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P06

水処理システムにおける水電解気泡の重力依存性

Gravity Dependence of Water Electrolysis Bubbles in Water Treatment Systems

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1. Introduction

Space exploration has made tremendous progress to date, and long-duration missions to the Moon and Mars are planned in the future. In such missions, life support is essential for human activities in space, and the Japan Aerospace Exploration Agency (JAXA) is conducting research and development of the Environment Control and Life Support System (ECLSS). Water supply is essential for human activities in space, but water transportation requires significant resources and is recognized as a major challenge for manned space activities. Therefore, some space ECLSS is equipped with autonomous water reclamation systems to minimize the amount of additional transport from Earth1). However, because of the different environment (μG in space, 1/6G on the moon, and 1/3G on Mars), the expected performance in space will likely not be achieved without an accurate evaluation of gravity dependence, which must be reflected in the design of the equipment to account for gravity dependence.

The water treatment system developed by JAXA1) uses electrolysis as part of the treatment process, and in electrolysis, bubbles are generated around electrodes. In order for the oxidative decomposition process to be efficient, the bubbles attached to the electrodes must be quickly removed. On the ground, the buoyancy force acting on the bubbles facilitates their release from the electrodes, but this is not expected to happen under microgravity because the buoyancy force is not effective. Several studies of electrolysis under microgravity have been reported, including a study of the gravity dependence of water electrolysis bubbles in a water treatment system1) and a study of ammonia oxidation reaction measurements on the International Space Station (ISS)2). However, with regard to the evaluation of forces acting on electrolysis bubbles, the former only evaluates buoyancy and drag force due to flow, while the latter does not.

This study describes the results of modeling the forces acting on bubbles generated by electrolysis in forced flow and order evaluation. In water treatment systems, the effect of bubble release by water flow is targeted, but the quality of treated water varies depending on the balance between treatment speed and flow velocity. The gravity dependence at the electrodes is examined from the hydrodynamic point of view as well as electrochemical factors.

2. Analysis Model Electrolysis Cell Overview

The electrolytic cell is modeled as shown in Figure 1, with a rod electrode of 6 mm diameter placed in the center of a circular tube of 10 mm inner diameter, with the rod electrode as the anode and the inner wall of the circular tube as the cathode. Since organic carbon must be reduced to produce drinking water from urine, electrolysis is performed at high temperature (250°C) and high pressure (5 MPa).

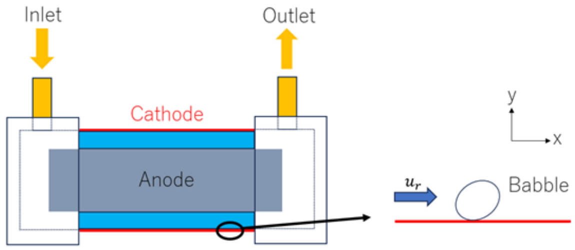

Figure 1. Schematic diagram of electrolytic cell

2.1. Evaluation of forces acting on electrolysis bubbles

Water electrolysis generates bubbles from the electrodes, and the desorption and transport of bubbles from the electrodes affect electrolytic performance. On the electrode, there is an inert region formed by supersaturation of dissolved components, which is a factor that reduces electrolytic performance. Therefore, it is important to detach air bubbles from the electrode.

In this study, an analysis based on the hydrodynamic point of view is performed. In order to determine the bubble detachment diameter, the balance of forces acting on the electrolysis bubbles was investigated. In doing so, the forces were resolved in the x- and y-directions in Figure 1.

The balance of forces at x-direction:

$$\sum F_x = F_{du,x} + F_{\sigma,x} + F_{qs} \tag{1}$$

The balance of forces at y-direction:

$$\sum F_y = F_{du,y} + F_{\sigma,y} + F_h + F_L + F_{cp} + F_B \tag{2}$$

where $F_{du,x}$ and $F_{du,y}$ are each components of the unsteady growth force acting as drag force [N], $F_{\sigma,x}$ and $F_{\sigma,y}$ are each components of the surface tension between the bubble and the electrode surface [N], F_{qs} is the drag force due to flow [N], F_h is the fluid force due to hydrodynamic pressure [N], F_L is the shear lift force [N], F_{cp} is the contact pressure [N], and F_B is the buoyancy force [N]. The following equations from (3) to (11) are obtained for the forces under consideration.

$$F_{du,x} = -\rho_L \pi r_b{}^2 \left(\frac{3}{2} C_s \dot{r}_b{}^2 + r_b \ddot{r}_b\right) \sin\theta_i \tag{3}$$

$$F_{du,y} = -\rho_L \pi r_b{}^2 \left(\frac{3}{2} C_s \dot{r}_b{}^2 + r_b \ddot{r}_b\right) cos\theta_i \tag{4}$$

where ρ_L is the density of the liquid [kg/m³], r_b is the bubble radius associated with the bubble growth rate [m], $\dot{r}_b$ and $\ddot{r}_b$ are first and second derivative with respect to time respectively, C_s is the empirical coefficient, and θ_i is the angle between the y axis and the growth force [rad]. The bubble radius is generally expressed by Equation (5).

$$r_b = \mathrm{A}t^{\gamma} \tag{5}$$

where A is the coefficient for each condition, t is the bubble growth time [s] and γ is the time coefficient.

$$F_{\sigma,x} = -1.25 d_w \sigma \frac{\pi(\alpha - \beta)}{\pi^2 - (\alpha - \beta)^2} (sin\alpha + sin\beta) \tag{6}$$

$$F_{\sigma,y} = -d_w \sigma \frac{\pi}{\alpha - \beta} (cos\beta - cos\alpha) \tag{7}$$

where d_w is the contact diameter [m], σ is the surface tension coefficient [N/m], α is the forward angle [rad], and β is the backward angle [rad]. The contact diameter is expressed by Equation (8).

$$d_w = d_b \sin\beta_m \tag{8}$$

where d_b is the bubble diameter [m] and β_m is the average contact angle [rad].

$$F_{qs} = \frac{3C_D \pi \mu_L Re_b}{\rho_L} \tag{9}$$

where C_D is the drag coefficient, μ_L is the viscosity coefficient of the liquid [Pa・s] and Re_b is the bubble Reynolds number, which is expressed by Equation (10).

$$Re_b = \frac{d_b u_r \rho_L}{\mu_L} \tag{10}$$

where u_r is the velocity of the center of the bubble [m/s].

$$F_B = \frac{\pi}{6} {d_b}^3 \Delta\rho g \tag{11}$$

where $\Delta\rho$ is the difference in density between the liquid and the bubble [kg/m^3] and g is the acceleration of gravity [m/s^2].

From the above, when the combined force of the components in each direction is zero, i.e., $\sum F_x = 0$ and $\sum F_y = 0$ are calculated to determine the peel diameter.

The forces acting on the bubbles are other than those shown in Equations (3) through (11), and only single bubbles are considered. In addition, at the present stage, we have not reached the point of order evaluation. Therefore, in the future, we plan to present the forces acting on bubbles that have not yet been shown at this stage, calculate the magnitude of each force, and conduct order evaluation by considering the existence of multiple bubbles. In this presentation, we will report the results of the order evaluation.

References

1) S. Matsumoto, M. Akashi, Y. Shido and H. Saruwatari: Gravity Effects on Bubble Behaviour during Electrolysis for Water Purification: ISTS (2023).

2) C. Morales-Navas, R.A. Martínez-Rodríguez, et al: Autonomous electrochemical system for ammonia oxidation reaction measurements at the International Space Station. npj Microgravity, 9 (2023) 20, DOI: https://doi.org/10.1038/s41526-023-00265-4.