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Spectral analysis of pressure drop fluctuations during flow boiling in a microchannel using FFT

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Abstract. This study investigates the dynamic characteristics of pressure drop fluctuations during flow boiling of water through a microchannel using numerical simulation and frequency-domain analysis. Transient pressure data was obtained from simulation of a heated microchannel under constant sidewalls temperature on ANSYS Fluent with static pressure monitored in flow domain. The time-domain signal revealed distinct oscillation patterns associated with successive flow regime transitions, including bubbly, slug, and annular flows. Fast Fourier Transform (FFT) analysis was applied to pressure data using MATLAB to quantify the dominant oscillation frequencies in the pressure drop signal. The spectral results indicated a dominated frequency peak of approximately 10 Hz which corresponded to the estimated slug/bubble passage frequency derived from the time-domain profile. The results demonstrated that frequency-domain analysis provides a quantitative means to characterize microscale boiling dynamics, revealing the relationship between pressure fluctuations, bubble dynamics and flow regime transitions.

Introduction

Flow boiling in microchannels has gained significant attention due to its high heat removal capabilities and compact size, making it ideal for advanced thermal management systems [1]. The main advantage of flow boiling through microchannel is the possibility of achieving high heat transfer coefficients using low coolant flow rates that requires a low pressure drop and consequently reduced pumping power requirements [2].

Pressure drop in microchannel is a vital factor that governs the flow boiling stability in the microchannel [3]. Due to the small hydraulic diameter of micro-channels (10–1000 μm), excessive pressure drop is always a concern. Flow instabilities were proved to cause pressure drop fluctuations and to deteriorate the heat transfer during flow boiling in uniformly heated micro-channels [4]. The hydrodynamic instabilities encountered in two-phase flow include severe pressure drop oscillations and mild channel instability [5]. Flow instabilities encountered in two-phase flow boiling result in pressure drop fluctuation and high amplitude temperature oscillation [6]. For high pressure drop, the nucleation time is reduced, and the bubble is taken downstream, leading to coagulation, which results in flow instability corresponding to critical heat flux condition [7].

Previous investigations into flow boiling have extensively characterized steady-state pressure drops across varying flow conditions. However, transient pressure variations which occur due to sudden phase transitions, bubble nucleation, growth, coalescence, and departure have received comparatively less attention. This gap is crucial, as transient conditions are common in real-world applications where heat loads or flow rates may fluctuate.

In flow boiling through microchannel, pressure drop is influenced by transient evolution of the liquid-vapor interface and regime transition. For a given mass flux, at low exit vapor qualities, the frictional pressure drop increased with flow pattern transition from bubbly flow to slug flow, which resulted in increased two-phase pressure drop [8]. Pressure drop increases after bubble detachment

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from the wall [9]. A 3D unsteady two-phase flow was simulated in a 30 mm long microtube with 0.6 mm diameter using a phase-change model coupled with the Volume of Fluid (VOF) approach. It was observed that initially, bubble detachment driven by evaporation momentum and buoyancy forces accelerates pressure loss. Further downstream, in the confined flow region, frictional forces dominate causing a continued pressure drop [10]. A 3D transient heat transfer analysis and flow visualization study in diverging microchannel was conducted. The Volume of Fluid (VOF) method coupled along with a phase-change model was implemented to study the two-phase flow in diverging microchannels and results were compared with those of straight 2D microchannel. The higher-pressure drop is observed in the diverging channel when compared to the straight channel due to less bubble coalescence and less flow reversal on account of higher inlet pressure in diverging channel [11]. Flow boiling was also numerically investigated for flow patterns in boiling within circular microchannels using VOF method in Ansys Fluent. It was observed that a pressure wave produced by adjacent bubbles transmits in microchannel and influences the bubble lifting off [12]. Another VOF based on three dimensional CFD modeling of flow boiling in microchannels was carried out with nonuniform heat flux. It was found that in two-phase pressure drop, the peaks correspond to instants at which the vapor volume fraction significantly increases and constrains the flow, and the valleys correspond to instants at which a large bubble (confined or plug) exits the domain [13].

A numerical investigation of flow boiling was carried out in interconnected microchannels (IMC) at varying mass fluxes and observed under high mass flux, flow friction resistance is the primary contributor to pressure drop during the initial stage of bubbly flow and later the instability of the two-phase flow is the main factor in the pressure drop. They also found that for IMCs, the greater the number of interconnected channels, the higher the pressure drop will be [14]. A 3D numerical study using the VOF model coupled with Lee model was conducted to investigate the effects of mass and heat flux on two-phase flow boiling in a microchannel. The results showed that pressure drop behavior is closely related to flow regime transitions from bubbly to slug, and slug to annular flow. It was found that initially pressure drop rises sharply as vaporization begins and then stabilizes with time as flow enters into more stable flow regime. Moreover, higher mass and heat fluxes lead to greater pressure drop and increased amplitude of quasi-steady fluctuations [15].

While these numerical studies substantially advance our understanding of pressure drop in flow boiling, few have systematically compared transient pressure fluctuations in different flow boiling regimes and FFT spectral analysis of pressure. Specifically, none combine time-resolved pressure tracking with spectral analysis.

The present study focuses on the transient pressure drop characteristics during flow boiling of water in 2D horizontal rectangular microchannel. Using time-dependent CFD simulations in ANSYS Fluent, this work aims to find the pressure fluctuation trends, quantifying and analyzing their FFT spectral behavior in line with temporal evolution of the flow boiling regimes.

Methodology and Computational Scheme

Geometry. The methodology involves designing and simulation of water flow boiling through a 2D rectangular microchannel with dimensions L=100mm and W=1mm as shown in Fig.1.The geometry is modeled using a commercial software Ansys Fluent. Water is used as a working fluid with inlet temperature 372.15 K and velocity 0.01m/s. To induce heat transfer and boiling, temperature is applied at the two sidewalls with $\triangle T=1K$. Mesh independence analysis showed that mesh with 14,722 cells was chosen as it ensured accuracy with negligible error while saving computational time.

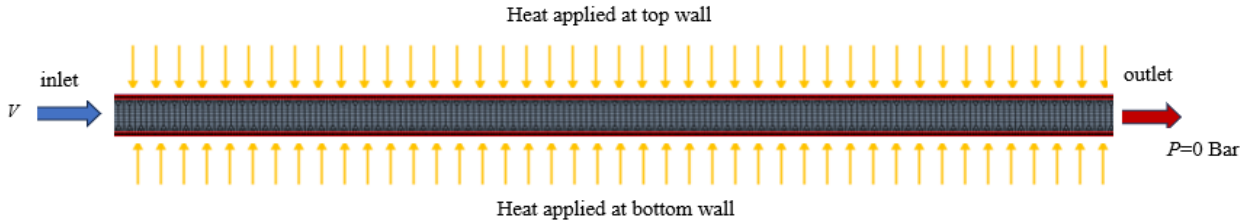


Fig. 1 Geometry of a rectangular microchannel

A Grid independence was carried out using three different grids with number of elements ranging from 1×10^5 to 2×10^5 at a reynolds no. of 20. It is observed that vapor volume fraction 'α_v' decreases with increase in the number of nodes and the percentage relative difference in 'α_v' between mesh 1 and mesh 2 is negligible (less than 1%) as compared to that with mesh 3 shown in Fig. 2. In order to save the computational time, mesh 2 with 147220 number of cells and 161380 nodes is selected to simulate flow boiling for this parametric study

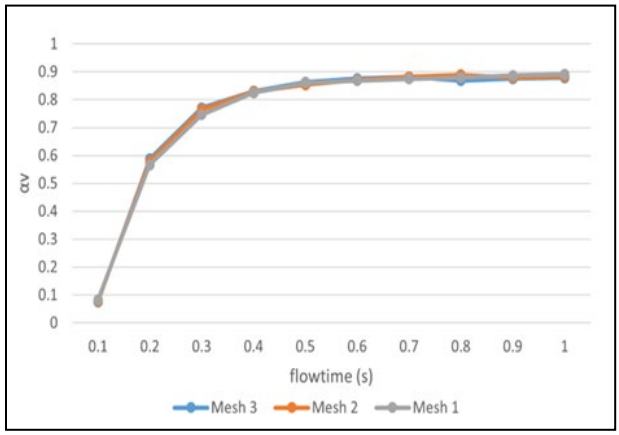


Fig. 2. Grid Independence Study

Computational Scheme. Following options were used as assumptions for computation:

- Incompressible flow with laminar flow regime.
- Multiphase (Two-Phase approach) with 'VOF' model
- Viscous dissipation effects were assumed to be zero

The above simulation methodology for flow boiling through microchannel is validated with the experimental study [16] for flow boiling of water through a single 3D rectangular channel of copper test section1(TS1). The convective heat transfer coefficient is found to be in good agreement with the experimental findings as shown in Fig.3.

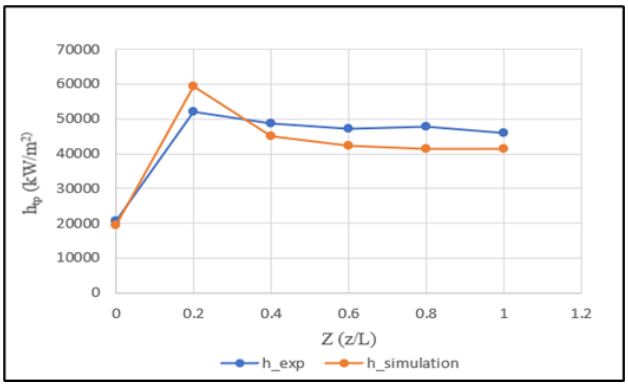


Fig. 3 Model validation study for water flow boiling using two-phase approach

Below given table1 summarizes the computational used in this study.

Table 1. Summary of Computational Scheme

Physics	**Model**
Configuration	2D
Time Analysis	Transient
Materials	Fluid: Water (Liquid & Vapor Phases) ; Solid: Aluminum
Equations	Continuity, Energy and Momentum
Viscous Model	Laminar (Low mass flux)
Multiphase Method	Volume of Fluid (VOF)
Phase Change Model	LEE Model
Surface Tension	CSF model with wall adhesion
Algorithm Scheme	SIMPLE (Semi-implicit method for pressure linked equations)
Discretization Scheme	Second Order Upwind

The convergence criteria for continuity, momentum and energy equations were set at 10^{-6} for residuals to ensure high accuracy of the results. The calculations were conducted under two phase laminar flow conditions to compute pressure drop in flow domain during flow boiling. The results obtained for transient pressure drop were analyzed through FFT spectrum to find out the reasons for variation of pressure signal in flow domain. The simulations were run for 200,000 iterations for 10,000 timesteps of size 10^{-4} s.

Results & Discussion

Pressure Signal Behavior and Flow Regime Evolution. The transient pressure drop contours as shown in Fig. 4 and pressure signal (Fig. 5(a)) obtained from the flow boiling simulation were analyzed to understand the dynamic boiling behavior within the microchannel. As shown in Fig. 5(a), the pressure initially increased sharply, peaking around 0.15–0.2 seconds. This increase is attributed to the onset of boiling (ONB) and rapid vapor generation due to nucleation on the heated walls. The sudden formation and growth of vapor bubbles resulted in localized expansion, leading to a steep pressure rise.

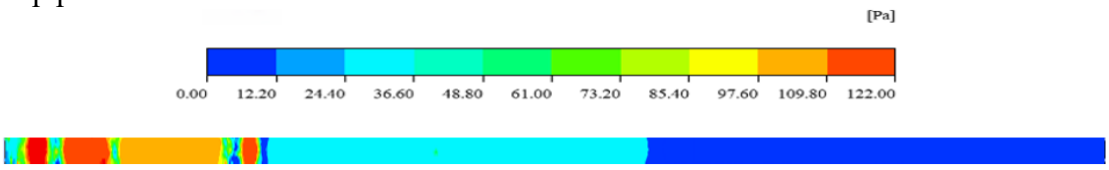


Fig. 4 Pressure Contours, t=1.0s

Following the initial peak, the pressure signal exhibited oscillatory behavior, gradually decaying in amplitude from 0.2 to 0.4 seconds. These oscillations are linked to bubble coalescence, slug formation, and the periodic passage of vapor structures within the microchannel. After 0.5 seconds, the pressure signal reached a quasi-steady state with lower amplitude fluctuations, indicating the development of a more stable two-phase flow regime, likely characterized by elongated slugs or annular flow patterns.

Frequency Domain Analysis via FFT. To identify the dominant frequencies associated with the flow dynamics, a Fast Fourier Transform (FFT) was performed on the pressure data using MATLAB as shown in Fig. 5(b). The frequency spectrum is dominated by components in the 5–15 Hz range with high amplitude, with a pronounced peak near 10 Hz with amplitude of ~440 Pa. This dominant frequency closely corresponds to the estimated slug or elongated bubble passage

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frequency inferred from the time-domain signal in Fig. 5(a), where individual slugs were observed to traverse the domain approximately every 0.1 s. This agreement confirms that the low-frequency oscillations in the pressure signal are directly linked to the periodic generation and detachment of vapor bubbles and transition to slug formation.

The minor spectral peaks in the 20–40 Hz range are also present, likely arising from secondary instabilities such as bubble collapse, intermittent coalescence events, or pressure wave reflections within the channel. Beyond 50 Hz, the spectral amplitude drops significantly, suggesting that high-frequency components are relatively weak and are more likely associated with small-scale turbulence or numerical noise characterizing the development of elongated slug /annular flow.

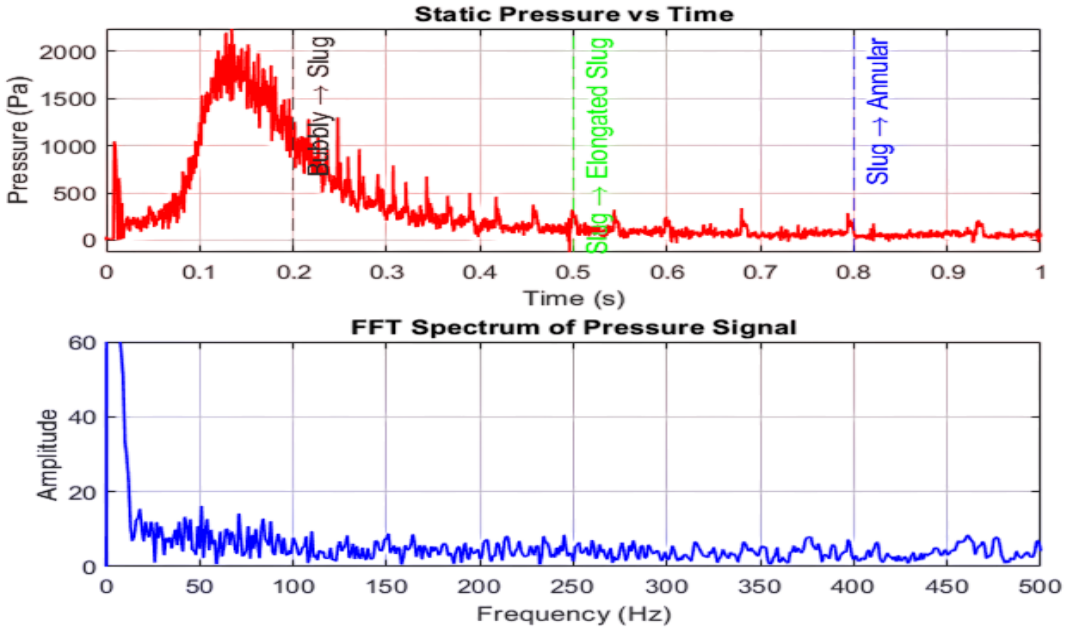


Fig.5. (a) Transient pressure signal (b) FFT frequency-amplitude spectrum

Correlation with Phase Contour Evolution. To correlate the pressure signal with flow regimes, phase contour plots were extracted at multiple time instances (t = 0.2 s to t = 1.0 s), as shown in Fig. 6 provide direct visual evidence. At t = 0.2 s, the flow is dominated by vapor nucleation and early slug formation. By t = 0.3 s, mature slugs are well-developed and spaced along the channel, correlating with high-amplitude pressure oscillations.

As time progresses (t = 0.5–0.8 s), the vapor structures become more elongated and fewer in number, indicating a shift toward elongated slug or annular flow. This regime transition corresponds to the reduced oscillation amplitude observed in the pressure signal and the flattening of the FFT spectrum. Finally, at t = 1.0 s, the vapor phase distribution stabilizes into a quasi-annular regime with uniform spacing and shape, reflecting the establishment of steady flow boiling. The corresponding pressure oscillations are minimal, and the FFT spectrum primarily contains low-frequency content, confirming the stabilized nature of the flow.

The sharp peak in the time-domain pressure at ~0.15 s coincides with the bubbly-to-slug transition seen in the vapor-volume contours. In the frequency domain, the FFT exhibits a dominant low-frequency component near 10 Hz, reflecting the slow, large-scale variation of the signal over the full 1.0s record (i.e., regime-scale dynamics). Time–frequency analysis (spectrogram/windowed FFT) shows that low-frequency energy is strongest during the 0–0.3s transition window and diminishes as the flow approaches slug/annular conditions. Thus, the time-localized event at 0.15 s generates most of the low-frequency content observed in the FFT, while mid-frequency components are associated with bubble-scale activity superimposed on the regime transition.

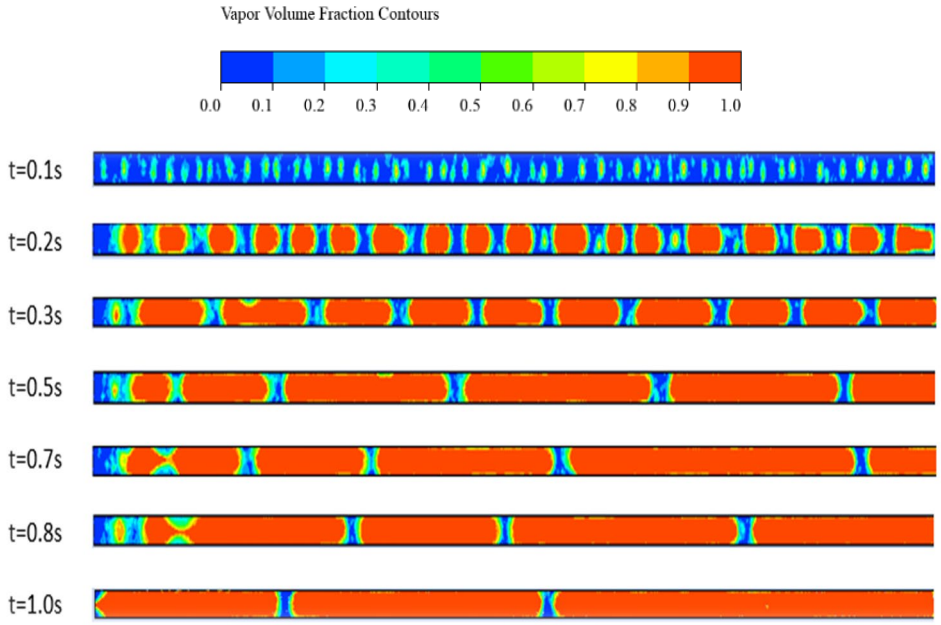


Fig. 6. Vapor volume fractions during flow boiling at different times

Table 2 quantitatively summarizes the peak pressures, fluctuation amplitudes, and dominant frequencies for each flow boiling regime.

Table 2. Summary of key observations for each identified regime.

Regime	Time Range (s)	Peak Pressure (Pa)	Oscillation Amplitude (Pa)	Dominant Frequency (Hz)
Bubbly	0.00–0.20	~2100	±250	~9.5
Slug	0.20–0.50	~1500	±200	~8.0
Elongated Slug	0.50–0.80	~700	±100	~8.2
Annular	0.80–1.00	~300	±50	~8.1

Conclusion

In this study, FFT spectral analysis was done for transient pressure drop in flow boiling through a rectangular microchannel. Computational Fluid Dynamics (CFD) analysis employs a VOF method coupled with phase-change Lee model. The combined pressure-time signal, FFT spectrum, and phase contour visualization offer a coherent understanding of the dynamic boiling process. The results confirm that pressure fluctuations are tightly linked to the evolution of vapor phase within the microchannel. The dominant frequencies identified in the FFT (~10 Hz) are consistent with vapor slug dynamics observed visually. This multimodal approach i.e. combining pressure signal analysis and flow visualization demonstrates a reliable framework for identifying boiling regime transitions in microchannel. The FFT spectral analysis reveals that the dominant low-frequency peak around 10 Hz corresponds to large-scale pressure oscillations during the bubbly-to-slug flow transition, while higher frequencies with lower amplitudes reflect smaller-scale flow dynamics and turbulence in the microchannel. The dominant low-frequency energy at ~10 Hz shows large-scale slug/regime events control pressure behavior, so measures that reduce slug formation or shorten slug residence time will be most effective.

References

[1] Fadi Alnaimat, Khadije El Kadi, Bobby Mathew,CFD investigation of R134a and propane condensation in square microchannel using VOF model: Parametric study using steady state solution, Thermal Science and Engineering Progress, Volume 38,2023. https://doi.org/10.1016/j.tsep.2023.101662

[2] S. Lin, K. Sofiane, J.R.E. Christy, Prospects of confined flow boiling in thermal management of microsystems, Applied Thermal Engineering, Volume 22, Issue 7,2002, Pages 825-837, ISSN 1359-4311. https://doi.org/10.1016/S1359-4311(01)00124-7

[3] Karayiannis, Tassos & Mahmoud, Mohamed. (2016). Flow boiling in microchannels: Fundamentals and applications. Applied Thermal Engineering. https://doi.org/10.1016/j.applthermaleng.2016.08.063

[4] G. Hetsroni, A. Mosyak, Z. Segal, G. Ziskind, A uniform temperature heat sink for cooling of electronic devices, Int. J. Heat Mass Transfer 45 (16) (2002) 3275-3286, ISSN 0017-9310. https://doi.org/10.1016/S0017-9310(02)00048-0

[5] Weilin Qu, Issam Mudawar, Measurement and prediction of pressure drop in two-phase micro-channel heat sinks, International Journal of Heat and Mass Transfer, Volume 46, Issue 15,2003, Pages 2737-2753, ISSN 0017-9310. https://doi.org/10.1016/S0017-9310(03)00044-9

[6] D. Bogojevic, K. Sefiane, A.J. Walton, H. Lin, G. Cummins, Two-phase flow instabilities in a silicon microchannels heat sink, Int. J. Heat Fluid Flow 30 (5) (2009) 854-867. ISSN 0142-727X. https://doi.org/10.1016/j.ijheatfluidflow.2009.03.013

[7] Bogojevic, Dario & Sefiane, Khellil & Walton, Anthony & Lin, Huamao & Cummins, Gerard. (2009). Two-phase flow instabilities in a silicon microchannels heat sink. International Journal of Heat and Fluid Flow. 30. 854-867. 10.1016/j.ijheatfluidflow.2009.03.013. https://doi.org/10.1016/j.ijheatfluidflow.2009.03.013

[8] Liaofei Yin, Peixue Jiang, Ruina Xu, Haowei Hu, Li Jia, Heat transfer and pressure drop characteristics of water flow boiling in open microchannels, International Journal of Heat and Mass Transfer, Volume 137,2019, Pages 204-215, ISSN 0017-9310. https://doi.org/10.1016/j.ijheatmasstransfer.2019.03.108

[9] Jaeseon Lee, Issam Mudawar, Fluid flow and heat transfer characteristics of low temperature two-phase micro-channel heat sinks - Part 2. Subcooled boiling pressure drop and heat transfer, International Journal of Heat and Mass Transfer, Volume 51, Issues 17-18,2008, Pages 4327-4341, ISSN 0017-9310. https://doi.org/10.1016/j.ijheatmasstransfer.2008.02.013

[10] Nishant Tiwari, Manoj Kumar Moharana, Conjugate heat transfer analysis of liquid-vapor two phase flow in a microtube: A numerical investigation, International Journal of Heat and Mass Transfer, Volume 142,2019,118427, ISSN 0017-9310. https://doi.org/10.1016/j.ijheatmasstransfer.2019.07.077

[11] Uday Kumar Alugoju, Satish Kumar Dubey, Arshad Javed,3D Transient heat transfer analysis and flow visualization study in diverging microchannel for instability mitigated two-phase flow:A numerical study, International Journal of Heat and Mass Transfer, Volume 160,2020,120212, ISSN 0017-9310. https://doi.org/10.1016/j.ijheatmasstransfer.2020.120212

[12] Rui Zhuan, Wen Wang, Flow pattern of boiling in micro-channel by numerical simulation, International Journal of Heat and Mass Transfer, Volume 55, Issues 5-6,2012, Pages 1741-1753,ISSN 0017-9310.

[13] Lorenzini, D., and Joshi, Y. K. (August 23, 2017). "Computational Fluid Dynamics Modeling of Flow Boiling in Microchannels with Nonuniform Heat Flux." ASME. J. Heat Transfer. January 2018; 140(1): 011501. https://doi.org/10.1115/1.4037343

[14] Li, Yuanhua & Chen, Zhanxiu & Huhe, Cang & Su, Yao & Xing, Hewei. (2024). Numerical Investigation of Flow Boiling in Interconnected Microchannels at Varying Mass Fluxes. Energies. 17. 1674. 10.3390/en17071674. https://doi.org/10.3390/en17071674

[15] Zhen Huang et al 2023 J. Phys.: Conf. Ser. 2599 012024 https://doi.org/10.1088/1742-6596/2599/1/012024

[16] Özdemir, M. R., Mahmoud, M. M., & Karayiannis, T. G. (2021). Flow boiling of water in a rectangular metallic microchannel. Heat Transfer Engineering, 42(6), 492-516. https://doi.org/10.1080/01457632.2019.1707390