

Single and two phase flow characteristic in a pin-interrupted mini channel

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1. Introduction

Compact heat exchangers have attracted increasing attention due to their high surface-to-volume ratio and superior heat transfer performance compared to conventional shell-and-tube systems. The performance of a heat exchanger can be characterized by the surface-to-volume ratio, where a higher value indicates greater compactness and enhanced thermal performance. As shown by Shah [1], compact heat exchangers can achieve significantly higher surface densities than traditional configurations. Among various compact heat exchangers, the Printed Circuit Heat Exchanger (PCHE) is capable of operating under high temperature and high pressure conditions and has been actively studied since its development in the early 1980s [2]. Due to its structural strength enabled by diffusion bonding [3], the PCHE is considered a promising candidate for compact steam generator applications.

When a PCHE is applied as a Printed Circuit Steam Generator (PCSG), phase change becomes unavoidable. While conventional heat exchangers primarily involve single-phase heat transfer [4,5,6], steam generators require accurate prediction of two-phase flow behavior, including void fraction, flow regime transition, and frictional pressure drop. The hydraulic performance under two-phase conditions directly affects pump sizing, system stability, and thermal efficiency. However, limited experimental data are available for two-phase flow in mini-channel geometries representative of PCHE internal structures. Unlike conventional mini-channel studies that assume smooth internal geometries, the present work introduces a structurally interrupted mini-channel that mimics the internal architecture of PCHE-based steam generators. The pin-induced periodic contraction–expansion topology fundamentally alters interfacial dynamics and momentum redistribution, leading to delayed slug formation, broadened transitional regimes, and elevated hydraulic resistance independent of void fraction magnitude. This geometrically driven two-phase modulation has not been experimentally documented in prior literature.

2. Methods and Results

Water is circulated continuously from the reservoir to the test section using a centrifugal pump. The flow rate is controlled and measured using turbine flow meters covering ranges of 0.1–2.5 LPM and 1.0–10 LPM to

ensure measurement accuracy over a wide operating range. Compressed air is supplied from an air compressor and regulated up to 3 bar before entering the mixing chamber. Air flow rate is controlled using parallel rotameters covering ranges of 0.1–1 LPM, 1–10 LPM, and 10–100 LPM. Fig. 1 shows the

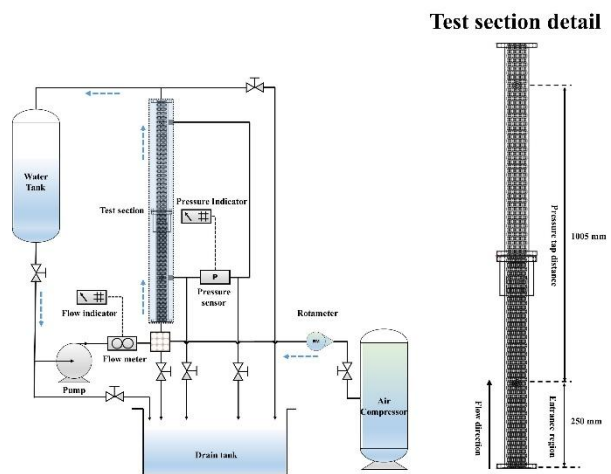


Fig. 1. Experimental setup used for hydraulic performance measurement and detailed view of the corrugated mini-channel test section showing the pressure tap locations and measurement region..

Air and water are combined in a mixer located upstream of the test section, generating a vertical upward gas–liquid two-phase flow. After passing through the test section, the mixture enters a separation tank where air is released to the atmosphere and water is recirculated to the reservoir.

The experimental conditions were selected based on the mini-channel flow regime map of Hibiki and Mishima [7,8]. A total of 144 operating conditions were tested by combining 12 water flow rates (0.50–3.50 LPM) and 12 air flow rates (0.1–4.0 LPM). This range corresponds primarily to bubbly and slug flow regimes under vertical upward flow conditions.

2.1 Flow regime identification

Representative flow regimes in the POMC are shown in Fig. 2. At low superficial gas velocity, bubbly flow was observed (Fig. 5(a)). However, bubble distribution appears confined within individual 2 mm × 2 mm sub-channels, leading to stronger geometric constraint effects.

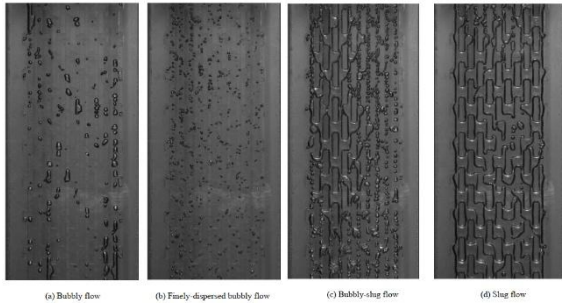


Fig. 1. Representative flow regime images in the POMC: (a) bubbly, (b) finely dispersed bubbly, (c) bubbly–slug, and (d) slug flow.

As gas velocity increases, a finely dispersed bubbly regime emerges, as shown in Fig. 2(b). In this regime, bubbles are noticeably smaller and more uniformly distributed compared to the rectangular duct case. The repeated contraction–expansion regions created by overlapping pins generate local acceleration and shear layers, which enhance bubble breakup and suppress large-scale coalescence. Consequently, formation of channel-spanning gas structures is delayed.

At intermediate gas velocities, a bubbly–slug transitional regime appears (Fig. 2(c)). Elongated gas structures form locally within certain sub-channels, while adjacent sub-channels still contain dispersed bubbles. The interrupted geometry prevents immediate development of a fully coherent slug across the entire flow width. Instead, gas structures are periodically fragmented and redistributed downstream due to pin-induced mixing.

At higher gas velocities, slug flow is eventually established (Fig. 2(d)). However, unlike the smooth rectangular duct, slugs in the POMC exhibit irregular shapes and are repeatedly distorted by the pin structures. The gas phase must navigate around the overlapping pins, leading to enhanced interfacial area and stronger void fraction fluctuations. The regime map for the POMC is shown in Fig. 3

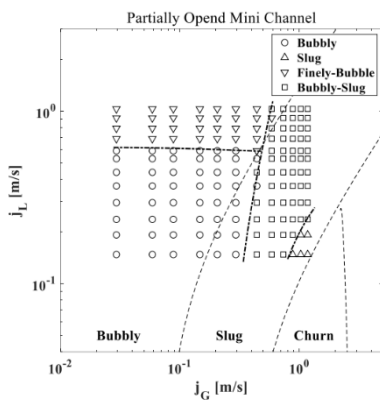


Fig. 3. Flow regime map of vertical upward air–water flow in the POMC in terms of superficial gas and liquid velocities.

2.2 Single-phase pressure drop

The single phase friction factor of POMC channel is shown in Fig.4. POMC exhibits premature deviation from laminar behavior at Reynolds numbers as low as 800–1000. This early transition indicates that geometric disturbances dominate the stability of the flow rather than viscous effects alone. The periodic pin interruptions generate repeated contraction–expansion regions, inducing local acceleration, boundary layer separation, and recirculation. These mechanisms enhance velocity fluctuations and destabilize the flow at significantly lower Reynolds numbers.

Moreover, the friction factor in the POMC remains substantially higher than that of the rectangular duct across the entire Reynolds number range. This increase cannot be explained solely by viscous shear; it reflects additional form drag and momentum redistribution imposed by the pin structures. The interrupted geometry therefore introduces a persistent structural resistance component independent of flow regime.

The results indicate that, even under single-phase conditions, the POMC behaves as a disturbance-enhanced channel rather than a conventional smooth duct. The combination of early transition and elevated friction factor suggests intensified mixing and energy dissipation. These characteristics provide a hydraulic foundation for understanding the modified two-phase regime transition and pressure drop behavior observed in subsequent sections.

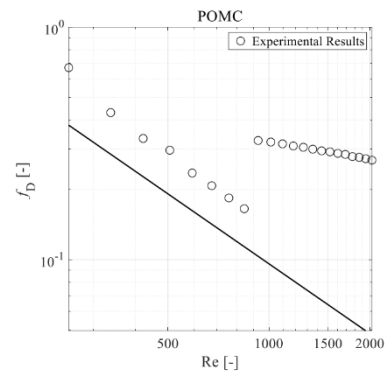


Fig. 4. Single-phase friction factor as a function of Reynolds number in the POMC. Symbols represent experimental data and the solid line indicates the theoretical laminar prediction.

2.3 Two-phase flow pressure drop

The measured two-phase frictional pressure drop and corresponding void fraction in the Partially Open Mini Channel (POMC) are presented together in Fig. 4 as functions of total superficial velocity, $J = j_G + j_L$. Figure 5(a) shows the frictional pressure drop, while Fig. 5(b) presents the void fraction measured using the impedance method.

As shown in Fig. 4(a), the two-phase pressure drop increases monotonically with increasing total superficial velocity and spans nearly two orders of magnitude within the tested range. However, the slope

of the pressure drop curve depends strongly on the flow regime.

In the bubbly regime, the pressure drop increases approximately linearly with J . The dispersed gas bubbles introduce moderate interfacial shear, and the hydraulic resistance is primarily governed by liquid-phase momentum transport.

In the finely dispersed bubbly regime, the pressure drop becomes noticeably higher despite relatively moderate void fraction values shown in Fig. 4(b). This indicates that geometric interruption enhances local acceleration and interfacial deformation. The elevated pressure drop in this regime is therefore driven more by form drag and shear amplification than by gas holdup magnitude alone.

During the bubbly–slug transitional regime, both pressure drop and void fraction increase simultaneously. The formation and fragmentation of elongated gas structures within sub-channels amplify local momentum redistribution, producing one of the steepest increases in hydraulic resistance.

In fully developed slug flow, the void fraction approaches approximately 0.5–0.6, while the pressure drop remains high. Although large gas structures occupy significant portions of the channel, the pin interruptions prevent full reduction of liquid-wall interaction. Persistent flow separation and contraction–expansion losses maintain elevated frictional resistance. The combined presentation in Fig. 5 demonstrates that in the POMC, pressure drop cannot be interpreted solely based on void fraction magnitude. Instead, the interrupted geometry modifies the coupling between phase distribution, interfacial dynamics, and hydraulic resistance.

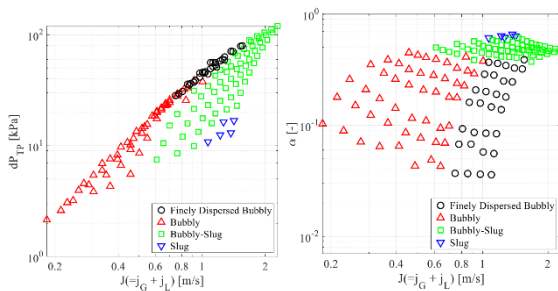


Fig. 5. (a) Two-phase frictional pressure drop and (b) void fraction as functions of total superficial velocity ($J = j_G + j_L$) in the POMC, categorized by flow regime.

3. Conclusions

An experimental investigation was conducted to examine single- and two-phase flow behavior in a pin-interrupted mini-channel under vertical upward air–water conditions. Flow visualization identified four distinct regimes: bubbly, finely dispersed bubbly, bubbly–slug, and slug flow. The interrupted geometry delayed slug formation and broadened the transitional region compared to conventional smooth channels.

Single-phase results revealed early deviation from classical laminar behavior at Reynolds numbers of approximately 800–1000, indicating that geometric disturbance dominates hydrodynamic stability. The friction factor remained significantly higher than theoretical laminar predictions due to contraction–expansion effects and form drag induced by the pin structures.

Under two-phase conditions, the frictional pressure drop increased monotonically with total superficial velocity and exhibited strong regime dependence. The results demonstrate that hydraulic resistance in the POMC cannot be interpreted solely based on void fraction magnitude, as geometry-induced interfacial deformation and momentum redistribution play a critical role.

These findings highlight the importance of accounting for interrupted channel topology when evaluating hydraulic performance in compact heat exchanger applications.

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