**Experimental Investigation of Bubble Dynamics During Loss of Coolant Accident Conditions in a Pressurized Water Small Modular Reactor (PWSMR)**

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Abstract – *The purpose of this investigation was to study bubble dynamics in an adiabatic air-water two-phase flow, mimicking the Loss of Coolant Accident (LOCA) scenario in a Pressurized Water Small Modular Reactor (PWSMR). A 5x5 rod bundle, with each rod 9.5 mm in diameter and a Pitch-to-Diameter ratio (P/D) of 1.33, was used to represent the fuel rods. A 4-point fiber optical probe was used to obtain detailed data on bubble dynamics, including local void fraction, bubble velocity, bubble chord length, interfacial area concentration, and bubble passage frequency at a wide range of water and air superficial velocities. The experiment was conducted at various axial and radial locations before and right after the spacer grids to assess the impact of spacer grid mixing vanes. Higher void fraction, bubble passage frequency, and interfacial area concentration were observed in the subchannels compared to those obtained in the gap between the rods at all conditions. However, no significant differences were observed for the bubble chord length and bubble velocity at low flow condition. This study offers valuable insights into the behavior of air-water two-phase flow in rod bundles, which is critical to improving the safety and effectiveness of nuclear reactor design and operation.*

**Keywords:** Bubble dynamics, void fraction, spacer grid, rod bundle, PWSMR, LOCA

I. Introduction

Recently, interest in Small Modular Reactors (SMRs) has grown globally. SMRs offer an alternative source of energy that is less harmful to the environment as a result of their low carbon emissions. After several severe nuclear accidents, the need for advanced safety systems in nuclear power plants became necessary. For that reason, SMRs provide a standardized, flexible, economical cost energy alternative[1]. Since there are several different features for SMRs, one of the important features in SMRs is the passive safety system which is designed to remove the heat produced by the reactor core even in conditions of flow instability. The International Atomic Energy Agency (IAEA) identifies SMRs as reactors that produce less than or equal 300 Mwe [2]. In a normal operation of SMRs, the water works as coolant and neutron moderator. However, if the temperature inside the reactor core becomes too high or in a Loss of Coolant Accident (LOCA) conditions, the coolant that is in physical contact with the bundles of fuel rods will evaporate around the rods. As a result of this occurrence, the flow changes from a single-phase to a two-phase flow relatively. The fuel rod bundles are susceptible to damage or melted down due to overheating, which is indicated by the critical heat flux condition (CHF). Understanding the hydrodynamics and bubble characteristics such as void fraction, bubble chord length, interfacial area concentration (IAC), bubble velocity plays a significant role in rod bundle to predict the two-phase flow behavior.

Over the past few decades, several experimental studies have utilized several types of two-phase measurements techniques, electrical conductivity probe [3]–[6] , wire mesh sensors [7]–[10], non-invasive gamma ray densitometry technique [11]–[13]. One of the most accurate resolution techniques employed has been the use of optical fiber probes [14]–[17]. The optical fiber probes are known for their ability to accurately measure local parameters, and they have a high spatial resolution comparing with electrical conductivity probe [18]. The fiber optical probes work based on the refractive index of the medium around the fiber optical probe tip. However, only limited experimental data is available for the local two-phase flow characteristics within the rod bundle. Paranjape et al. (2008, 2011) conducted experiments on air-water two-phase flow in an 8×8 rod bundle channel to identify different flow regimes at various axial locations in the channel using. They classified the observed flow patterns into four distinct categories. The flows under consideration are characterized by their dynamic behavior, specifically their tendency to exhibit bubbly, cap-bubbly, cap-turbulent, and churn-turbulent [19], [20]. Yang et al., (2012) conducted a localized assessment of void fraction and interfacial area concentration within an 8×8 rod bundle geometry. This investigation involved the utilization of wire meshes and conductivity probes [21]. A double and four-sensor fiber optical probes were used by (Han et al., 2020; Shen et al., 2019) to investigate the flow behavior of 6×6 rod bundle channel under bubbly flow. The octant triangular measuring region of 16 measurement points were measured at the subchannels, wall channels, and the gaps between the rods [16], [17].

The purpose of this study is to investigate the local bubble dynamics including void fraction, bubble passage frequency, bubble chord length, interfacial area concentration (IAC), bubble velocity simultaneously. Additionally, the spacer grid effect has been examined before and just after the spacer grid to evaluate its impact on the two-phase flow. The local measurements data of 5×5 unheated rod bundle was collected using a four-point optical fiber probe under bubbly flow and at different flow conditions.

II. Experimental facility

The experimental facility has been designed and constructed in Multiphase Flow and Reactors Engineering and Applications Laboratory (mFReal) at Missouri University of Science and Technology (MST). Air and water were chosen as the two-phase working fluids for the experiment, which was conducted under adiabatic conditions with ambient pressure. The test loop as shown in Fig. 1 is designed to be capable of simulating the actual thermo-hydrodynamic behavior of a 5x5 PWSMR core covering single- and two-phase flow experiments.



*Figure 1. Flow schematic diagram of the experimental loop system.*

The entire system consists of the test section, water pump, water tank, an upper separator tank, flowmeters for water and air, air compressor, valves, and piping. The test section of the rod bundle is shown in Fig. 2.

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|  | (a) |
|  |  |
|  | (b) |
| *Figure 2. (a) Schematic diagram of test section. (b) cross-section view of 5x5 rod bundle* |  |

The housing test section comprises a transparent acrylic square tube with dimensions of 69 mm x 69 mm, with a wall thickness of 3 mm. It comprises various components, including 25 stainless steel rods, each rod diameter DR is 9.5 mm and 1.5 m in height, a lower tie plate, an upper tie plate, and a 3-D printing split-type mixing vane spacer grids (MVSG) as in Fig. 3.

Table 1 summarized the important physical dimensions such as wetted perimeter *Pw*, the flow area *AF*, the hydraulic diameter *DH* of the entire cross-section. The hydraulic diameter of the whole cross-section is expressed by:

|  |  |
| --- | --- |
|  | (1) |

The liquid phase is pumped from the water tank to the lower part of the test section. Then, oil-free dry air was introduced continuously into the system as the gas phase from the lower part of the apparatus to mix it with the water in the mixture chamber.

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| --- | --- |
| *Table 1 Important physical dimensions of test section* | |
| Wetted perimeter *Pw* | 1.0255 m |
| Rod diameter *DR* | 0.0095 m |
| Pitch-to-Diameter rate *P/D* | 1.33 |
| Flow area *AF* | 0.0031 m2 |
| Hydraulic diameter *DH* | 0.012 m |

A white square object with spikes

Description automatically generated

*Figure 3. 3-D printing mixing vane spacer grid*

The flow rate of the water and gas phases is controlled by a set of calibrated rotameters. The air is then separated and subsequently discharged into the atmosphere at the outlet of the test section, while the water is returned to the water tank. Therefore, the experiments were conducted under three operation conditions (*Jf* = 0.3 m/s, *Jg* = 0. 142 m/s; *Jf* =0.6, *Jg* = 0.043 m/s; *Jf* = 1.0 m/s, *Jg* = 0.2 m/s). These flow conditions were selected for bubbly flow based on the flow regime map [22] at 2 axial locations *z/DH* = 67.6 and 85.8 which are upstream and downstream the spacer grid.

III. Local measurement method

In two-phase flow applications, optical fiber probes have been used commonly to assess phase distribution.

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| --- | --- |
| (a) | (b) |
|  |  |
| (c) | (d) |
|  |  |
| *Figure 4. Schematic/photo of: (a) the probe tips, (b) the head on view probe position, (c) tips configuration, (d) tips layers* | |

In this experiment, a novel in-house developed four-point optical fiber probe as illustrated in Fig. 5(a) is used to measure the local bubble properties. Basically, the probe configuration consists of four standard glass fiber tips. Three of the tips of the probe are equal in length and placed in the shape of the triangle. The fourth tip is about 2 mm longer than the three others and placed in the center of the triangle as in Fig. 5(b) and (c). Around 0.6 mm interval distance the center tip from each of the other tips on all sides. Each tip has a diameter of 200 μm and surrounded by a layer of silicon with diameter of 380 μm and Teflon protective layer with a 600 μm overall diameter as indicated in Fig. 5(d). The main concept of the probe is based on different mediums due to the difference in reflection index between the water and gas. Furthermore, the probe measures the bubble chord length, interfacial area concentration, bubble velocity, local void fraction, bubble passage frequency, and the distribution and their time series.

The void fraction is an extremely important parameter for designing and understanding the two-phase flow dynamics. The void fraction analysis in this experiment is conducted by comparing the duration time of the central tip in the gas phase to the overall duration time of the measurement, [23], and can be expressed as:

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| --- | --- |
|  | (2) |

For local interfacial area concentration, bubble velocity, bubble chord length measurements, discussed extensively in Xue et al., (2003) [23].

IV. Results

The void fraction is a significant parameter that plays an essential part in the characterization of the hydrodynamic structures of two-phase systems. Moreover, void fraction is influenced by a multitude of factors. The factors to consider in this context are the spacer grids, geometric design of the column, such as rectangular ducts or round pipes, as well as the characteristics of the wall surface, gas distributor configuration, and the physical properties of both the liquid and gas phases. Further, the influence of operational parameters, including superficial velocities of gas and liquid phases, pressure, and temperature, should not be overlooked. Figure 5 illustrates the findings pertaining to the distribution of local void fraction across the radial locations within the cross-sectional region of a 5x5 rod bundle. It is important to note that the semi-transparent pink bars in Fig 5 represent the rods. The void fraction distribution profiles for the wall-peak, core-peak, and the transition have been effectively obtained. In the low flow condition of the two-phase flow (*Jf =* 0.3 m/s, *Jg* = 0.124 m/s) the void fraction exhibits a radial core-peaking profile in the cross section at *z/DH* = 67.6. The void fraction measured at the subchannel, and wall channel is significantly higher than those in the gap between the rods. This phenomenon occurs due to the expansion of the large bubbles, as well as their movement from low liquid velocity areas to the high liquid velocity areas. For the high flow condition (*Jf* = 1.0 m/s, *Jg* = 0.2 m/s) The observed radial wall-peaking profiles can potentially be attributed to turbulence effect and strong swirling bubble motions which lead the bubble heading toward to the wall (rods). In the given flow condition (*Jf* = 0.6 m/s, *Jg* = 0.043 m/s), the radial void fraction profile does not exhibit either a core-peaking or wall-peaking. The observed flow condition can be considered as a transitional profile pattern that lies between the core-peaking and the wall-peaking phenomena.

To further investigate the void fraction findings, the bubble passage frequency, which is directly related to the void faction was measured. Bubble passage frequency refers to the number of bubbles traversing a specified volume per unit of time. In this study, bubble passage frequency refers to the number of bubbles that have passed through the central tip during the sampling period. Thus, very few of studies the effect of the bubble passage frequency in rod bundles [24], [25]. However, Fig 5 (b) shows the local bubble passage frequency radial profile for vary flow conditions. Also, bubble passage frequency confirms the void fraction behavior as noted in Fig 5 (a) and (b). Ren et al., (2018) reported that the bubble passage frequency impacted by multiple factors such as void fraction, bubble size, bubble velocity [24].

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| (a) |
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| (b) |
|  |
| (c) |
|  |
| (d) |
|  |
| (e) |
|  |
| *Figure 5. Radial local parameters at z/DH=67.6* |

Interfacial area concentration is described as the total surface area for all interfaces divided by the total volume of the two-phase mixture. Measured local interfacial area concentration radial profile of the 5x5 rod assembly cross section during low, high flow conditions (*Jf* = 0.3 m/s, *Jg* = 0.124 m/s; *Jf* = 1.0 m/s, *Jg* = 0.2 m/s) has shown in fig 5(e) which exhibits similar trends to the void fraction for both radial profiles of the core-peaking and wall-peaking. During bubbly flow regime, the bubble chord length does not vary that much in the radial profile at low flow condition (*Jf* = 0.3 m/s, *Jg* = 0.124 m/s), while in flow conditions (*Jf* = 1.0 m/s, *Jg*= 0.2 m/s; *Jf* = 0.6 m/s, *Jg* = 0.043 m/s) the rod geometry effect is obvious trend to core-peaking pattern due to the narrow gap between the rods which makes it easier for bubbles to be move towards to the center of the sub-channels or wall-channels. Fig 5(d) demonstrates the characteristics of the local bubble velocity radial profile does it show that the low and high flow conditions are nearly smooth shape with only little differences in the center of the subchannels, while the (*Jf* = 0.6 m/s, *Jg* = 0.043 m/s) exhibits a notable core-peaking pattern in its radial profile.

The spacer grid is one of the most crucial components in nuclear fuel assemblies. Its primary purpose is to support and maintain the position of the fuel rods, preventing any potential vibrations. Additionally, it plays a significant role in enhancing the heat transfer performance by increasing turbulence between the rods. Therefore, it is essential to investigate the spacer grid's effects on the overall thermal performance of the nuclear assembly by examining its vicinity. In this study, the impact of the mixing vane spacer grid on the local parameters is measured by analyzing the bubble properties at two axial locations at *z/DH* = 67.6 and 85.8 as shown in Fig 6. Observing the radial profile, fluctuations in void fraction and interfacial area concentration are evident, with significantly different values between *z/DH* = 67.6 and *z/DH* = 85.8. The higher void fraction and interfacial area concentration at *z/DH* = 85.8 are attributed to the wake region just after the spacer grid. Additionally, the spacer grid significantly contributes to the break-up of the bubbles which resulting in a reduction of bubble size and causes also to reduction in the bubbles velocity after the bubbles pass through the spacer grid, as shown in Fig 6(c) and (d).

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| (a) |
|  |
| (b) |
|  |
| (c) |
| (d) |
|  |
| (e) |
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| *Figure 6. Effect of MVSG on local parameters at flow condition (Jf=0.6 m/s, Jg=0.043 m/s)* |

V. Conclusions

This study conducted an examination of the local two-phase flow characteristics in a 5x5 rod bundle with a spacer grid using a four-point optical fiber probe to measure various bubble parameters. The primary conclusions derived from this investigation can be described as follows:

* The measured local void fraction distribution exhibited the profiles based on the flow conditions, transitioning from core-peaking, and passing to transition pattern to wall-peaking as flow conditions increased.
* The bubble passage frequency was found to depend on the behavior of the void fraction and was influenced by various factors such as bubbles size and bubbles velocity.
* The spacer grid caused considerable changes in local parameters like void fraction, interfacial area concentration, and bubble velocity, particularly in its downstream wake region.
* These findings provide valuable insights for future work on optimizing spacer grid designs and advancing the understanding of two-phase flow characteristics in nuclear fuel assemblies.

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Nomenclature

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| --- | --- |
| PWSMR | Pressurized Water Small Modular Reactor |
| LOCA | Loss of Coolant Accident |
| MVSG | Mixing Vane Spacer Grid |
| P/D | Pitch-to-Diameter ratio |
| IAC | Interfacial Area Concentration |
| *DR* | Fuel rod diameter |
| *Pw* | Wetted perimeter |
| *AF* | Flow area |
| *z* | Axial height |
| *DH* | Hydraulic diameter of the flow channel |
| *ε* | Void fraction |
| *T* | Time |
| *Jf* | Liquid superficial velocity |
| *Jg* | Gas superficial velocity |

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