales by helical descending liquid flow.

1. Introduction

Gas absorption is a mass transfer unit operation in which a gas mixture is treated with a liquid absorbent to remove one or more components, such as toxic or environmentally harmful species. It is widely used in industry. The absorption efficiency of the gas absorbed into the liquid depends largely on the geometry of the gas-liquid contactor and the hydrodynamic properties of the liquid at the contactor[1].

Cong et al. [2]proposed helical liquid-bridge flow as a promising new mode of mass and heat transfer liquid flow that provides a larger gas-liquid interface and external gas-liquid contact. Zhang et al. have applied helical liquid-bridge flow to distillation processes and gas-liquid mass transfer processes[3]. However, the formation and flow mechanism of helical liquid-bridge flow still need to be supplemented.

In order to better apply liquid-bridge flow to enhance gas-liquid reactions, this study aims to elucidate the formation mechanism and hydrodynamic behaviour of liquid-bridge in the flow process. Through hydrodynamic experiments, the morphology of liquid-bridge at micrometer and millimeter scales are compared to elucidate the effects of various factors on helical liquid-bridge flow at different scales. The cross-sectional geometrical configurations of different liquid bridges are reshaped, a fluid flow model is developed, the residence time and bridge profile are predicted, and the fluid flow characteristics of the helical liquid-bridge flow are refined, and the results obtained are of great significance for the enhancement of non-homogeneous mass and heat transfer processes.

2. Methods

Figure 1 shows a fluid flow experimental setup. The liquid phase was injected into the liquid distributor via a syringe pump (2PB-2020, SZWEICO, China). The liquid overflowed from the distributor onto the helical structure and descended along the helix, realizing helical descending liquid flow. The flow characteristics were captured by a high-speed video camera (1M-2000, AcutEye, China), and the local film thickness of the liquid bridge was analyzed using image processing software (ImageJ180).

3. Results and discussion

3.1 Liquid bridge formation and flow

The liquid flows down the helical string and this form of flow is known as helical liquid-bridge flow. As shown in Figure 2, we have photographed the flow of micrometer-scale and millimeter-scale liquid bridges. By comparing the flow at the two different scales, it can be found that the relative liquid-phase drop height at the millimeter scale was larger than that at the micrometer scale. The reason for this may lie in the fact that the liquid flow at micrometer scale spacing needs to overcome greater viscous resistance.

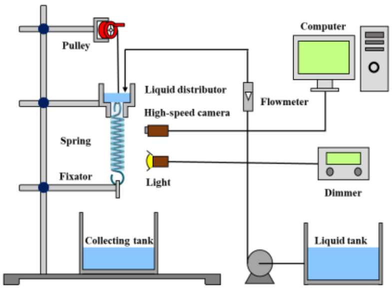

Figure 1. Fluid flow devices

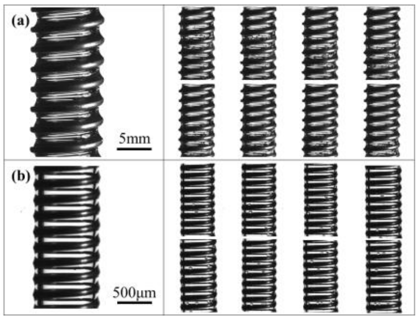

Figure 2. Helical liquid-bridge flow at different scales

3.2 Flow Modeling

Discussing the profile changes of the liquid bridge separately from the flow process can avoid the difficulties caused by direct calculations.

In this study, the liquid-bridge profiles under different liquid phase loads were firstly constructed. Then, the flow equations of the descending fluid process were established and calculated in combination with the liquid-bridge profiles. It is worth noting that the fluid flow law at the micrometer scale was different from the conventional size description. The micrometer-scale liquid-bridge flow process needs to introduce the effect of the boundary adhesion layer on the flow.

3.3 Model Prediction

There is no article on how to predict the shape of a flowing liquid-bridge, mainly because it is difficult to establish a reasonable connection between the flow process of the fluid and the shape of the liquid-bridge. We used energy conservation as a link to connect the liquid-bridge profile to the equations of fluid dynamics and finally formed an iterative calculation method of the liquid-bridge profile based on energy conservation. We calculated the eigenvalue d by substituting the helix parameters and operating conditions from Han et al. into the iterative liquid-bridge profile formulation and compared them to verify the reliability of the process. After calculation, R^2 = 0.96265 and RMSE = 0.049334 mm. From the results, it can be seen that this iterative algorithm for liquid-bridge profile based on energy conservation can predict the liquid-bridge thickness well.

4. Conclusions

In this study, we successfully constructed millimeter-scale and micrometer-scale helical liquid-bridge flows and clarified the effects of multiple factors on the liquid-bridge morphology. By reshaping the cross-sectional geometrical configurations of different liquid bridges, a fluid flow model is developed to predict the residence time and the liquid-bridge profile, and an iterative algorithm based on energy conservation is found to predict the liquid-bridge morphology well when compared with the experimental data of other scholars. The results show that the helical liquid-bridge flow has the advantages of long residence time and uniform liquid distribution. The helical liquid-bridge flow has great potential for application in microscale gas-liquid countercurrent processes, which provides a new idea for enhancing microscale gas-liquid reactions.

References

[1] PAVLENKO Aleksandr, PECHERKIN Nikolay, et al. Hydrodynamics in falling liquid films on surfaces with complex geometry[J]. Microgravity Science and Technology, 2009, 21 (1), 207-213.

[2] CONG Haifeng, ZHAO Zhenyu, LI Xingang, et al. Liquid-bridge flow in the channel of helical string and its application to gas–liquid contacting process[J]. AIChE Journal, 2018, 64 (9), 3360-3368.

[3] ZHANG Zhen, HAN Hong-ming, CONG Hai-feng, et al. Liquid-bridge flow on a vertical spiral spring and its mass transfer characteristics[J]. Chemical Engineering Science, 2023, 275, 118738.

Keywords

Helical liquid-bridge flow; Fluid flow; Liquid film; Microscale