2. Design Concept and Theory Background

2.1 Effect of Miniaturization on Force

In the large scale, the CO_2 gas bubbles leave the catalyst layer by buoyancy. However, in the microscale they will be trapped on the catalyst layer, when resultant forces balance between surface tension and buoyancy. This is because the influence of line force becomes stronger than volume force when the scale decreases, shown in Fig. 2.1, as the surface tension and buoyancy are line force ($\sim L^1$) and volume force ($\sim L^3$), respectively.

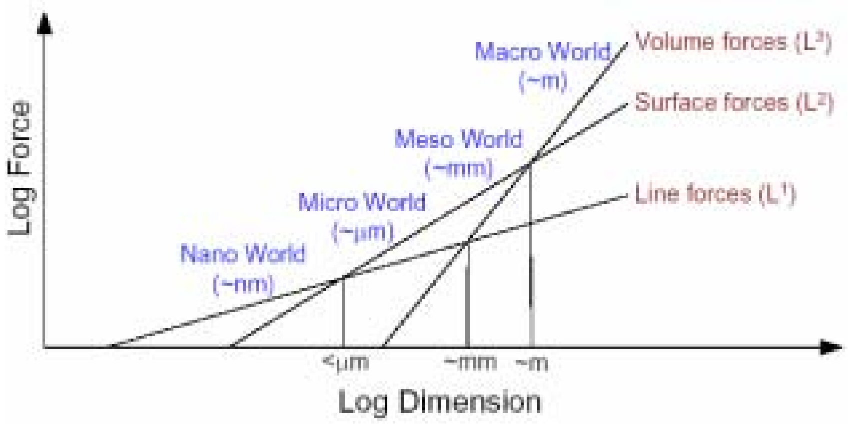


Fig. 2.1 The relation of line, surface, and volume force [11]

Assume that the CO_2 gas bubble in a liquid is hemisphere with contact angle is 90°. If the surface tension effect is greater than buoyancy effect, the CO_2 gas bubble is trapped:

$$\gamma \times 2\pi R \times \frac{1}{2} \geq \rho \times \frac{4}{3}\pi R^3 \times \frac{1}{2} \tag{2.1}$$

where R is the radius of the bubble.

Let the surface tension of water $\gamma = 0.0728 N/m$ and the density of fuel $\rho = 998 kg/m^3$, it is found that the bubble will be trapped with its radius smaller than 3mm. According to the literatures [3,12,13], all the bubble radii are much smaller than 3mm in low current μDMFC. Therefore, the influence of surface tension force should be considered carefully in μDMFC design.

2.2 Surface Tension Theory and Contact Angle

Surface tension [14~16] can be explained from the molecular point of view by considering that each molecule is subjected to attractive forces from its surrounding fellows, as shown in Fig. 2.2. The cohesive forces between molecules down within a liquid are balanced with all neighboring molecules. Those on the surface have no neighboring molecules above, and exhibit stronger attractive forces upon their nearest neighbors on the surface. This enhanced intermolecular attractive forces at the surface is called surface tension. The surface tension tends to minimije the surface area of the liquid.

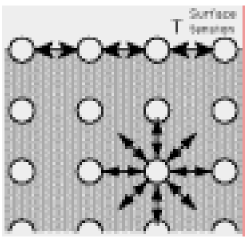


Fig. 2.2 The formation of surface tension [15]

The formation of liquid drops and bubbles are examples associated with surface tension. The droplet on a hydrophobic plate has a large contact angle because the cohesive force is stronger than the adhesive force, and the reverse is true for a droplet on a hydrophilic plate. The force diagrams for a liquid droplet on a hydrophobic and a hydrophilic plate are shown in Fig. 2.3. On the contrary, for a bubble, a large contact angle is caused on a hydrophilic plate. By changing the resultant forces could drive the droplet or the bubble to move.

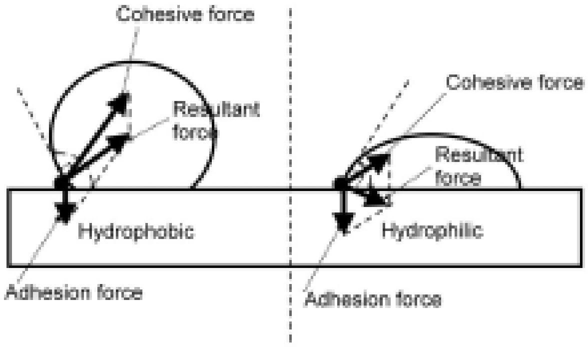


Fig. 2.3 The liquid droplet on hydrophobic and hydrophilic plate [16]

2.3 Young-Laplace Equation

The surface tension stress is balanced by the gas-pressure, as shown in Fig. 2.4

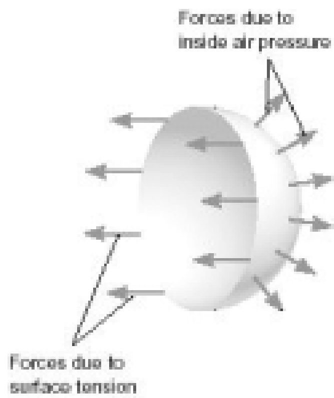


Fig. 2.4 The balance between surface tension stress and gas pressure [17]

The Young-Laplace or Laplace equation provides the pressure drop across an arbitrarily curved surface in Eq. 2.2

$$\Delta P = \sigma\left(\frac{1}{R_1} + \frac{1}{R_2}\right) \tag{2.2}$$

For a spherical liquid drop in atmosphere, $R_1 = R_2 = R$, the pressure drop

$$\Delta P = \frac{2\sigma}{R} \tag{2.3}$$

This result also holds for a spherical bubble in a liquid.

For a bubble in a liquid with a contact angle θ, the forced diagrams are shown in Fig. 2.5 (a). The surface tension of the bubble is $T = \frac{2\sigma \cdot \sin\theta}{R}$. According to Eq. 2.3, the pressure in a bubble with contact angle θ could be presented as

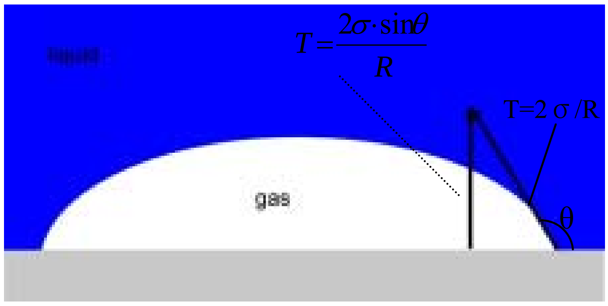
$$\Delta P = \frac{2\sigma \cdot \sin\theta}{R} \tag{2.4}$$

For a bubble on a hole in anti-buoyancy direction, according to the Laplace Equation in Eq. 2.4

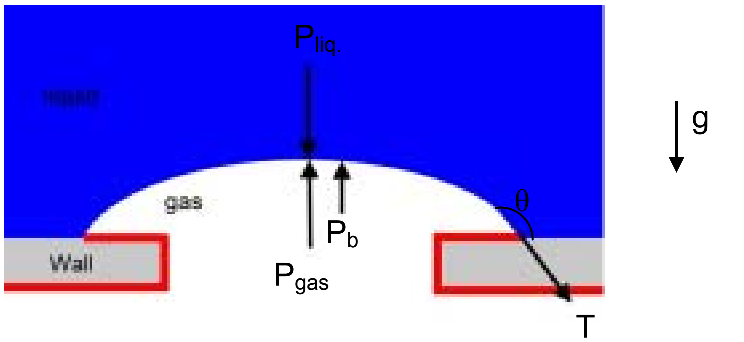
$$P_{liq} - P_{gas} \approx \frac{2\sigma \cdot \sin\theta}{R} + P_b \tag{2.5}$$

where P_b is buoyancy.

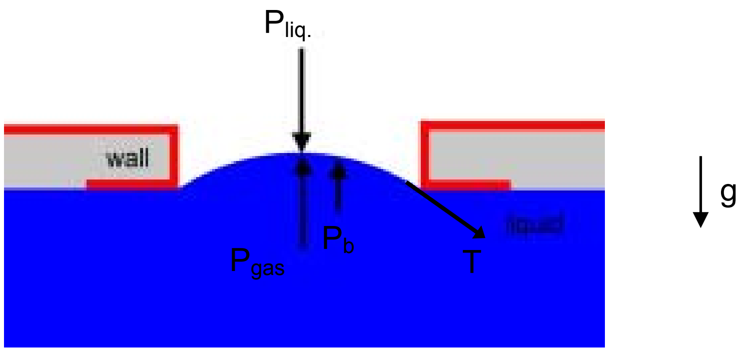
For the situation shown in Fig. 2.5(b), when the hole's vicinity is hydrophobic, θ tends to be smaller than $\pi/2$ so that $\frac{2\sigma \cdot \sin\theta}{R}$ becomes smaller. Therefore, the bubble will be mostly breathed out. Leaving only a small fraction at the balance of surface tension, buoyancy, P_{liq}, and P_{gas}. Furthermore, when the bubble around a hole is in the co-buoyancy direction, shown in Fig. 2.5(c), the buoyancy would help expel the bubble.



(a)



(b)



(c)

Fig. 2.5 (a) A bubble in a liquid with a contact angle θ

(b) A bubble in a liquid on the hole with a contact angle θ (in anti-buoyancy direction)

(c) The balanced force surface after a bubble is expelled (in co-buoyancy direction)