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Mono-dispersed droplets formation from capillary jet of liquid metal by applying an electric field

Y. Hamaguchi^{1a}, K. Matsumoto^{1,2}, S. Shimasaki^{3b} and S. Taniguchi⁴

¹ Bachelor student of National Institute of Technology, Kagawa College, Takamatsu, Japan

² Now master student of Tsukuba University, Tsukuba, Japan

³ National Institute of Technology, Kagawa College, Takamatsu, Japan

⁴ Emeritus Professor of Tohoku University, Sendai, Japan

Corresponding author: ^a hamaguchi.416@gmail.com, ^b shimasaki@t.kagawa-nct.ac.jp

Abstract

Purpose of our research is to develop a manufacturing process of mono-dispersed metal balls for spherical silicon solar cell. The spherical silicon solar cell is a solar cell that uses silicon spheres of 1 mm in diameter and has drawn great attention due to its high productivity. Silicon spheres are manufactured by a jet dropping method. In this method, silicon droplets are generated from breakup of a capillary jet of molten silicon. The droplets are solidified while falling in a cooling tower, and then spherical silicon balls are obtained. However, it is found to occur that the silicon balls are not mono-dispersed due to coalescence of the droplets during falling. In order to solve this problem, we proposed the droplet electrification method by applying high voltage electric field. A repulsive force will act between each charged droplets and prevent them from coalescence. In our experiments, capillary jets of water, glycerol and molten gallium were used instead of molten silicon to investigate the effect of the electrification. The experimental results are found that coalescence frequency is depending on a dimensionless parameter, which represents a ratio of electrostatic potential over kinetic energy of droplets.

Key words: spherical silicon solar cell; droplet; applying an electric field

Introduction

Solar power generation attracts attention as an environmentally friendly power generation method. Among them, a spherical silicon solar cell as shown in Fig. 1 was developed. The spherical silicon solar cell is a solar cell that uses silicon spheres of 1 mm in diameter and has several advantages as follows: (1) Productivity is high because the spheres are directly produced from molten silicon. (2) Material yield of silicon is high because there is no cutting process of silicon ingot. (3) There is little directivity of light. The spherical silicon solar cell can accept wide angle of light. (4) A module of the spherical silicon solar cell has high flexibility. It can be fit to a curved surface.

However, the spherical silicon solar cell has still a problem of production process. A mass-production method of silicon spheres at low cost has not been established yet. In the dropping method, silicon droplets are formed by breakup of a capillary jet of molten silicon. Then the molten droplets are allowed to solidify in free fall through a cooling tower and the solidified particles are collected at a bottom of the tower. The problem of the process is that the size of the particles is not uniform, because the jet breakup is not uniform and the droplets coalesce due to velocity difference between droplets in free fall. As a result, the productivity of the spheres is decreased.

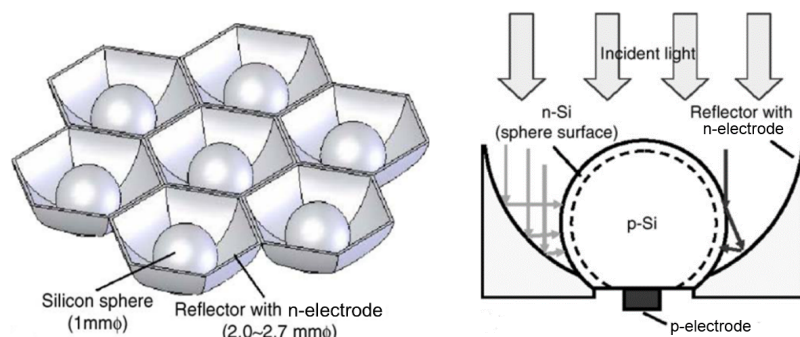


Fig. 1: Schematic diagram of spherical solar silicon cell [1].

In previous studies [2], it was shown that droplets could be electrified by an applying high voltage during disrupting of a

capillary jet. Then, repulsive forces acting on electrified droplets prevented them from coalescence. In order to design manufacturing equipment, it is necessary to know a charge amount per droplet to prevent coalescence. The purpose of this research is to construct a prediction model of a charge amount per droplet to prevent coalescence. Therefore, we investigate the relationship between a charge amount per droplet and coalescence frequency.

Principle of droplet electrification

Coalescence of droplets can be prevented by electrification of droplets. The principle of droplet electrification is shown in Fig. 2. A capillary jet is surrounded by a grounded cylindrical electrode. The jet has a high-electrostatic potential, which is maintained by a high-voltage power supply of several thousand volts. The capillary jet have an equipotential surface charge, and the charge will be trapped by droplets detaching from the tip of the jet. The charged droplets have a repulsive force preventing them from coalescence.

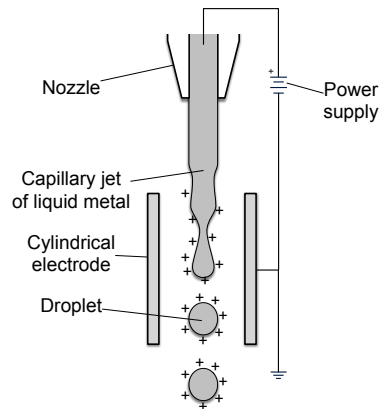


Fig. 2: Prevention of droplets coalescence by electrification [2].

Experimental method

The experimental equipment is shown in Fig. 3. The liquid, which was electrically connected to the high-voltage power supply, was issued from the nozzle and the capillary jet was formed. The cylindrical electrode was arranged near the breakup point of the liquid jet, and the electrode was connected to ground. In this experiment, a charge amount per droplet was measured by the electrometer and motion of the droplet during dropping was observed by the high-speed camera.

A coalescence frequency was measured from the image of the high-speed camera. Experimental conditions are shown in Table 1. Cold model experiments were carried out. Water, glycerol and gallium were used as jet liquid. Effects of the experimental conditions of liquid medium, nozzle diameter, inner diameter of cylindrical electrode and applied voltage on coalescence prevention of droplets were examined.

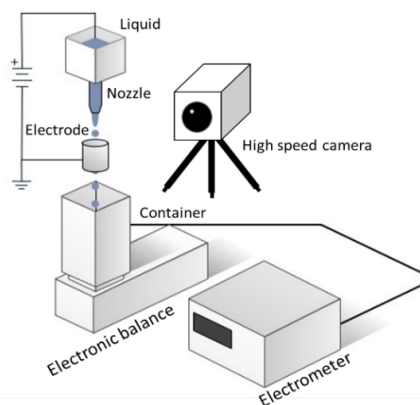


Fig. 3: Experimental equipment.

Table 1: Experimental conditions.

liquid	water, glycerol, gallium
voltage, φ / kV	0–3.0
Inner diameter of cylindrical electrode, d_e / mm	11.6, 17.5
nozzle diameter, d_n / mm	1.58, 2.14
photographing speed, F / s ⁻¹	8000

Experimental results

The change in the coalescence frequency with the charge per droplet is shown in Fig. 4. The vertical axis is the coalescence frequency and horizontal axis is the charge q . It shows a tendency to decrease the coalescence frequency f with increasing of the droplet charge q , however it has large variance.

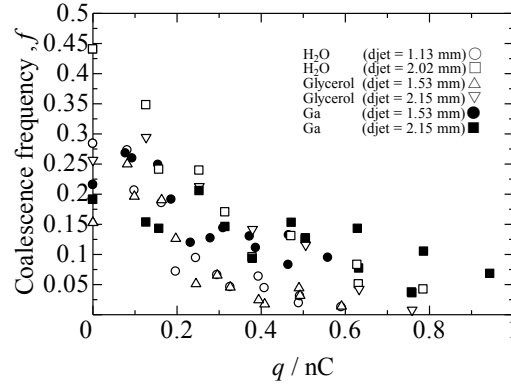


Fig. 4: Change of coalescence frequency with dimensionless parameter q .

In order to reduce the large variance in Fig. 4, we have proposed a mathematical model to consider the coalescence phenomena. Suppose that two droplets of d_d in diameter are approaching each other with relative velocity Δv . An initial distance between the droplets is equal to the breakup length of the capillary jet λ_{op} and the droplets have an electrical charge q . If the mechanical energy is preserved before and after coalescence of droplets, we have formulated an equation of energy balance as follows:

$$\frac{1}{2} m \Delta v^2 + \frac{q^2}{4\pi\epsilon_e \lambda_{op}} = \frac{q^2}{4\pi\epsilon_e d_d}. \quad (1)$$

The left and the right hand side of equation (1) represent a sum of a kinetic energy and a potential energy before and after the coalescence respectively. The equation can be converted:

$$\frac{1}{2} m \Delta v^2 = \frac{q^2}{4\pi\epsilon_e} \left(\frac{1}{d_d} - \frac{1}{\lambda_{op}} \right). \quad (2)$$

The ratio of the kinetic energy (the left hand side) to the electrostatic potential energy (the right hand side) of equation (2) was taken:

$$R \equiv \frac{q^2}{2\pi\epsilon_e m \Delta v^2} \left(\frac{1}{d_d} - \frac{1}{\lambda_{op}} \right). \quad (3)$$

If $R > 1$, it means that the electrostatic potential energy, which represents repulsive force acting on droplets, is larger than the kinetic energy, so the droplets don't coalesce. A graph of the ratio R and coalescence frequency f is shown in Fig. 5. The vertical axis is the coalescence frequency f and horizontal axis is the parameter R . Comparing Fig. 5 with Fig. 4, it is clearly shown that the parameter R is more useful to predict the coalescence frequency. For example, when the value of the parameter R is higher than 0.1, the coalescence frequency is suppressed to be about 5% or less.

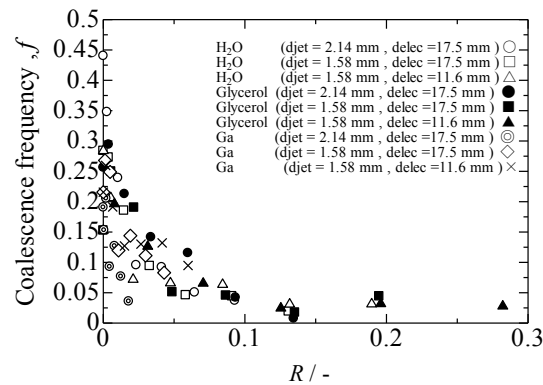


Fig. 5: Change of coalescence frequency with dimensionless parameter R .

Conclusions

Following conclusions were obtained:

- The experiment on the dropping method with droplet electrification was carried out. The relation between the droplet charge and the coalescence frequency was obtained.
- The mathematical model to consider the coalescence phenomena was proposed. The model is based on the energy balance between before and after the coalescence. A new dimensionless parameter, which is the ratio between the kinetic energy and the electrostatic potential energy, is derived to predict the coalescence frequency. It is estimated that if the value of the parameter R is higher than 0.1, the coalescence frequency is suppressed to be about 5% or less.

Acknowledgment

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