

A Review of Two-Phase Flow Boiling Instabilities in a Vertical Upward Annular Channel

Dongbin Yun^a, Taeseok Kim^{a, b, *}

^aDepartment of Energy Engineering, Jeju National University, Jeju, 63243, Republic of Korea

^bDepartment of Electrical and Energy Engineering, Jeju National University, Jeju, 63243, Republic of Korea

*Corresponding author: tkim@jejunu.ac.kr

***Keywords :** two-phase flow boiling, flow instability, dynamic instability, density wave oscillation

1. Introduction

Two-phase flow boiling provides better heat transfer performance than single-phase convective heat transfer and is therefore used in various thermal-hydraulic systems, including nuclear, aerospace, and refrigeration applications. However, flow instabilities arising during boiling can cause fluctuations in mass flow rate, pressure drop, and wall temperature and, in severe cases, may be associated with mechanical vibration, heated channel damage, and a reduction in critical heat flux. Accordingly, experimental and analytical studies have continuously been conducted to clarify the mechanisms and stability boundaries of two-phase flow instabilities [1].

Li et al. [1] classified two-phase flow boiling instabilities into static and dynamic instabilities based on previous studies and summarized the mechanisms of density wave oscillation (DWO), pressure drop oscillation (PDO), thermal oscillation (TO), and other instability modes. They also reviewed experimental and numerical approaches and identified mass flux, system pressure, heat flux, and inlet subcooling as major influencing parameters, summarizing previous findings for each parameter. Based on this review, they presented active and passive methods for suppressing flow instabilities and suggested directions for future research.

This classification and synthesis provide a useful framework for understanding two-phase flow instabilities. Nevertheless, the individual studies included in the review employed widely different working fluids, channel geometries, flow directions, pressures, and thermal conditions, and even the influence of the same operating parameter varied with the instability type and test conditions. In addition, actual test loops contain pumps and various other components; therefore, it is necessary to distinguish whether measured oscillations originate from flow instability itself or are related to the influence of system components.

Accordingly, this study critically reviews the paper by Li et al. [1] from the perspectives of instability classification, operating parameters, and identification methods and, based on this review, proposes major considerations and experimental directions for two-phase flow boiling instability tests to be conducted in a vertical upward annular channel.

2. Previous Review of Two-Phase Flow Boiling Instabilities

2.1 Classification of instabilities

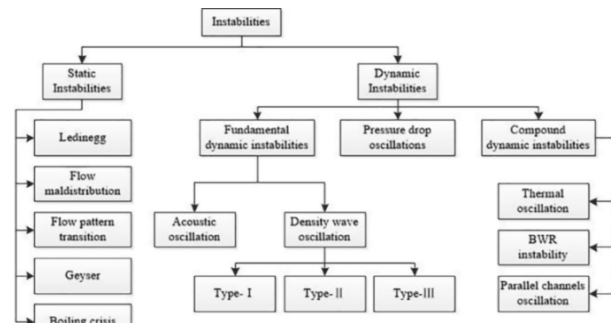


Fig. 1. Classification of flow instabilities (adapted from Li et al. [1])

Li et al. [1] based on the classification proposed by Bouré et al., categorized two-phase flow boiling instabilities according to their temporal behavior into static and dynamic instabilities. Fig. 1 summarizes this classification. Static instabilities include Ledinegg instability, flow maldistribution, flow pattern transition, geyser instability, and boiling crisis (CHF), whereas dynamic instabilities include density wave oscillation (DWO), pressure drop oscillation (PDO), and thermal oscillation (TO). This section focuses on representative instabilities that are highly relevant to the planned experimental conditions and introduces about two-phase flow instabilities.

2.2 Static instabilities

Static instability is described as a phenomenon in which the system moves from an unstable operating point to a different operating point and cannot spontaneously return to its original state [1]. Representative static instabilities include Ledinegg instability, geyser instability, and boiling crisis (CHF), each of which has a different mechanism.

2.2.1 Ledinegg instability

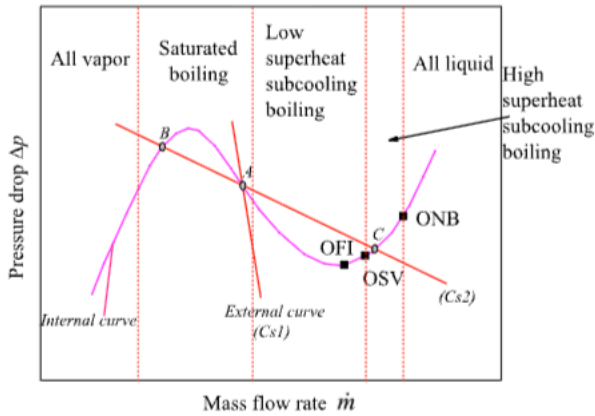


Fig. 2. Hydraulic characteristics for a boiling system (adapted from Li et al. [1])

Ledinegg instability, also referred to as flow excursion, is a representative static instability that occurs when the pressure drop-mass flow rate internal characteristic curve of a heated channel becomes multivalued [1]. As shown in Fig. 2, the internal characteristic curve may exhibit an N-shaped or S-shaped form and includes a negative-slope region in which the pressure drop decreases even as the mass flow rate increases. System stability is determined by the relative slopes of the internal characteristic curve and the external driving system characteristic curve. At an unstable operating point, even a small mass-flow-rate perturbation may cause the system to move to another stable operating point rather than returning to its original state.

In Fig. 2, the external characteristic curve Cs1 intersects the internal characteristic curve at a single stable operating point, whereas Cs2 produces three operating points. The operating point located in the negative-slope region can be unstable to perturbations. Under a fixed driving-pressure condition, the minimum point at which the positive- and negative-slope portions of the internal characteristic curve meet can be used as a criterion for the onset of flow instability (OFI) [1].

2.2.2 Geyser instability

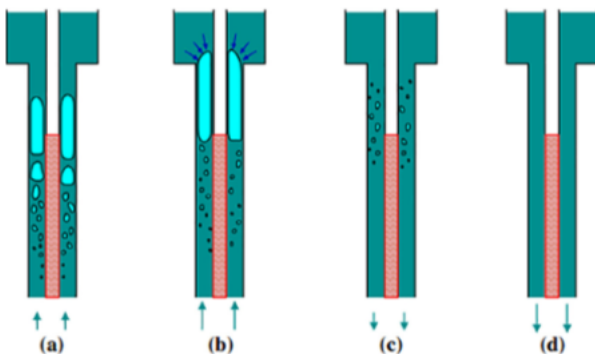


Fig. 3. Geyser instability process (adapted from Li et al. [1])

Geyser instability is mainly observed in liquid-filled tubes under low-pressure and low-heat-flux conditions and is characterized by repeated large-scale vaporization and sudden vapor ejection followed by the reflux of subcooled liquid [1]. During this process, temperature, pressure, mass flow rate, and void fraction can vary periodically with large amplitudes. Li et al. [1] organized the geyser instability process shown in Fig. 3 into four stages: (a) subcooled boiling, (b) flow oscillation, (c) vapor gushing, and (d) reflux cooling.

As vapor accumulates due to heating, flow oscillation and vapor ejection occur. Subcooled liquid then re-enters the channel and cools it, returning the system to its initial state and creating a periodic behavior. Geyser instability has been reported not only in natural circulation systems but also in forced circulation systems and tubes with one closed end, and geometrical parameters such as the length to diameter ratio can influence its occurrence and intensity [1].

2.2.3 Boiling crisis

Li et al. [1] treated boiling crisis, or critical heat flux (CHF), as a static instability because it involves a one-time transition from an unstable state to a new stable state. When boiling crisis occurs, the heated-wall temperature rises sharply, while system pressure and mass flow rate may decrease. If insufficient liquid supply to the wall leads to a vapor-dominated heat-transfer condition, the heat transfer coefficient can decrease substantially, potentially resulting in heated-surface damage or burnout.

Thus, unlike Ledinegg instability or geyser instability, the principal feature of CHF is not repetitive flow oscillation but a rapid transition in the heat-transfer regime accompanied by a sharp wall-temperature rise. Li et al. [1] particularly introduced cases of boiling crisis associated with vapor blockage under small hydraulic diameters and low-pressure conditions.

2.3 Dynamic instabilities

Dynamic instability is described as a sustained oscillatory phenomenon caused by interaction and feedback among system variables such as mass flow rate, pressure, heat flux, and inlet subcooling [1]. In general, mass flow rate, pressure drop, and wall temperature repeatedly vary with characteristic amplitudes and periods.

Fig. 4 shows the pressure drop-mass flow rate characteristic curves and the stable, PDO, DWO, and TO regions observed by Pan et al. [3] at different heat fluxes. Because these instability regions were obtained under the specific experimental conditions of Pan et al. [3], they should not be regarded as universal stability boundaries

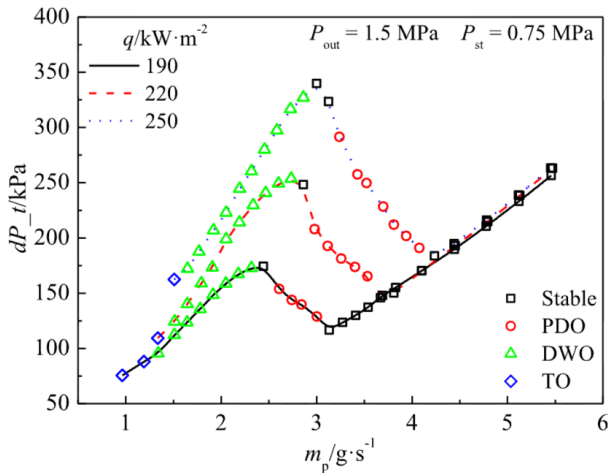


Fig. 4. Oscillation region and pressure drop of the test loop at different heat flux (adapted from Pan et al. [3])

2.3.1 Pressure drop oscillation (PDO)

Pressure drop oscillation (PDO) is a compound dynamic instability associated with Ledinegg instability and is generally reported to occur in the negative-slope region of a multivalued pressure drop – mass flow rate characteristic curve [1]. In Fig. 4, PDO is also mainly distributed in the negative-slope region. PDO typically exhibits relatively large-amplitude and long-period fluctuations in pressure and mass flow rate. Previous studies have reported that the oscillation amplitude increases as the vapor volume in the channel increases, whereas the oscillation period tends to decrease with increasing heat flux [1].

Compressible volume (CV) is also considered an important factor in PDO [1]. Reverse flow can significantly increase the amplitude and frequency of PDO, and studies have reported that pressure and mass-flow-rate variations caused by PDO can trigger DWO or that the two phenomena can overlap [1]. Therefore, PDO should not be identified solely from the presence of a negative-slope region; the existence of CV, oscillation period and amplitude, and the occurrence of reverse flow should also be considered.

2.3.2 Density wave oscillation (DWO)

Density wave oscillation (DWO) is a dynamic instability that mainly appears at low flow rates in the positive-slope region of the pressure drop-mass flow rate characteristic curve and is accompanied by periodic oscillations in mass flow rate, pressure drop, and wall temperature [1]. Fukuda and Kobori [2] classified two-phase flow instabilities based on the dominant pressure drop mechanism, providing the basis for distinguishing different types of DWO.

Type-I DWO is associated with gravitational effects and is mainly observed in vertical upward flow under low-pressure and low mass flux conditions. Type-II

DWO is explained by feedback caused by changes in hydraulic resistance due to nonuniform density in the two-phase region and by the propagation delay of disturbances. Type-III DWO is categorized as a momentum-related mode [1]. Because Type-I and Type-II DWO have different mechanisms, the same change in an operating parameter can have different effects on the two types.

2.3.3 Thermal oscillation (TO)

Thermal oscillation (TO) is described as a phenomenon in which disturbances to the vapor film under film-boiling conditions alter the heat transfer characteristics, causing periodic variations in the heated wall temperature [1]. In Fig. 4, TO is shown as an observation region distinct from PDO and DWO, indicating that different dynamic instabilities may appear on the same pressure drop-mass flow rate characteristic curve. TO is classified into independent thermal oscillation and compound thermal oscillation.

Independent TO is caused by oscillation of the mixture-to-vapor transition point and occurs without accompanying DWO or PDO. In contrast, compound TO is caused by the system and may be superimposed with DWO [1].

3. Research gap in Applying the Existing Review

3.1 Research gap of instability classification and application

The classification and Fig. 1 presented by Li et al. [1] provide useful criteria for distinguishing and understanding the representative mechanisms of individual instabilities. However, there are limitations to uniquely assigning oscillations observed in actual tests to a single instability type. The review also notes that different fundamental instabilities can interact to form a mixing instability. In the results of Park et al. summarized in the review, DWO was superimposed when the mass flow rate changed sharply due to long-period PDO, and the pressure and mass-flow-rate variations caused by PDO could in turn trigger DWO [1].

In addition, as shown in Fig. 4, stable, PDO, DWO, and TO regions can appear adjacent to one another on the pressure-drop– mass-flow-rate characteristic curve, and the observed regions can shift as operating conditions such as heat flux change. The distinction between static and dynamic instabilities is also not absolute under all conditions. Li et al. [1] explained that flow pattern transition instability may show dynamic behavior under certain conditions through repeated transitions. Therefore, identification of an observed phenomenon requires comprehensive consideration of the operating point on the characteristic curve,

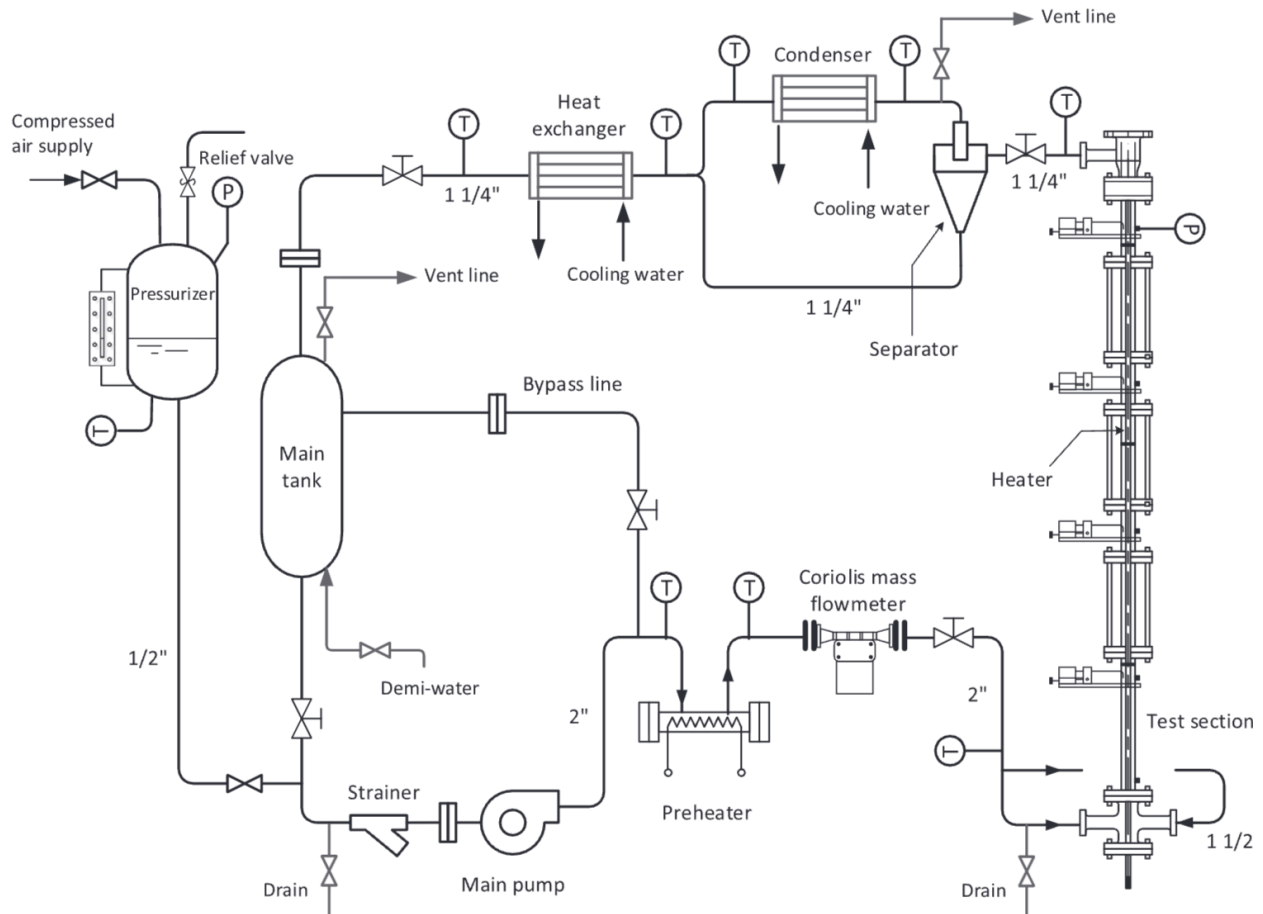


Fig. 5. Schematic diagram of the forced convective boiling test facility at JNU (adapted from Lee et al. [4])

oscillation period and amplitude, simultaneous changes in mass flow rate, pressure, and wall temperature, and system compressibility.

3.2 Research gaps in interpreting influencing parameters

Li et al. [1] identified mass flux, system pressure, heat flux, and inlet subcooling as major influencing parameters and described the overall tendencies that increasing mass flux and system pressure can contribute to stabilization, whereas increasing heat flux can contribute to destabilization. However, the individual studies included in the review used different working fluids, channel sizes, flow directions, natural or forced circulation configurations, and pressure ranges. Therefore, these relationships cannot be applied uniformly to all test systems and all instability modes.

For example, although increasing system pressure generally tends to improve stability, some DWO studies did not show a monotonic decrease in oscillation with increasing pressure. Under different CV conditions, small-amplitude oscillations at 3 MPa converged to stable periodic oscillations, whereas relatively large-amplitude divergent oscillations were reported at 6 MPa [1]. In addition, the results of Pan et al. shown in Fig. 4

indicate that changes in heat flux alter the negative-slope portion of the pressure-drop characteristic curve as well as the distributions of PDO, DWO, and TO. This demonstrates the difficulty of interpreting one operating parameter independently of the other conditions.

The influence of inlet subcooling is likewise not identical for different instability types. In the results of Tang et al., increasing inlet subcooling had opposite effects on Type-I and Type-II DWO, whereas the experiments of Park et al. showed that DWO gradually disappeared as inlet subcooling decreased [1]. Therefore, the effect of an operating parameter should not be interpreted simply as stabilizing or destabilizing but should instead be evaluated in conjunction with the instability type, pressure, heat flux, mass flux, compressible volume (CV), and test-loop geometry.

4. Further research plan of our group

4.1 Test facility

The forced-convective boiling test facility used in this study is based on the experimental loop constructed at Jeju National University and reported by Lee et al. [4]. The facility consists mainly of a main tank, main pump, preheater, Coriolis mass flowmeter, vertical boiling test

section, steam-water separator, condenser, heat exchanger, and pressurizer.

The test section is a vertical concentric annulus with a 30-mm outer tube inner diameter and a 10-mm heater rod diameter. The effective heated length is 2,000 mm [4]. Fluid and wall temperatures, test-section inlet and outlet pressures, pressure drop, and mass flow rate are measured to characterize transient thermal-hydraulic behavior

These components allow the inlet thermal condition and system pressure to be controlled independently while monitoring the thermal-hydraulic response of the test section. In particular, the simultaneous measurements of temperature, pressure, pressure drop, and mass flow rate provide the information required to examine the temporal relationship among variables during oscillatory flow behavior

4.2 Experimental plan and purpose

The present study focuses on an oscillatory phenomenon in which upward flow periodically weakens or temporarily stagnates and subsequently recovers, accompanied by pressure and temperature fluctuations. The objective is to determine whether this behavior is associated with previously reported flow-boiling instabilities such as DWO or PDO or the response of system components.

Once reproducible oscillatory phenomena are identified, their periods, amplitudes, and temporal relationships among the measured thermal-hydraulic variables will be analyzed in detail. The observed characteristics will be compared with previously reported flow-boiling instabilities such as DWO and PDO to determine their possible mechanisms and classification. Because previous experiments using the same facility showed that two-phase flow behavior varies with axial position and operating conditions [4], such changes will also be considered when interpreting the experimentally observed phenomena.

5. Conclusion

This study reviewed the major instabilities occurring in two-phase flow boiling by classifying them into static and dynamic instabilities and examining the mechanisms and principal characteristics of Ledinegg instability, geyser instability, CHF, PDO, DWO, and TO. The literature review indicates that different instabilities can overlap in actual boiling systems and that the effects of major operating parameters such as mass flux, system pressure, heat flux, and inlet subcooling can vary with instability type and test conditions. Therefore, there are limitations to simplifying the influence of each operating parameter into a universal stabilizing or destabilizing tendency.

Based on this literature review, planned experiments using a vertical upward boiling-flow test facility are planned. In the future tests, operating conditions will be varied primarily through changes in test section pressure and inlet subcooling, while mass-flux and heat-flux conditions will also be considered to investigate the characteristics of temperature and pressure fluctuations in the test section. Through these experiments, the occurrence conditions of oscillatory phenomena observed in low-pressure vertical upward boiling flow will be identified, and their relationship to previously reported flow-boiling instabilities will be examined.

REFERENCES

- [1] Chong Li, Xiande Fang, Qiumin Dai, *Two-phase flow boiling instabilities: A review*, *Annals of Nuclear Energy*, Volume 173, 2022, 109099
- [2] FUKUDA, K., & KOBORI, T. (1979). *Classification of Two-Phase Flow Instability by Density Wave Oscillation Model*. *Journal of Nuclear Science and Technology*, 16(2), 95–108. <https://doi.org/10.1080/18811248.1979.9730878>
- [3] Hui Pan, Qincheng Bi, Weiwei Tan, Pengju Yang, Fan Feng, *Dynamic flow instabilities of hydrocarbon fuel in a horizontal heating tube*, *Acta Astronautica*, Volume 185, 2021, Pages 89-101, ISSN 0094-5765
- [4] Yeon-Gun Lee, Il Woong Park, Ji-Woong Yoo, Sin Kim, *Measurement of multi-dimensional distribution of local bubble parameters in a vertical annulus under subcooled boiling conditions*, *International Journal of Heat and Mass Transfer*, Volume 140, 2019, Pages