Introduction of water electrolysis to simulate boiling flow of water applicable to compact-type steam generators in SMRs

Haekyun Park*, Jaeduck Seo, Jeonghun Seo
School of Energy Engineering, Kyungpook National University 80, Daehak-ro, Buk-gu, Daegu, 41566, Korea
**Corresponding author: hkyunp@knu.ac.kr*

***Keywords:** small modular reactors, helical coil steam generator, printed circuit steam generator, water electrolysis, flow boiling visualization

1. Introduction

Integral-type pressurized water reactors are being developed for small modular reactors (SMR). They potentially adopt helical-coil steam generators (HCSG), which will be installed within the vessel itself to accommodate compactness [1]. For a similar reason, non-water-cooled reactors, such as modular integrated gas-cooled high-temperature reactor (MIGHTR) also adopt compact type steam generator, printed circuit steam generator (PCSG) [2]. Unlike conventional shell-and-tube-type, such the steam generators are once-through type consist of numerous parallel channels where boiling occurs inside the narrow channel. This distinguished feature may induce various two-phase flow instabilities and flow maldistribution. Moreover, identification of two-phase flow regime affecting heat transfer characteristics due to the boiling (diabatic flow) in high pressure conditions is challenging task. Although several advanced techniques have been developed such as gamma densitometry, optical fiber probe, electrical resistance tomography and wire mesh sensor [3], there is nothing more informative and accurate method than in situ identification using visible light.

Besides high pressure condition, it is expected that particular geometrical features of HCSG and PCSG would yield quite different flow regime compared to the conventional flow regime map based on the straight channel; existence of secondary flow due to curvature in HCSG and small channel gap (~ 2 mm) with zigzag flow channel in PCSG. Obviously, better understanding of flow regime expected inside HCSG and PCSG under such the operating conditions would contribute safe and effective operation of SMR.

In this paper, the authors firstly suggest an experimental method to identify two-phase flow regime under high pressure condition of water, applicable to HCSG and PCSG by utilizing water electrolysis. Hydrogen (or oxygen) generation at the electrode by electrochemical reaction simulates vaporization of water under high pressure condition based on similar nucleation theory. There are several big advantages of utilizing water electrolysis; the system is essentially thermal-free condition so that thin transparent window or silicon tube can be used and small bubble departure diameter of hydrogen (~0.1 mm) under atmospheric condition is comparable to that of vapor bubble departure diameter under high pressure condition. In short, this methodology enables in situ observation of flow regime using high-speed camera under atmospheric condition.

2. Backgrounds

Basic idea of the proposed methodology using water electrolysis is that the two-phase flow regime is affected by a ratio of channel gap to the bubble diameter as void fraction inside a channel varies according to the channel gap [4]. More recently, Dang and Ishii [5] experimentally observed that the difference of the transition boundary according to the pipe size due to the pipe wall effect on the bubble distribution and relative motion.

2.1 Bubble diameter in high pressure water

Due to the inherent problem to design and perform high pressure condition experiments, the physics of the boiling process in such high pressure conditions is still poorly understood [6]. Despite the harsh condition, one can be summarized in open literature as shown in Fig. 1. The bubble departure diameter, D_d obviously shows decreasing trend with pressure in both the pool and flow boiling experiments. For the high pressure conditions expected in HCSG (~3 MPa), the measured D_d are scattered roughly from 0.05 to 0.20 mm, which are more than 10 times smaller than those for atmospheric condition (~ 2 mm).

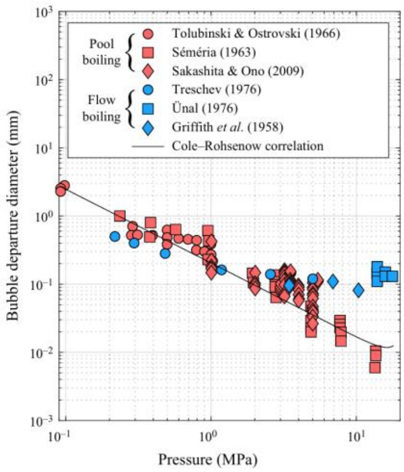

Fig. 1. Bubble departure diameters according to pressure [6].

2.2 Bubble diameter in water electrolysis

The water electrolysis generates hydrogen gas and oxygen gas at the cathode and anode electrode, respectively, by means of the electrochemical reaction. It is interesting point that nucleation of hydrogen gas occurs by the heterogeneous mechanism like the boiling system [7]. And hydrogen bubble, which has a critical diameter, grows and detaches by the force balance between surface tension and buoyancy force [8]. However, based on the different natures between the boiling and electrochemical reaction, the size of activated surface cavity is different. This difference makes D_d of hydrogen much smaller than that in boiling system. Fig. 2 compares D_d for water electrolysis (hydrogen) and boiling systems. The hydrogen D_d also varies with various experimental conditions such as current density, electrolyte type and electrode material, they typically distributed ~ 0.1 mm scale under atmospheric condition.

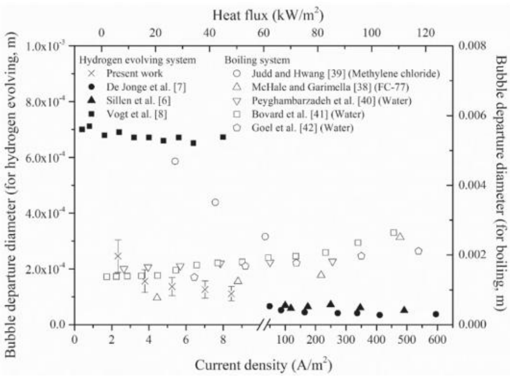

Fig. 2. Comparison of bubble departure diameters [9].

3. Parametric analysis

3.1 Physical properties of working fluid

Primary forces affecting the flow regime are inertia, buoyancy (density difference), surface tension and viscous force [10]. Table I lists key physical properties of working fluids; water at high pressure conditions (assumed to be saturated), and 1.5 M of sulfuric acid solution for water electrolysis at SATP. Gas density, surface tension and viscosity between boiling and water electrolysis system showed large discrepancy. However, as density difference is mainly governed by liquid density, which shows acceptable range. And surface tension of H_2SO_4 solution can be lowered using surfactant, cetrimonium bromide (CTAB). The authors' previous work [11] showed that the surface tension of H_2SO_4 solution was reduce down to 35.11 mN/m, which is similar scale to the high pressure water conditions. To deal with unacceptable difference in viscosity, parameter absorption should be performed by dimensional analysis using proper dimensionless numbers.

Table I: Comparison of physical properties

	Water (vapor)		H_2SO_4 solution (hydrogen)
P (MPa)	1	3	0.101 (1 atm)
ρ_l (kg/m^3)	887.1	821.9	1076.6
ρ_g (kg/m^3)	5.1	15.0	0.084
σ (mN/m)	42.2	29.8	74.5
μ_l (μPa-s)	150.2	113.9	~ 1700

3.2 Key non-dimensional numbers

To simulate vapor bubble behaviors in high pressure condition using hydrogen generated by a water electrolysis, some primary non-dimensional numbers such as Bond, Capillary and Weber numbers, which play a key role inside channel would link between vapor and hydrogen bubble.

$$Bo = \frac{(\rho_l - \rho_g) g D_d^2}{\sigma}, \tag{1}$$

$$Ca = \frac{\mu_l U_l}{\sigma}, \tag{2}$$

$$We = \frac{\rho_l {U_l}^2 D_d}{\sigma}. \tag{3}$$

Excluding constant value (g), the parameters related to the fluid's physical properties are density difference, D_d, viscosity and surface tension. It is expected that possible missing non-dimensional number would include those physical parameters.

4. Experimental methodology

As the proposed methodology is now being developed, we shall focus on two-phase flow using simple rectangular channels at this stage. Fig. 3 shows schematic design of water electrolysis to identify two-phase flow regime. One of key different feature of test rig from that of boiling system is that the electrolysis system needs two or more channels to separate hydrogen and oxygen, respectively.

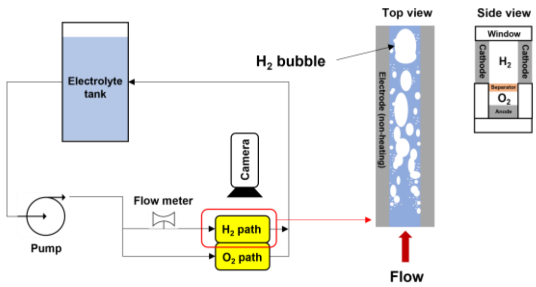

Fig. 3. Schematic of simple loop and test rig.

By increasing current density gradually using power supply, two-component flow (hydrogen and electrolyte) would be made. As hydrogen is non-condensable gas, the system can only simulate saturated boiling system. The width of channel will be varied from 2 mm to 2 cm, which covers potential hydraulic diameter of PCSG and HCSG. Once the flow regime is confirmed, comparative analysis will be performed using conventional flow regime map, function of superficial velocities and physical properties.

5. Conclusions

An experimental method to identify two-phase flow regime is firstly proposed applicable to compact type steam generators such as HCSG and PCSG. However, boiling experiment together with visualization for such the components is hardly available due to the high pressure and complex geometrical condition. To overcome those challenging issues, utilization of water electrolysis would be a solution.

The authors' previous works revealed that the bubble departure diameters of high pressure vapor in boiling and hydrogen in water electrolysis under atmospheric pressure condition have similar scale. Simple experiments to validate the proposed experimental method are being designed to compare with conventional well-known flow regime map.

On the hypothesis that once the method is validated, more complex geometries to mimic HCSG and PCSG will be designed to confirm various instabilities including density wave oscillation and flow maldistribution. Ultimately, the results from the proposed experimental method would give valuable insight to consolidate model or phenomenological understanding regarding friction loss, flow regime and of instabilities.

REFERENCES

[1] P. K. Bhowmik, D. Chowdhury, H. H. Abdellatif, S. Wahlquist, S. Kumar, S. Sharma, A. Ali, F. Mascari, and P. Sabharwall, Flow instabilities in helical-coil steam generators for small modular reactors: A review, Nuclear Engineering and Design, Vol.433, 113846, 2025.

[2] J. Y. Kim, H. K. Park and X. Sun, Experimental investigation of a compact diffusion-bonded steam generator for high-temperature gas reactors, The proceedings of 21st International Topical Meeting on Nuclear Reactor Thermal Hydraulics (NURETH-21), Busan, Korea, 2025.

[3] T. Wang, Z. Liu, M. Gui, Q. Bi, Z. Sui, Flow regime identification of steam-water two-phase flow using optical probes, based on local parameters in vertical tube bundles, Flow Measurement and Instrumentation, Vol.79, 101928, 2021.

[4] T. Hibiki, and K. Mishima, Flow regime transition criteria for upward two-phase flow in vertical narrow rectangular channels, Nuclear Engineering and Design, Vol.203, pp. 117-131, 2001.

[5] Z. Dang, and M. Ishii, Experimental study of the effect of pipe size on bubbly to beyond-bubbly flow regime transition, Experimental Thermal and Fluid Science, Vol.134, 110591, 2022.

[6] A. Kossolapov, M. T. Hughes, B. Phillips, and M. Bucci, Bubble departure and sliding in high-pressure flow boiling of water, Journal of Fluid Mechanics, Vol.987, A35, 2024.

[7] S. R. German, M. A. Edwards, H. Ren, and H. S. White, Critical nuclei size, rate, and activation energy of H_2 gas nucleation, Journal of the American Chemical Society, Vol.140, pp. 4047-4053, 2018.

[8] H. Vogt, The problem of the departure diameter of bubbles at gas-evolving electrodes, Electrochimica Acta, Vol.34, pp. 1429-1432, 1989.

[9] H. K. Park and B. J. Chung, Comparison of bubble parameters between boiling and hydrogen evolving systems, Experimental Thermal and Fluid Science, Vol.122, 110316, 2021.

[10] S. K. Das and D. Chatterjee, Vapor liquid two phase flow and phase change, Springer Nature, Switzerland AG, 2023.

[11] D. H. Park, H. K. Park and B. J. Chung, Influence of surface tension on the critical current density at sulfuric acid electrolysis, Heat and Mass Transfer, Vol.55, pp. 2097-2105, 2022.