

Effect of Air Gap on Flow and Heat Transfer Characteristics in Rectangular Channels under Bubbling Conditions

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Abstract

This study investigates the blistering phenomenon occurring in plate-type fuel assemblies of nuclear reactors through numerical simulation using Fluent software, and compares the differences between fission gas blisters and solid blisters from previous research. The findings reveal that: gas blisters cause local temperature elevation, with heat flux density around the blister increasing threefold, while the overall heat flux change in the fuel plate remains relatively small; the formation of blisters enhances local heat transfer capability by approximately 10% and increases the heat flux on the blister side by about 4%; under high flow velocity conditions, the presence of blisters leads to significant pressure differentials in the fluid on both sides of the fuel plate, causing deformation of the fuel plate and even blockage of the flow channel. The research results provide important reference for the design and safety assessment of plate-type fuel elements.

Full Text

Study on the Effect of Air Gap on Flow and Heat Transfer Behavior in Rectangular Channels Under Bubbling Conditions

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Abstract

This study investigates the bubbling phenomenon in plate-type fuel assemblies within nuclear reactors using numerical simulation with Fluent software, com-

paring fission gas bubbles with solid bubbles examined in previous research. The findings reveal that gas bubbles cause localized temperature increases, with heat flux density around the bubbles tripling, though the overall heat flux of the fuel plate changes minimally. Bubble formation enhances local heat transfer capability by approximately 10% and increases heat flux on the bubble side by about 4%. Under high flow velocity conditions, the presence of bubbles creates a significant pressure differential across the fuel plate, leading to plate deformation and potential flow channel blockage. These results provide important references for the design and safety assessment of plate-type fuel elements.

Keywords: Plate fuel; Gas gap bubbling; Flow and heat transfer characteristics; Rectangular channel

Introduction

In nuclear reactors, fuel assemblies are critical components for heat generation and maintaining the fission chain reaction. Compared to rod-type fuel assemblies, plate-type fuel assemblies exhibit superior characteristics: lower fuel temperatures that enhance safety, and larger heat dissipation areas that improve power density in the active region. These advantages have led to widespread application in research reactors, marine propulsion reactors, and small power reactors [1].

The coolant channels in plate-type fuel assemblies form closed parallel flow paths with extremely narrow gaps, typically only a few millimeters wide. In these narrow channels, even minor geometric variations can significantly affect the temperature distribution and mass flow balance across fuel plates, potentially causing plate rupture and even core damage. Plate-type fuel elements exhibit a unique failure mode known as bubbling. During operational transients or minor accidents, fuel temperatures may temporarily exceed critical thresholds, forming bubbles on fuel plates. This bubbling results from combined radiation and thermal effects; prolonged irradiation releases substantial fission gases that accumulate locally, causing cladding deformation.

For dispersion fuels, interactions between fuel particles and metal matrix, as well as between fuel plates and cladding, are considered primary causes of bubble formation. Early experiments with uranium-molybdenum dispersion fuel and later studies on silicide-coated fuel demonstrated that suppressing particle-matrix interactions significantly reduces fuel swelling at low burnup, while fuel particle recrystallization causes expansion at high burnup [2]. Examinations of bubbled regions revealed that oxide inclusions at fuel-cladding interfaces coincide with bubble locations [3]. These studies collectively indicate that fission gas release results from material interactions. Additional temperature increases induce considerable thermal stress and gas pressure, affecting certain cladding regions and causing large plastic deformations that manifest as bubble-like protrusions on the cladding surface [4]. Xu Wei [5] investigated flow blockage caused by pellet swelling in narrow rectangular channels through experimental and numerical

methods, examining flow and heat transfer characteristics under various blockage conditions. Results showed that spherical protrusions significantly alter convective heat transfer and flow behavior in rectangular channels. Alshroof et al. [6] numerically studied combined effects of spherical dimples and protrusions in laminar flow through narrow rectangular channels, concluding that single protrusions yield significant heat transfer enhancement with marginal pressure drop increases. Other studies [9,10,11] have also experimentally investigated protrusion effects.

Existing research often focuses on describing flow redistribution, streamlines, and temperature field alterations in coolant and cladding surfaces while neglecting the importance of internal fuel element structure. Furthermore, many studies assume bubbles are solid, contradicting the actual gas-filled nature of bubbles. Consequently, these models fail to accurately reflect thermal-hydraulic behavior under realistic operating conditions.

This paper presents numerical simulations of plate-type fuel elements under bubbling conditions using Fluent' s dynamic mesh technology, specifically examining the effects of gas gap bubbles on temperature fields and heat flux, with comparative analysis against solid bubbles from previous studies.

1. Calculation Model

1.1 Geometric Configuration

This study selected a fuel plate and its adjacent two flow channels as the computational domain, with detailed geometric parameters provided in Table 1 . To ensure fully developed flow at the inlet and reduce backflow, 70 mm flow development sections were specified at both inlet and outlet regions. This design improves computational accuracy and reliability for better simulation of actual hydrodynamic conditions. The overall model schematic is shown in Figure 1 [Figure 1: see original paper] (not to scale).

To investigate gas bubble effects on fuel plate temperature distribution and heat exchange efficiency, and to compare with solid bubbles from conventional studies, three experimental cases were designed: solid bubbling, gas bubbling, and a non-bubbling reference case. To simplify calculations, the computational domain was divided into two layers: the upper plate with internal heat source but no bubbles (non-bubbling side), and the lower plate with bubbles but no internal heat source (bubbling side). Local schematic and detailed dimensions of the bubble location are shown in Figure 2 [Figure 2: see original paper] and Table 2 .

To make gas bubble simulation more realistic, this study employed advanced dynamic mesh technology. During simulation, helium gas with initial pressure was injected into the cavity, using gas pressure to naturally form bubbles in the cladding, ensuring bubble morphology more closely resembles actual conditions. This approach enhances simulation credibility and provides robust technical

support for future related research.

1.2 CFD Model Setup

In the Fluent simulation, the inlet boundary condition was set as velocity inlet, the outlet as pressure outlet, and all other surfaces as wall boundaries. To enhance pressure-velocity coupling calculation accuracy, the coupled algorithm was employed. Since only single-phase fluid was considered, the Realizable k-model was selected as the turbulence model. Developed by V. Yakhot et al. [12] in 1986 as an improvement to the Standard k-model, this model accounts for vortex effects on turbulent flow and provides analytical expressions rather than empirical constants for Prandtl numbers, improving prediction accuracy for rotational flows.

For the viscous sublayer region near walls, the Scalable wall function was adopted. This function evaluates mesh quality through the wall Y^+ value, a dimensionless wall distance parameter. Since the model's Y^+ value is approximately 10 (see Figure 3 [Figure 3: see original paper]), using the Standard wall function could result in Y^+ values below 15, typically reducing solution accuracy. The Scalable wall function maintains computational accuracy by imposing limits that force the Standard wall function to employ the logarithmic law when Y^+ values are too small. In the discretization process, energy and momentum equations were discretized using second-order upwind schemes, while k and ϵ equations used first-order upwind schemes.

1.3 Mesh Independence Verification

Mesh independence was verified by analyzing temperature along the centerline of the non-bubbling channel side. Thirty coordinate points were uniformly distributed along the flow direction for reference. Four mesh configurations were tested: case1 (553,418 cells), case2 (1,026,315 cells), case3 (2,325,637 cells), and case4 (3,123,546 cells). Comparison of pressure curves in Figure 4 [Figure 4: see original paper] shows that case3 and case4 produce nearly identical results, while case1 and case2 show significant differences from case4. This indicates that results achieve sufficient accuracy at 2,325,637 cells. Therefore, to balance computational precision and efficiency, the simulation employed a mesh strategy of 2,325,637 cells.

1.4 Model Validation

While this study employs simulation methods, analysis of gas gap bubbles lacks direct experimental data for complete validation. To ensure accuracy and credibility, a relevant experimental study (Reference [5]) was selected for comparative verification.

Based on experimental results from Table 2 in the reference, a corresponding simulation model was established with identical initial and boundary conditions. Consistency between simulation and experimental data was verified, with

detailed results shown in Table 3 . Using outlet temperature as the key parameter, differences between simulation and experimental results were maintained within 1% maximum relative error, thereby validating the simulation method's accuracy.

2. Results and Analysis

2.1 Fuel Plate Temperature Distribution

Figure 5 [Figure 5: see original paper] presents local temperature distribution contours for the fuel plate under three different conditions, from top to bottom: non-bubbling (a), solid bubbling (b), and gas bubbling (c). The gas bubbling case shows a localized high-temperature region at the bubble location not observed in the other cases. Additionally, fluid temperatures on both sides of the fuel plate differ, with the non-bubbling side exhibiting significantly higher fluid temperature than the bubbling side. Temperature profiles against the flow direction at the heated plate are plotted in Figure 6 [Figure 6: see original paper]. The gas bubbling case shows significantly elevated temperature at the fuel plate center, with temperature decreasing at bubble edges. The local high temperature is not substantially different from solid bubbling, though the bubble center temperature remains lower than the temperature at the fuel plate end.

Furthermore, temperature distribution along a straight line through the gas bubble center along the Y-axis was compared. As shown in Figure 7 [Figure 7: see original paper], despite the gas gap blocking heat transfer from one side, the overall temperature difference across the fuel plate is not significant compared to other cases. However, the maximum temperature in the gas bubbling case is closer to the bubbling side than in solid bubbling, because most heat is transferred through the non-bubbling side in the gas bubbling case, a phenomenon discussed further below.

2.2 Heat Flux Distribution and Surface Heat Transfer Coefficient

Figure 8 [Figure 8: see original paper] shows heat flux distribution within the fuel plate under three conditions, from top to bottom: non-bubbling (a), solid bubbling (b), and gas bubbling (c). The data reveal that heat flux at the gas bubble location is nearly zero, while around the gas bubble, particularly at the interface between bubbling and non-bubbling sides, heat flux reaches three times that of the same location in solid bubbling (circled area in Figure 8-c and symmetric position). Figure 9 [Figure 9: see original paper] further illustrates heat flux distribution along the Z-axis through the gas bubble center (left to right corresponds to bottom to top in Figure 8). Solid bubbling exhibits higher heat flux on the bubbling side, while gas bubbling shows higher heat flux on the non-bubbling side. However, total heat flux at this location is similar between both cases.

Figure 10 [Figure 10: see original paper] shows the proportion of heat flux on bubbling and non-bubbling sides under nearly identical total heat flux across

three cases. Bubble presence significantly enhances convective heat transfer on the bubbling side, making heat flux higher than on the non-bubbling side. This can be attributed to flow disturbance caused by bubbles, which disrupts the local boundary layer and enhances heat transfer efficiency, consistent with Guo Jiuyuan's findings [7]. Additionally, in the gas bubbling case, despite bubbles partially blocking heat transfer, overall heat transfer efficiency on the bubbling side still improves due to enhanced flow disturbance. Compared to solid bubbling where bubbling side heat flux accounts for 58%, gas bubbling side heat flux increases to approximately 54%.

The heat transfer coefficient was calculated at the interface between bubble center and fluid. Based on data in Table 4, both gas and solid bubbles increase surface heat transfer coefficients. Specifically, gas bubbles increase the coefficient by approximately 9%, while solid bubbles increase it by about 10%. This indicates that bubbles effectively improve heat transfer efficiency, though gas pressure-formed bubbles provide slightly weaker enhancement compared to spherical bubbles in previous studies.

2.3 Deformation Behavior of Fuel Plates

This study further investigated thermo-mechanical coupling phenomena in bubbled fuel plates under high flow velocity conditions. Using ANSYS fluid-structure interaction technology at inlet velocities up to 10 m/s, the effects of bubbles on structural forces in narrow rectangular channels were examined. Results show that when bubbles obstruct the channel, surrounding fluid velocity increases significantly, causing local pressure reduction. This flow effect induces severe fuel plate deformation, potentially leading to complete flow channel blockage. Figure 11 [Figure 11: see original paper] illustrates fuel plate deformation. Without contact detection, the upper plate tail exhibits noticeable depression, while the lower plate at and behind the bubble location shows upward protrusion, with cross-compression occurring between the two plates.

3. Conclusions

Based on computational fluid dynamics using Fluent software, this study compares temperature fields and heat flux between solid bubbles from previous research and actual gas bubbles to analyze gas gap effects on flow and heat transfer in narrow rectangular bubbling channels. The following conclusions are obtained:

1. Under gas bubbling conditions, localized fuel plate temperature increases significantly, with high-temperature points closer to the bubble location. Heat flux density around gas bubbles is three times that of solid bubbles.
2. Bubble presence enhances local heat transfer capability by approximately 10%, increasing heat flux on the bubbling side by about 4%, though this

enhancement is slightly weaker than that of solid bubbles in previous studies.

3. Under high flow velocity conditions, bubble formation may cause larger pressure differentials across fuel plates, leading to plate bending and potential flow channel blockage.

These findings provide new perspectives on the importance of bubbling phenomena in nuclear fuel plate design and safety assessment, offering significant implications for optimizing thermal-hydraulic design and improving nuclear reactor safety.

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Author Contributions

Chuangdong Liu performed simulation, result analysis, and manuscript writing; Wei Xu contributed to manuscript revision and polishing; Hui He provided funding and equipment support; Xiaojing Liu designed the study and reviewed/revised the manuscript.

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Note: Figure translations are in progress. See original paper for figures.

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