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Review of two-phase flow instabilities in macro- and micro-channel systems

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ABSTRACT

Study of two-phase flow instabilities began in the late 1920's, and in the nearly 100 years since, significant progress has been made in both experimental and theoretical understanding of them. Despite these advances, many key deficiencies remain, solution of which will provide appreciable value for system designers looking to leverage phase change heat transfer technologies in a safe and repeatable manner. The present review provides a systematic overview of all key two-phase instabilities focusing on the fundamental mechanisms leading to their occurrence. Emphasis is placed on how these mechanisms may change depending on whether flow may be classified as macro- or micro-channel, particularly relevant due to the modern proliferation of parallel micro-channel heat sinks. Extensive literature surveys are performed for each instability type, and strengths and weaknesses of existing literature assessed. Focus is placed on providing recommendations for future work based on the status of current literature. Important takeaways include the significant mechanistic differences for Density Wave Oscillations and Parallel Channel Instability between macro- and micro-channels, the need for better understanding of the role of parallel micro-channels on external pressure curves (impacting Ledinegg instability and Pressure Drop Oscillations), and the influence of size and position of compressible volume on Pressure Drop Oscillations.

1. Introduction

1.1. Phase change heat transfer and multiphase flow

Engineers and scientists worldwide are transitioning away from traditional single-phase heat transfer systems towards those utilizing phase change due to orders-of-magnitude improvement in both heat transfer coefficient and thermal transport capacity. These improvements have allowed innovative advancements in thermal management and transport solutions across industries including electronics thermal management, nuclear power, and heating, ventilation, air-conditioning, and refrigeration (HVAC&R) [1,2].

Along with these advantages in performance have come challenges associated with accurate prediction of important design parameters including critical heat flux (CHF), heat transfer coefficient, and pressure drop, each necessitating detailed investigation. Numerous studies have been conducted on boiling in a variety of configurations including pool boiling [3,4], flow boiling in macro- [5-10] and micro-channels [11-18], jet impingement [19,20], spray cooling [21-25], and hybrid schemes involving multiple approaches [26,27]. Similarly, condensation configurations include falling film [28-30], flow through single mini-channels [31-38], flow through parallel micro-channel arrays [39-44], and dropwise condensation [45-47].

Despite the proliferation of studies investigating boiling and condensation heat transfer (as well as numerous on multiphase flow without phase change), one area of deficiency in existing literature is multiphase instabilities and dynamic behavior. Whether brought on by boiling (or any mode of phase change) within the system or inherent to multiphase flow, there are numerous different instability modes that may manifest depending on operating conditions.

1.2. Study of two-phase flow instabilities

The study of two-phase flow instabilities is relevant to engineers and scientists in all fields encountering phase change heat transfer and multiphase flow. Often adopted for their superior transport (heat and/or mass) capabilities, systems relying on multiphase flow are prone to several unique modes of instability. These may render some combinations of operating conditions unachievable or lead to significant oscillatory behavior in others, which may

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Nomenclature

A	area; amplitude
Bo	Bond number
c_p	specific heat at constant pressure
Co	confinement number
D	diameter
$Eö$	Eötvös number
Eu	Euler number
f	friction factor; frequency
F	force
Fr	Froude number
G	mass velocity
g	Earth's gravitational constant
h	enthalpy
H	height
h_{fg}	latent heat of vaporization
I	inertia
j	superficial velocity
k	conductivity
K	restriction coefficient
K_{orf}	inlet orifice loss coefficient
L	length
$\dot{m}$	mass flowrate
N_{pch}	phase change number
N_{sub}	subcooling number
Nu	Nusselt number
p	perimeter
P	pressure
P_R	reduced pressure
Pe	Peclet number
Pr	Prandtl number
q''	heat flux
Q	total heat transfer
R	temperature ratio (OFI correlation); force ratio (DWOs in micro-channels)
Re	Reynolds number
St	Stanton number
T	temperature
t	time
U	velocity
v	specific volume
W	width
We	Weber number
x_e	thermodynamic equilibrium quality

Greek symbol

α	void fraction; channel inclination
δ	indicates a perturbation
Γ	mass flowrate
Λ	friction number
μ	dynamic viscosity
η	correlation constant
ρ	density
σ	surface tension

Subscripts

0-n	indicates a time span ($t = 0$ to $t = n$)
c	channel (ΔT_c); cross sectional (area)
cap	capillary
f	saturated liquid
fdb	fully-developed boiling
fg	liquid-vapor (commonly for mass transfer due to phase change)
g	saturated vapor
h	hydraulic (diameter)
H	heated (length, diameter)
in	inlet
n	axial measurement station ($n = 0 - 11$)
out	outlet
res	reservoir
sat	saturation
tran	transition
w	wetted (perimeter)

Acronyms

CHF	critical heat flux
CTI	charge transition instability
DWO	density wave oscillations
FECV	flow expansion with compressible volume
OFI	onset of flow instability
ONB	onset of nucleate boiling
OSV	onset of significant vapor
PCI	parallel channel instability
PDO	pressure drop oscillations

adversely affect system performance and safety. As such, knowledge and understanding of different instability modes and the conditions under which they are encountered is critical to design and operation of multiphase flow systems.

Prior reviews on the field of two-phase flow instabilities provide overviews on state-of-the-art (at the time the review was written) understanding of instabilities. One of the earliest and most influential of these was prepared by Boure et al. [48]. They structured their review around an important distinction between *Static Instabilities*, which involve departure from one unstable operating condition to a new, stable operating condition, and *Dynamic Instabilities*, which involve feedback between competing influences on flow (i.e., body force, void fraction, flowrate) and lead to periodic fluctuations around a near-constant operating point. They also provided guidelines on expected frequencies for different dynamic instabilities that contributed to a proliferation of frequency-based analysis by current researchers leveraging more advanced data acquisition and signal processing capabilities.

Many other reviews in the interim have served to provide updated summaries on literature regarding two-phase flow instabilities, both for general instability analysis [49-53] as well as those focused on a specific instability mode [54], and instabilities in nuclear power systems [55-57], refrigeration systems [58], and parallel micro-channel heat sinks [59,60]. Despite these works seeking to provide updated, unified analysis of existing instability literature, significant disagreement remains in modern literature regarding how to properly classify unstable behavior observed during experimentation or practical implementation.

In particular, much work remains to rectify the classical approach developed in macro-scale systems (often associated with nuclear reactor design and commonly neglected small-scale effects such as growth of individual bubbles) with phenomena observed in micro-scale systems (particularly parallel micro-channel heat sinks). As this is a major focus of the current work, a brief explanation of key differences between mini/macro-scale and micro-scale systems will be provided in the following subsection.

1.3. Classification of mini/macro- and micro-scale systems

With advances in manufacturing capabilities and increasing adoption of two-phase flow thermal management for electronics has come the increasing popularity of micro-channels and parallel micro-channel heat sinks. Significant reductions to hydraulic diameter and inclusion of multiple flow passages allow micro-channel heat sinks to offer superior heat transfer performance compared to traditional, macro-channel systems with the same footprint. This reduction in channel diameter, however, can lead to differences in key two-phase flow mechanisms as compared to macro-channel systems. These differences are important for thermal, hydraulic, and stability reasons, so it is critical to be able to distinguish whether a given set of operating conditions will behave as a 'macro-channel system' or a 'micro-channel system'.

Parameters most commonly used to distinguish between mini/macro- and micro-channel systems are confinement number,

$$Co = \frac{1}{D_h}\sqrt{\frac{\sigma}{g\left(\rho_f - \rho_g\right)}}, \tag{1}$$

Bond number,

$$Bo = \frac{g\left(\rho_f - \rho_g\right)D_h^2}{\sigma}, \tag{2}$$

Eötvös number,

$$E\ddot{o} = \frac{g\left(\rho_f - \rho_g\right)D_h^2}{8\sigma}, \tag{3}$$

and capillary length,

$$L_{cap} = \sqrt{\frac{\sigma}{g\left(\rho_f - \rho_g\right)}}. \tag{4}$$

As pointed out by Ong and Thome [61], Eq.'s (1) – (3) are all related to one another by the relationship

$$E\ddot{o} = \frac{Bo}{8} = \frac{1}{8Co^2}, \tag{5}$$

and it is also clear capillary length L_{cap} is present in each dimensionless group. They decided to express their own transition criteria and that of Kew and Cornwell [62], Brauner and Ullmann [63], and Li and Wang [64] in terms of confinement number to offer a unified summary of transition criteria present in the literature. Transition criteria listed above, as well as others found in available literature, are provided in Table 1.

A general conclusion which may be drawn from analysis of the transition criteria in Table 1 is that a micro-channel is defined as a system where capillary length L_{cap} is approximately equal to the hydraulic diameter (resulting in $Co \sim 1$). This makes intuitive physical sense, as the capillary length is often used as a characteristic length associated with bubble formation (Taylor wavelength in Rayleigh-Taylor instability), meaning experimental setups with $Co \sim 1$ produce bubbles of a size similar to that of the channel cross-section. This leads to fundamental differences compared with traditional mini/macro systems, where bubbles are appreciably smaller than the channel, and liquid displacement due to nucleation is a much less appreciable phenomenon as compared to micro-channels.

This definition is not necessarily apt for flow condensation, however, where bubble dynamics are significantly different than for flow boiling. The only criterion in Table 1 defined based on condensation data is that of Li and Wang [64], and it shows a stringent value of $D_h < L_{cap}/4.46$ for transition to micro-channel flow. This transition for flow condensation warrants investigation in future work.

Fig. 1(a) and (b) provide samples of transition criteria for flow boiling and flow condensation, respectively, plotted as diameter versus reduced pressure for FC-72, water, and R134a. Superimposed on each plot are representative operating conditions taken from many commonly cited flow boiling and flow condensation works to give a feel for how different setups may be classified as mini/macro- or micro-channel depending on working fluid and operating pressure.

Fig. 1(c) also provides a sample of differences between observed behavior near the transition between macro- and micro-channels for both water and FC-72 (adapted from Mukherjee and Mudawar [16]). Visualization images show the significantly large size of bubbles formed using water as compared to FC-72, explaining its propensity to perform as a micro-channel for larger diameters where FC-72 will exhibit macro-channel behavior.

For the sake of the current study, it is sufficient to recognize there are fundamental differences between macro-channel flows and those in micro-channels, largely attributable to the relative sizes of capillary length and hydraulic diameter. Discussion of the influence of channel classification on the mechanisms behind formation and propagation of various instability modes will be discussed at length in later sections.

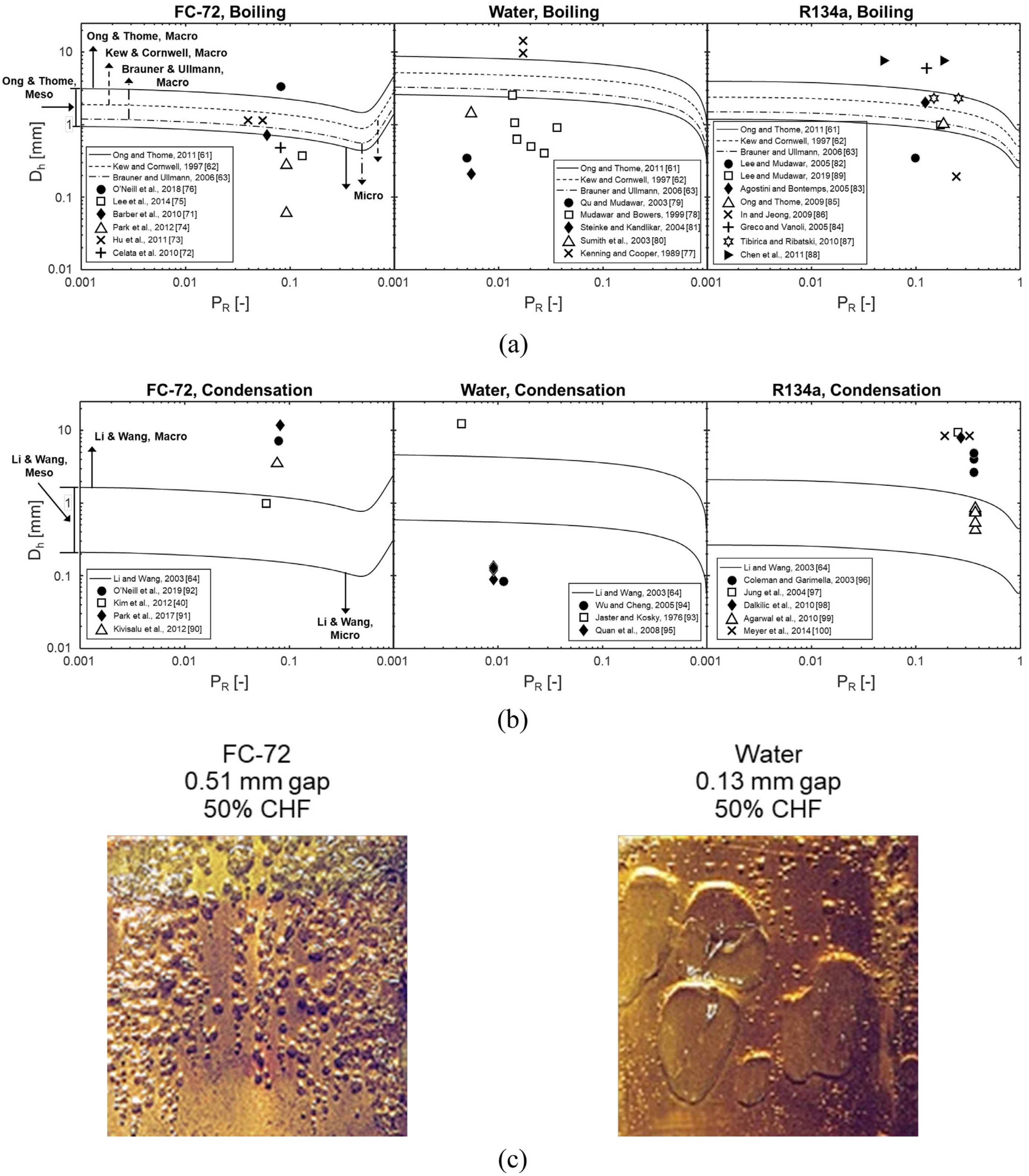
1.4. Objectives of the present review

The present review aims to present a comprehensive summary of literature dealing with two-phase flow instabilities and dynamic behavior. Efforts will be focused on providing a fundamental, physics-based description of all key instabilities prior to detailing relevant studies concerning each instability mode. Special emphasis will be placed on presenting works which display relevant theoretical work (i.e., modeling) alongside experimental results, and focus will be placed on examining similarities and differences between manifestation of instability modes in macro- and micro-channel systems. Methods for suppressing and avoiding instabilities will also be highlighted, focusing on how modifications to the system and knowledge of operating boundaries may enable instability mitigation.

Basic structure of the review will be based on that used by Boure et al. [48] in their seminal work: namely, dividing the field of study into *Static* and *Dynamic* instabilities. These two broad categories will be further subdivided by key instability types, with an additional section provided for detailed summary of the field. Table 2 provides an overview of the structure described here, with brief notes on each instability type provided.

The present review is one in a recent series prepared by the Purdue University Boiling and Two-Phase Flow Laboratory (PU-BTPFL) covering a broad spectrum of fundamental topics in boiling and condensation. Topics include predictive tools for flow boiling and flow condensation pressure drop and heat transfer [101,102], CHF in microgravity [103] and general microgravity boiling and condensation [104], flow boiling critical flow and dryout [105], computational studies on boiling and condensation [106], droplet impact on liquid films and heated walls [107,108], spray cooling [109,110], pool boiling CHF [111,112], pool boiling enhancement via additives and surface modification [113,114], and flow boiling enhancement via nanofluids and surface modification [115,116]. These studies all provide descriptions of associated fundamental physical processes and summarize key works investigating each topic and serve as excellent starting points for delving into boiling and condensation.

It should also be noted that a primary motivation for investigation into two-phase flow instabilities by the present authors is the upcoming Flow Boiling and Condensation Experiment (FBCE). A collaborative effort between the Purdue University Boiling and Two-Phase Flow Laboratory (PU-BTPFL) and NASA Glenn Research Center, FBCE will place a test bed on the International Space Station (ISS) capable of gathering long-duration microgravity flow boiling and condensation results. In addition to its key aim of exploring the impact of body force effects on flow boiling CHF (to augment prior work at multiple orientations in 1-g [117,118] and in parabolic flight [119]), it will also offer the possibility of explor-



(a)

(b)

(c)

Fig. 1. Plots of channel hydraulic diameter and reduced pressure representing operating conditions for many common studies on (a) flow boiling and (b) flow condensation with FC-72, water, and R134a as working fluids. Mini/macro-to-micro channel transition criteria of Ong and Thome [61], Kew and Cornwell [62], Brauner and Ullmann [63] are superimposed with boiling studies, while that of Li and Wang [64] is superimposed for condensation studies. Provided in (c) are flow visualization images highlighting differences between macro- to micro-channel transition for FC-72 and water (adapted from Mukherjee and Mudawar [16]). (See inset of each plot [71–100]).

Table 1
Mini/macro- to micro-channel transition criteria.

Study	Transition Criteria	Notes
Kew & Cornwell, 1997 [62]	$Co > 0.5$ for microscale $Co < 0.5$ for macroscale	Early transition criteria, state if hydraulic diameter is less than half the capillary length, flow is confined (micro-channel), more than half, flow is not confined (mini/macro-channel).
Triplett et al., 1999 [65]	$Co > 1$ for microscale $Co < 1$ for macroscale	Similar to Kew and Cornwell [62], but transition point is taken to be $Co = 1$. This criterion is omitted here as it is the same as the upper limit of Ong and Thome [61].
Li &Wang, 2003 [64]	$Co > 4.46$ for microscale $4.46 > Co > 0.57$ for transition $Co < 0.57$ for macroscale	The first authors to include a 'transition region' (later referred to as meso–scale by Ong and Thome [61]) between micro-channel (confined) behavior and mini/macro-channel (non-confined). Based their criteria on condensation data.
Kandlikar & Grande, 2003 [66]	$D_h >$ 3 mm for macroscale 3 mm $\geq D_h >$ 0.2 mm for miniscale 0.2 mm $\geq D_h >$ 10 μm for microscale 10 μm $\geq D_h >$ 1 μm for transitional microscale 1 μm $\geq D_h >$ 0.1 μm for transitional nanoscale 0.1 μm $\geq D_h$ for nanoscale	Does not take fluid properties into account making it less applicable than alternatives. Based loosely on Knudsen number (molecular mean-free path divided by hydraulic diameter).
Brauner & Ullmann, 2006 [63]	$Co > 0.79$ for microscale $Co < 0.79$ for macroscale	Similar to Kew and Cornwell [62], but transition point $Co = 0.79$ is used.
Cheng & Wu, 2006 [67]	$Co >$ 4.472 for microscale 4.472 $> Co >$ 0.577 for transition $Co <$ 0.577 for macroscale	Included a meso–scale transition region between $Co \langle 4.472$ and $Co \rangle 0.577$. Compared to later relationships, offers a much more stringent confinement number relationship for microscale phenomenon.
Harirchian & Garimella, 2010 [68]	Convective Confinement Number' $Bo^{0.5}\mathrm{Re}_f = \frac{\mathrm{Re}_f}{Co} = (\frac{g(\rho_f-\rho_g)}{\sigma})^{0.5}\frac{GD_h^2}{\mu_f}$ $Re_f / Co < 160$ for microscale $Re_f / Co > 160$ for macroscale	Attempted to incorporate flow inertia into a confinement criterion, but has the implication all low velocity flows are well described by assuming confined flow (this is not true). Omitted from current analysis.
Ong & Thome, 2011 [61]	$Co > 1$ for microscale $1 > Co > \sim 0.3–0.4$ for transition $Co < \sim 0.3–0.4$ for macroscale	Found a meso–scale transition region between $Co \langle 1$ and $Co \rangle \sim 0.3–0.4$ where flow is not well described by macroscale phenomena but is not fully confined either.
Mudawar 2011 [69]	Used Webber number instead of Confinement: $We_{tran} = \frac{160}{9}\frac{1}{(1+\frac{160}{3\mathrm{Re}_{tran}})}$ or $D_{tran} = \frac{160}{9}\frac{(\sigma\rho_f - 3\mu_f G)}{G^2}$	Defined transition from mini/macro-channel to micro-channel in terms of surface tension and flow inertia (neglecting body force). Derivation based on equating liquid drag force on bubble to surface tension force on the same.
Tribica & Ribatski, 2015 [70]	Modified Confinement Number $Co{*} = Co\sqrt{8\cos(\theta_f)}$ $Co^* >$ 1 for microscale $Co^* <$1 for macroscale	Modified characteristic length scale by multiplication with contact angle θ_f. Difficult to evaluate dynamic contact angle as a function of operating conditions, omitted here.

ing both boiling and condensation instabilities in the absence of gravity.

2. Static instabilities

As mentioned in the preceding section, *Static Instabilities* are commonly characterized as a single-event departure from one unstable operating condition to a new, distinctly different operating condition. Important to note here is the key distinction between *Static* and *Dynamic* instabilities: Namely, *Static Instabilities* are best represented as a one-time departure from operating conditions *A* to a distinctly different set of conditions *B* in response to an incremental perturbation at point *A*.

To best illustrate the nature of *Static Instabilities* it is helpful to first discuss Critical Heat Flux (CHF, also referred to as Boiling Crisis). This commonly investigated facet of all boiling systems (flow boiling, pool boiling, *etc.*) is in fact a *Static Instability*.

2.1. Critical heat flux (CHF)

Arguably the most studied aspect of boiling, CHF is commonly described as a rapid, unstable rise in heated wall temperature once vapor production becomes so vigorous as to prevent liquid contact with the heated surface. For lower heat flux values, nucleate boiling is the dominant heat transfer mechanism, but, as CHF is approached, vapor production becomes more vigorous and liquid access to the heated surface becomes restricted.

Just prior to CHF, a minimal amount of liquid accesses the heated wall and boiling is still the dominant mechanism for energy removal. A slight increase in heat flux at this point causes the onset of the CHF transient, however, where vapor production entirely occludes liquid access to the heated wall and the wall temperature rises rapidly (as the dominant heat transfer mechanism is now single-phase convection of vapor at the wall, possessing a much smaller heat transfer coefficient than boiling). It is this one-time transition from an unstable operating point to a new, stable operating condition which leads to CHF's classification as a static instability.

At the new, stable operating condition after CHF, wall superheat (defined as the difference between wall temperature and local saturation temperature) may be several hundred degrees. This often leads to material failure and is almost never a desired operating point for systems employing phase change heat transfer. Due to these adverse conditions, significant research efforts have focused on predicting CHF in a variety of boiling configurations spanning both macro- and micro-channel length-scales, and it is considered a subfield of phase change heat transfer separate from instabilities and dynamic behavior. As such, additional space will not be devoted to it here, but, for those interested, studies by Liang and Mudawar [111,112] are recommended for review of pool boiling CHF mechanisms and predictive tools, those by Boyd [120] and Konishi and Mudawar [103] for flow boiling CHF, Liang and Mudawar [110] for spray cooling CHF, and Wolf et al. [121] for jet impingement CHF.

Table 2
Key topics in two-phase flow instabilities and dynamic behavior.

Type	Brief Description	Key Characteristics	Present in:
Static Instabilities			
Critical Heat Flux (CHF), 2.1	Also called boiling crisis, occurs when vapor production occludes liquid access to a heated wall.	Rapid, unstable temperature rise, commonly spanning an order of magnitude. May lead to heater burnout and/or other material failure.	All boiling configurations (flow, pool, spray, *etc.*).
Ledinegg Instability, 2.2	Also called flow excursion or excursive instability, occurs when slope of pump pressure versus flowrate curve is greater than that of system internal characteristic curve.	Significant, single-event increase or decrease in flowrate to stable system operating point. Decrease may lead to CHF.	Flow boiling only.
Boiling Curve Hysteresis, 2.3	For testing with low contact angle fluid/surface combinations and all other conditions held constant, increasing vsersus decreasing heat flux leads to different boiling curves, primarily near the boiling incipience point.	Initial onset of nucleation requires a higher heat flux than deactivation of nucleation sites.	All boiling configurations.
Vapor Burst, 2.3	For well de-gassed, low contact angle fluids, onset of boiling may involve significant pressure 'shock' within the system.	Amplitude of pressure spike depends on volume of system relative to that of newly produced vapor.	All boiling configurations.
Flow Pattern Transition Instability, 2.4	Operating near a boundary between dissimilar flow regimes allows the possibility of transition from one to the other for a small change in operating conditions, leading to (potentially) significant differences in pressure drop and heat transfer.	Commonly classified as a static instability, it is also possible for it to manifest in dynamic fashion (repeated, cyclical transition between regimes).	Flow boiling and flow condensation.
Dynamic Instabilities			
Density Wave Oscillation (DWO), 3.1	Also referred to as Density Wave Instability (DWI). Results from unstable feedback mechanisms present in multiphase flows. For macro-channels, this relates to relative magnitude of single- and two-phase pressure drop (which oscillate out of phase). For micro-channels, this is due to rapid expansion of confined bubbles towards the inlet.	These typically have periods of oscillation on the order of 1–2 times liquid transit time through the flow channel. They most commonly occur on positive-slope regions of the internal characteristic curve. Many different factors may lead to their occurrence depending on operating conditions and orientation.	Flow boiling and flow condensation.
Parallel Channel Instability (PCI), 3.2	Static mode (Flow Maldistribution) is Ledinegg instability, dynamic mode results from interacting DWOs in channels. More likely to lead to backflow compared to single-channel DWOs due to presence of parallel flow paths. Also, mechanistically different in micro- versus macro-channels.	As the fundamental mechanism is DWOs, many parametric trends for onset and characteristics are the same as those outlined in Section 3.1. In parallel micro-channel heat sinks, usually manifest as oscillations in inlet pressure but not outlet.	Flow boiling and flow condensation.
Pressure Drop Oscillation (PDO), 3.3	Occurs when operating on negative-slope portion of internal characteristic curve with a compressible volume (e.g., surge tank) present in the system.	Flowrate and pressure oscillate 180° out-of-phase. Period of oscillation is typically long compared to other oscillatory phenomena, amplitudes are large.	Flow boiling only.
Acoustic Oscillation, 3.4	Usually generated by vapor bubble collapse in subcooled flow boiling, liquid droplet impingement on liquid films, and presence of rotating machinery in two-phase flow loops.	Generally used as a catch-all term for high-frequency (~ 20 – 10,000 Hz) oscillations observed during two-phase flow. Amplitude of oscillations is typically low.	Flow boiling and flow condensation.
Other Reported Dynamic Behavior, 3.5	*Bumping, geysering, chugging, flashing,* and *thermal oscillations*	*Bumping* and *geysering* are unique instabilities occurring only in very specific situations. *Chugging* is largely a misnomer. *Flashing* is not an instability, but its occurrence may impact manifestation of instabilities. *Thermal oscillations* usually occur as a part of or result of other dynamic instabilities, and are important in thermal management applications.	*Bumping* and *geysering* are boiling only. *Chugging, flashing,* and *thermal oscillations* may occur in boiling or condensation.

It should be noted that CHF discussed in this section is intended to describe 'classic' CHF, not CHF brought on by other instability modes. CHF induced by other instabilities present in the system will be treated separately later in this review.

2.2. Ledinegg (excursive) instability

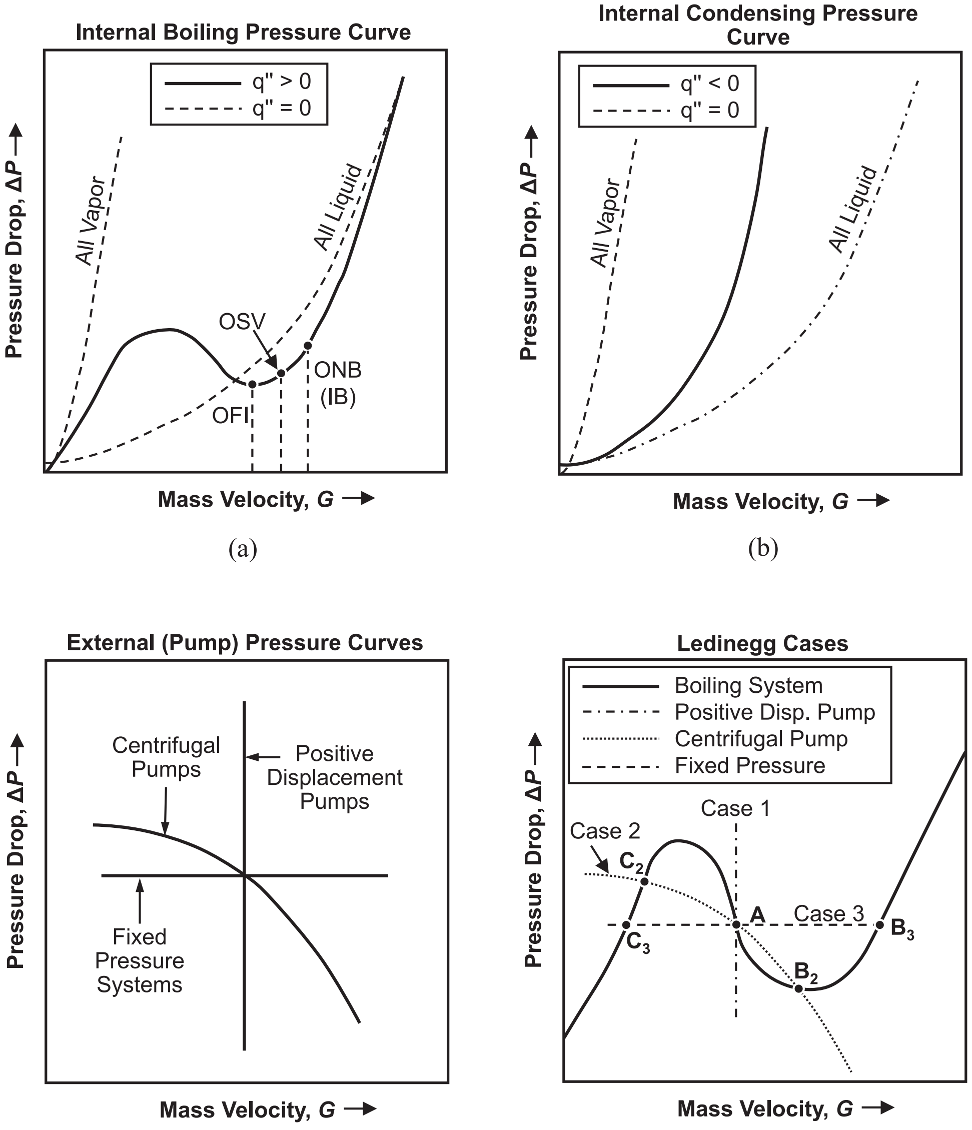
Prior to discussing Ledinegg instability (also referred to as Flow Excursion Instability or Excursive Instability) it is useful to first provide discussion on internal and external characteristic pressure curves. These are relevant to understanding Ledinegg instability and will also be referred to when discussing later instability modes.

Also, it is worth noting that as Ledinegg instability is a system level instability, its behavior is near-identical in two-phase flow systems employing either traditional macro-channels or micro-channels. Some commentary will be provided at the end of this section discussing potential differences for micro-channel systems, although this warrants further investigation.

As a general guideline, 'system-level' instabilities are those relating to interaction between one or more components (i.e. evaporator(s), condenser(s), compressible volume(s)) within a two-phase system. Examples of system level instabilities are Ledinegg instability and pressure drop oscillations (PDOs). 'Device-level' instabilities are those resulting from local phenomena present in evaporators and/or condensers, such as density wave oscillations (DWOs).

2.2.1. Characteristic pressure curves

Used in analysis of stability for flow boiling and flow condensation systems, characteristic pressure curves indicate how pressure responds to changes in flowrate when other operating conditions are fixed. Two-phase flow instability researchers typically refer to two key pressure characteristic curves: That of the flow loop (primarily the test section), referred to as an *Internal Pressure Characteristic Curve*, and that of the external, driving force for the flow loop as seen by the test section, referred to as an *External Pressure Characteristic Curve*. It is the intersection of these internal and external curves that determines whether a given operating point is



(a) (b)

(c) (d)

Fig. 2. Pressure versus mass velocity characteristic curves for (a) flow boiling (internal characteristic, $q'' > 0$, (b) flow condensation (internal characteristic, $q'' < 0$, (c) different pump types (external characteristic), and (d) sample cases for describing existence/non-existence of Ledinegg instability with (1) positive displacement pump, (2) centrifugal pump, and (3) fixed pressure drop boundary condition.

stable or if it will experience an excursion (Ledinegg instability) to a stable operating point.

Fig. 2(a), (b), and (c) provide qualitative depictions of internal pressure curves for boiling and condensation, and external pressure curves for different types of systems, respectively. Fig. 2(a), corresponding to an internal characteristic curve for a boiling test section, is easiest to interpret by moving from right to left. For a fixed, nonzero heat flux, very high mass velocities will exhibit no boiling behavior, and pressure drop will be near-identical to that for single-phase liquid flow. As mass velocity decreases, boiling begins to occur, pressure drop behavior begins to deviate from that for single-phase flow, and several key points are encountered: *Onset of Nucleate Boiling (ONB), Onset of Significant Vapor/Void (OSV),* and *Onset of Flow Instability (OFI)*. The ONB point is self-explanatory, the OFI point is defined as the local minimum in the pressure drop versus flowrate curve, and OSV has a varying definition but always falls between ONB and OFI. The implications of these locations for system stability analysis will be discussed further in later subsections.

As mass velocity is reduced further in Fig. 2(a), pressure drop begins to increase due to added body force and acceleration effects present in two-phase flows. Past a point, however, pressure drop begins to decrease again, as void fraction is sufficiently large that flow begins to approximate that of single-phase vapor within much of the channel.

It is the negative slope region of Fig. 2(a) that differentiates boiling flows from those for single-phase liquid and vapor, and well as condensing flows as shown in Fig. 2(b). In all other cases, internal pressure drop exhibits a monotonic increase with flowrate, and it is the presence of this region of decreasing pressure drop with increasing flowrate that may lead to Ledinegg instability.

It is not enough to simply analyze the system internal pressure characteristics, however, as external pressure is equally important in determining whether a system will be prone to Ledinegg instability. Fig. 2(c) shows pressure curves for the three most common types of two-phase flow system 'drivers': *Positive Displacement Pumps* (i.e., gear pumps), *Centrifugal Pumps,* and *Fixed Pressure Systems* (i.e., those with many parallel tubes between inlet and exit manifolds).

Positive Displacement Pumps are shown as having a near-infinite negative slope on pressure drop versus flowrate curves. This is due to the fact they operate by displacing a finite volume of fluid at a given speed, meaning flowrate is fixed and pressure provided is sufficient to achieve that flowrate.

Centrifugal Pumps, meanwhile, operate at a fixed speed and exhibit coupled pressure drop and flowrate characteristics. Fig. 2(c) shows how, as flowrate approaches zero, centrifugal pumps provide a max (still finite) pressure head, and as flowrate increases significantly, pressure increase across the pump approaches zero.

Finally, *Fixed Pressure Systems* exhibit a flat (zero-slope) response to changes in flowrate. As mentioned previously, this is characteristic of systems with many parallel channels sharing inlet and exit plenums, a common configuration for many early boilers, nuclear power systems, and still relevant to applications with parallel micro-channel heat sinks.

Having established basics of internal and external pressure characteristics for boiling and condensing systems, it is possible to provide an explicit description of Ledinegg instability and the conditions under which it occurs.

2.2.2. Existence and characteristics of Ledinegg instability

Mathematical formulation of Ledinegg instability is straightforward and may be found in many relevant works on the topic. A brief overview will be provided here, based largely on the explanation provided by Lahey and Podowski [122].

The transient momentum equation for a flow loop may be written in the simplified form

$$I\frac{d\dot{m}}{dt} = \left(\Delta P_{pump} - \Delta P_{loop}\right), \tag{6}$$

where $\dot{m}$ is mass flowrate, ΔP_{pump} pump pressure rise, ΔP_{loop} loop pressure drop, and I inertia of the loop given by

$$I = \sum_{i=1}^{n} \frac{L_i}{A_i}, \tag{7}$$

with L_i and A_i representing the length and area, respectively, of flow section i. In the case of true steady flow, the right-hand side of Eq. (6) is equal to zero. Perturbations from mechanical (or other sources) are common, however, so it is relevant to consider the case of a small perturbation in mass flowrate

$$\dot{m}(t) = \dot{m}_0 + \delta\dot{m}(t). \tag{8}$$

Combing Eqs. (8) and (6) simplifies to

$$I\frac{d(\delta\dot{m})}{dt} + \left[\left.\frac{\partial\left(\Delta P_{loop}\right)}{\partial\dot{m}}\right|_{\dot{m}_0} - \left.\frac{\partial\left(\Delta P_{pump}\right)}{\partial\dot{m}}\right|_{\dot{m}_0}\right]\delta\dot{m} = 0\,, \tag{9}$$

which has the solution

$$\delta\dot{m}(t) = \delta\dot{m}(0)\left\{\exp\left(-\left[\left.\frac{\partial\left(\Delta P_{loop}\right)}{\partial\dot{m}}\right|_{\dot{m}_0} - \left.\frac{\partial\left(\Delta P_{pump}\right)}{\partial\dot{m}}\right|_{\dot{m}_0}\right]\frac{t}{I}\right)\right\}. \tag{10}$$

This system is then said to be stable at a given operating point $\dot{m}_0$ if

$$\lim_{t\to\infty}\delta\dot{m}(t) \to 0, \tag{11}$$

a condition which is satisfied when

$$\left.\frac{\partial\left(\Delta P_{loop}\right)}{\partial\dot{m}}\right|_{\dot{m}_0} > \left.\frac{\partial\left(\Delta P_{pump}\right)}{\partial\dot{m}}\right|_{\dot{m}_0}. \tag{12}$$

In plain English, Eq. (12) states the system will be stable operating at mass flowrate $\dot{m}_0$ if the slope of the internal pressure curve is greater than the external (pump) pressure curve. Based on the characteristic curves presented in Fig. 2(a) and (b), this is always the case for single-phase flow and flow condensation, but there is the possibility of flow boiling systems failing to satisfy this condition (depending on specific operating conditions) due to the negative slope region of their characteristic curves.

Fig. 2(d) provides a closer look at internal and external pressure curves for boiling systems to illustrate situations when Ledinegg instability will manifest. Again drawing from the example of Lahey and Podowski [122], three cases are shown: A flow boiling system with (1) a positive displacement pump, (2) a centrifugal pump, and (3) operated with a constant pressure difference (i.e., parallel tubes). In these examples, point **A** represents the operating conditions of interest (equivalent to $\dot{m}_0$ in the above derivation).

In case 1, the system is stable at point **A** due to the slop of the external pressure curve approaching -∞ while that of the boiling system remains a finite negative value. In physical terms, a slight increase in mass flowrate ($+\delta\dot{m}$) within the system will decrease internal pressure drop. Pump pressure will decrease further, however, driving flowrate back towards the original operating point **A**.

In case 2, however, slope of the external pressure curve is now less negative than that of the internal curve at point **A**. This means that, for a slight increase in mass flowrate within the system, system pressure drop will decrease more than pump pressure head at that new flowrate. This will drive the flowrate to increase further and further until a point is reached at which system pressure drop is equal to pump pressure *and* slope of the system curve is greater than that of the external curve. For case 2, this point is labelled as $\mathbf{B_2}$on Fig. 2(d).

Similarly, a slight decrease in mass flowrate ($-\delta\dot{m}$) at point **A** for conditions associated with case 2 will lead to an increase in system pressure drop. Pump pressure will also increase, but not enough to compensate for the new system pressure drop, leading flowrate to decrease until stable point $\mathbf{C_2}$is reached.

Case 3, corresponding to a fixed pressure condition, will exhibit behavior similar to that of Case 2 for perturbations in mass flowrate about point **A**. This time, however, new stable operating conditions $\mathbf{B_3}$and $\mathbf{C_3}$will be even farther from the desired condition **A**. Point $\mathbf{C_3}$ is dangerous, as the low flowrate and correspondingly high void fraction commonly lead to CHF and system failure. Thankfully, many researchers have investigated Ledinegg instability over the years, and a wide variety of strategies exist to combat its negative influence on safe system operation.

2.2.3. Studies investigating Ledinegg instability

Although apparently first reported by Schnackenberg in 1937 [123], origination of analysis on the excursive instability commonly referred to as Ledinegg instability is frequently attributed to the 1938 work of Ledinegg [124]. As with these early studies, much of the work on Ledinegg instability focuses on prevention to avoid premature CHF and system failure associated with excursion to a lower flowrate, higher void fraction operating point. Fig. 3, adapted from the work of Mishima et al. [125], provides an excellent example of both CHF encountered during nominal system operation, Fig. 3(a), and that brought on by Ledinegg instability, Fig. 3(b). Fig. 3(b) clearly shows the rapid, unsteady rise in heated wall temperature is brought on by a sharp decrease in flowrate just prior to CHF (identified as 'Flow Excursion' in the figure).

Many researchers have devoted time to analysis of Ledinegg instability, but relatively few have provided experimental evidence of its occurrence. In addition to the work of Mishima et al. [125] referenced above, notable experimental works include those of Whittle and Forgan [126], Lee et al.[127], Ishii and Fauske [128], and Shin and No [129].

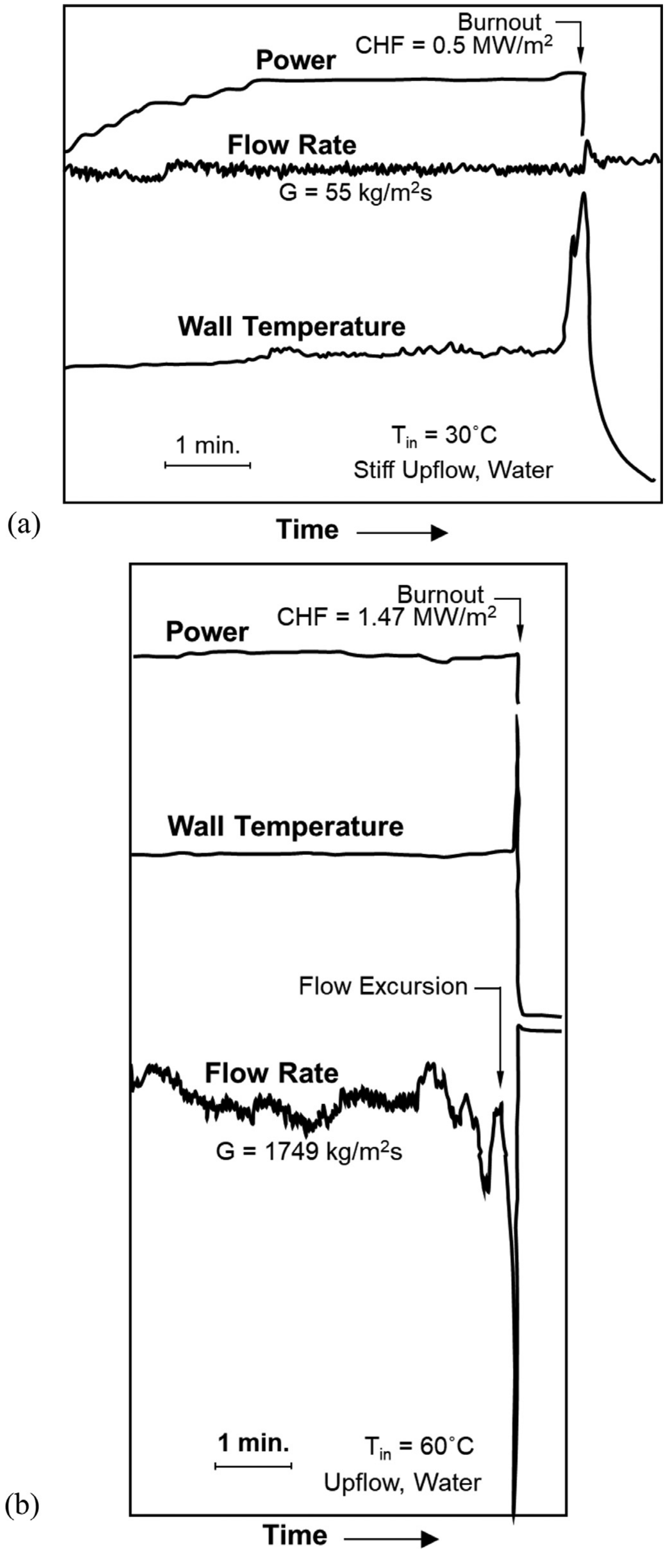


Fig. 3. Sample test cases indicating (a) nominal progression of heat flux increments leading to CHF, and (b) Ledinegg instability (Flow Excursion) leading to CHF. Adapted from Mishima et al. [125].

In their 1967, work involving water flow circulated through a single, rectangular boiling channel by use of a centrifugal pump, Whittle and Forgan [126] provided clear evidence of a stable flow experiencing an excursive instability after being subjected to a small change in operating conditions. They showed this transition point occurred at the minima in the pressure drop – flow rate characteristic curve (the OFI point) and investigated how changes in operating conditions affect the location of this point. They used their results to generate one of the most commonly referenced OFI correlations in literature.

Lee et al. [127] recently offered an updated version of the approach taken by Whittle and Forgan [126]. By investigating water flow circulated using a centrifugal pump through a single rectangular channel (using channels of three different aspect ratios) they were able to experimentally observe Ledinegg instability, evaluate the correlation of Whittle and Forgan [126], and offer their own, updated correlation for OFI.

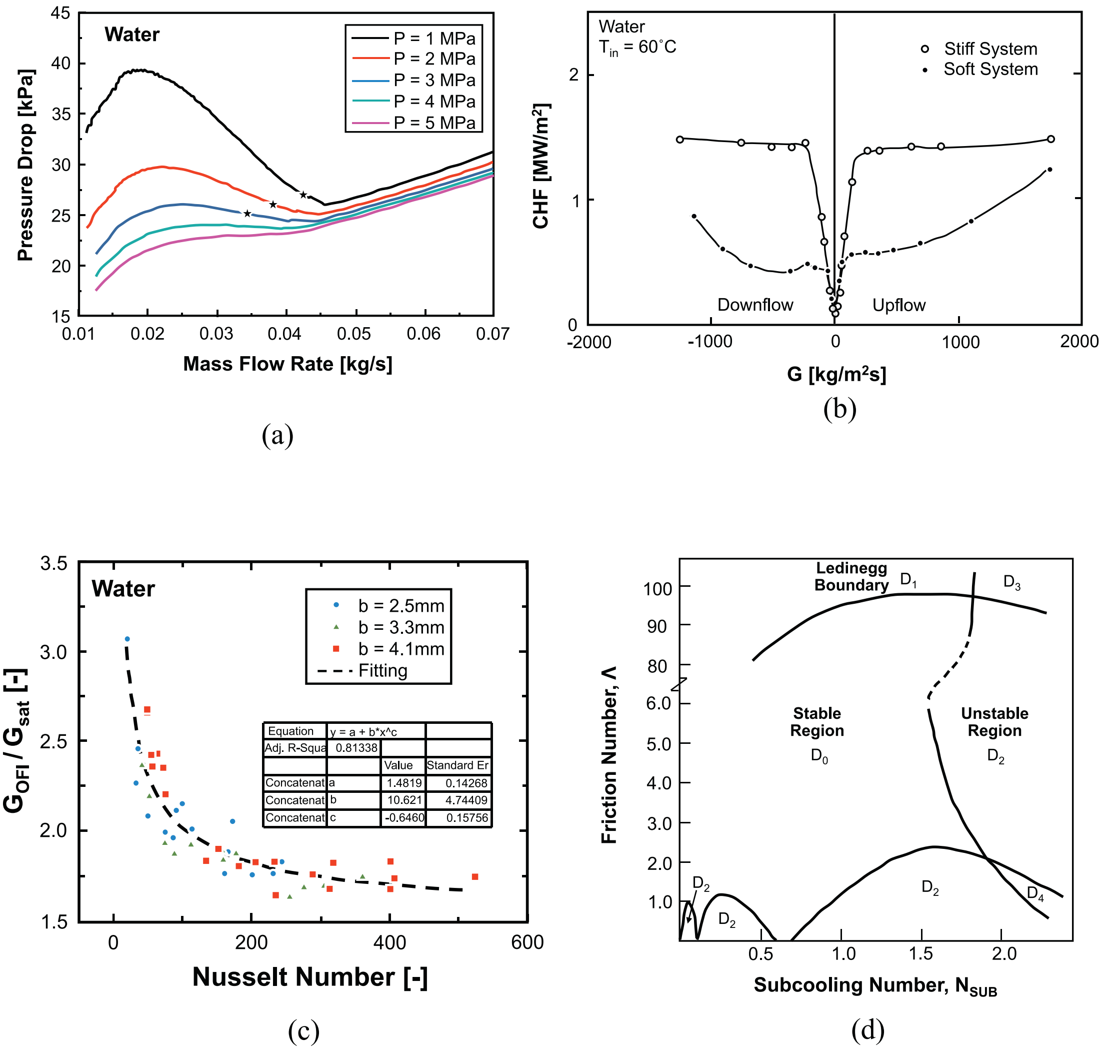
Ishii and Fauske [128] investigated natural circulation in Liquid Metal Fast Breeder Reactors (LMFBRs) to determine the dominant mechanisms leading to burnout in these systems. Natural circulation represents a particularly interesting case for Ledinegg instabilities, as both internal and external pressure characteristics change significantly with operating conditions. They found that in many cases burnout may be due to flow excursion leading to a high quality, low flowrate condition, and developed an extensive model for both internal and external system pressure characteristics to better predict flow excursion. They compared their model predictions to experimental results of Garrison et al. [130] and Haga et al. [131] and found good agreement between their Ledinegg instability model predictions and the experimental burnout values.

Shin and No [129] recently investigated flow instabilities with water in a Printed Circuit Heat Exchanger (PCHE), a parallel microchannel heat exchanger designed specifically for application with Small Modular Reactors (SMRs). They clearly demonstrated the occurrence of Ledinegg instability within their experimental system and developed a model for predicting system internal pressure curves.

The majority of studies on Ledinegg instability avoid directly encountering the instability mode and instead focus on how it may be avoided. Avoidance strategies may be classified into two broad categories: *Modifications to the System* and *Knowledge of Operating Boundaries.*

Modificationsto the System are focused on eliminating the negative slope portion of the internal pressure curve altogether, commonly accomplished by including a throttling valve upstream of the test section (increasing frictional pressure drop to where it dwarfs two-phase effects and eliminates the negative slope portion) or raising system pressure. Fig. 4(a) presents an example of the effect of raising system pressure on the shape of the internal pressure curve, adapted from the work of Genglei et al. [132]. They investigated boiling instabilities in systems with parallel, narrow channels using the RELAP5 analysis code (commonly used for analysis of nuclear thermohydraulic systems). They undertook extensive parametric analysis, one of the conclusions of which was increases in system pressure, as shown in Fig. 4(a), lead to reductions in density ratio between phases and Ledinegg instability (indicated with star symbols in Fig. 4(a)) no longer manifesting

The other approach to *Modifications to the System* mentioned above, inclusion of a throttling valve at the channel inlet, leads to a family of curves similar to those shown in Fig. 4(a) (this time with increasing inlet restriction coefficient replacing increasing pressure). Practically, inclusion of throttling valves with large pressure drops has led to the elimination of Ledinegg instability and significant improvements in system performance. Fig. 4(b) provides an example of this, taken from the work of Mishima et al. [120]. They provide flow boiling CHF results for both vertical upflow and downflow orientations using no inlet restriction (Soft System) and a throttling valve at the channel inlet (Stiff System). At low flow velocities, Fig. 4(b) shows CHF values are similar for both systems, but, as velocity is increased, significant differences are seen between 'Soft' and 'Stiff' system results. Mishima et al. state this difference is due to the occurrence of Ledinegg instability in



(a)

(b)

(c)

(d)

Fig. 4. Avoidance of Ledinegg instability may be achieved through elimination of the negative slope of the boiling curve as shown in (a) (adapted from Genglei et al. [132]) which may result in appreciable improvements in CHF values (b) as seen by Mishima et al. [125]. Also shown are methods for avoiding operating conditions where Ledinegg instability is likely to occur (negative-slope region), including (c) correlation for Onset of Flow Instability (OFI), adapted here from Lee et al. [127], and (d) stability maps, adapted here from Achard et al. [147].

the 'Soft' system, yielding burnout at lower heat fluxes than those encountered for the 'Stiff' system at a similar mass velocity.

Modifications to the System offer methods for eliminating the possibility of Ledinegg instability occurring within a system, but usually come with their own incurred costs: Raising system pressure may require changes to flow loop hardware to accommodate heightened pressures and temperatures (as boiling point increases with increasing pressure). Similarly, inclusion of a throttling valve at the channel inlet may require a larger pump (larger driving pressure head) to accommodate the increased pressure drop. Because of these adverse side effects, significant effort has been devoted to *Knowledge of Operating Boundaries*, or understanding what operating conditions may lead to Ledinegg instabilities in a given system.

The most straightforward method employed to gain *Knowledge of Operating Boundaries* is use of 'Onset of Flow Instability' (OFI) correlations. As described in preceding subsections, the OFI point is the local minimum in the internal pressure drop versus flowrate characteristic curve. Correlations for this point allow system designers and/or operators to know, for all other operating conditions held constant, the minimum mass velocity allowable for the system to remain on the positive-slope region of the internal characteristic curve (thus avoiding the potential for Ledinegg instability).

One of the earliest works to provide an OFI correlation was that of Whittle and Forgan [126] and, as such, their work has influenced many subsequent investigators. One of the best, most recent examples is the work of Lee et al. [127]. They provided experimental evidence their system was susceptible to Ledinegg instability, generated a database of conditions where the onset of Ledinegg instability was observed, evaluated prior correlations for OFI, and presented a new correlation of their own. Fig. 4(c) provides a plot of data reduction used to generate their new correlation, including data for three different gap spacings (*b*) in their rectangular boiling channel and statistics for the curve fit performed.

Many authors generated databases of OFI points, evaluated common correlations, and even proposed new correlations to best fit existing results. Table 3 presents much of the relevant work regarding experimental determination and correlation of OFI points. All works included have utility, but those of Whittle and Forgan [121], Siman-Tov et al. [130], Stelling [132], Kennedy [133], and Lee et al. [127] are strongly recommended.

Table 3
Works dealing with OFI correlations.

Authors	Correlation	Correlation(s) Evaluated	Comments
Whittle & Forgan [126], 1967	$R = \frac{\Delta T_c}{\Delta T_{sat}} = \frac{1}{1+\eta/(L_H/D_H)}$ $\eta = 25, \Delta T_{sat} = T_{sat} - T_{in},$ $\Delta T_c = T_{out} - T_{in}$	Whittle & Forgan [126]	Investigated subcooled water flowing in narrow (L_H/D_H= 94.5, 83, 100, 191, 95) channels. Vertical upflow orientation. Show direct evidence of Ledinegg instability, tabulate results for OFI point.
Saha & Zuber [133], 1974	$St = \frac{q''}{\rho_f c_{p,f} U_f (T_{sat} - T_{f,fdb})}$ $\Delta T_{sub,OSV} = T_{sat} - T_{in} = 0.0022 \frac{q'' D}{k_f}, forPe \leq 70,000$ $\Delta T_{sub,OSV} = T_{sat} - T_{in} = 154 \frac{q''}{G c_{p,f}}, forPe > 70,000$ $U_f = \mathrm{LiquidVelocity},$ $T_{f,fdb} = \mathrm{Temp.@fullydevelopedsubcooledboiling}$	NA	Correlation originally for OSV, commonly used in/with correlations for OFI. Included here for reference.
Yang et al. [134], 1993	Modified Saha-Zuber: $Q_{OFI} = \dot{m} c_{p,f} (T_{sat} - T_{in})[1 + \frac{0.25 D_h}{St\, L}]^{-1}$	Saha & Zuber [133]	Vertical downflow of water in annulus, one without ribs (73.64-mm OD, 59.61-mm ID, 3.66-m length), and one with ribs (73.46-mm OD, 59.61-mm ID, 3.66-m length).
Siman-Tov et al. [135], 1995	Proposed a modification to the Saha and Zuber correlation to account for inlet subcooling: $\mathrm{for} Pe > 70,000:$ $St_{OFI} = \frac{q''_{OFI}}{G_{OFI} c_{p,f} (T_{sat} - T_{in})} = 0.0065 \eta_{sub} = 0.0065[0.55 + \frac{11.21}{T_{sat} - T_{in}}],$ $\mathrm{for} Pe \leq 70,000:$ $Nu_{OFI} = \frac{q''_{OFI} D_h}{k(T_{sat} - T_{in})} = 455 \eta_{sub} = 455[0.55 + \frac{11.21}{T_{sat} - T_{in}}],$	Costa [136], Whittle & Forgan [126], Saha & Zuber [133], Siman-Tov et al.[135]	Vertical upflow of water in a single channel, 507-mm long, 12.7-mm wide, and 1.27-mm gap. Include 'soft' and 'stiff' configurations to show cases with and without Ledinegg instability. Used a database from authors in the 1950's and 1960's to develop and evaluate their correlation. Found it was necessary to account for high inlet subcooling in their correlation.
Stelling et al. [137], 1996	$Q_{ratio} = \frac{q'' \pi DL}{\dot{m} c_{p,f} (T_{sat} - T_{in})} = \frac{1}{(1+0.25[St_{OSV}(L_H/D_H)]^{-1})}$ $St_{OSV} = 0.0065 \mathrm{for} Pe \geq 70,000 (\mathrm{Saha\&Zuber}[88])$ $Pe = \mathrm{Re}\,\mathrm{Pr} = \frac{\rho_f U_f D_H}{\mu_f}\,\mathrm{Pr}$	Stelling et al. [137]	Vertical downflow of water in stainless-steel and Inconel tubes. Tube diameters of 25.4, 19, 15.5, 9.1, 28, 15.2, and 15.8 mm used.
Kennedy et al. [138], 2000	$q''_{OFI} = 0.9 q''_{sat} = 0.9 \frac{GA(h_f - h_{in})}{p_H L_H}$ $G_{OFI} = 1.11 G_{sat} = 1.11 \frac{q'' p_H L_H}{A(h_f - h_{in})}$	Saha & Zuber [133], Kennedy et al.[138]	Water flow through 1.17-mm and 1.45-mm diameter tubes, 16-cm heated length. Horizontal flow.
Yeoh et al. [139], 2004	$\alpha_{out,\,OFI} \sim 0.1$	None	Compare model predictions with experimental results from CEA-Grenoble. Vertical upflow, 600-mm heated length, 38-mm wide, 3.6-mm deep, water flow.
Wang et al. [140], 2011	Proposed modification technique for existing correlations (only applied for OSV correlations) to account for single-sided heating configuration. This involved multiplication by ratio of wetted to heated perimeters.	Kennedy et al. [138]	Vertical upflow of water in 470-mm long, 40-mm wide, 3-mm deep channel. Note OFI may be predicted well by transition from Bubbly to Bubbly-Churn flow regime at channel exit. Should be noted they define OFI as location where mass flowrate fluctuations become larger with increasing flowrate.
Lee et al. [127], 2013	$G_{OFI} = G_{sat}[1.48 + \frac{10.6}{Nu^{0.65}}]$ $Nu = \frac{q'' D_h}{k_l \Delta T_{OSV}}$ $\Delta T_{OSV} = T_{sat} - (T_{in} + \frac{p_H L_H q''}{A c_{p,f} G_{OSV}})$	Whittle & Forgan [126], Saha &Zuber [133], Kennedy et al. [138], Lee et al. [127]	Vertical downflow of water through a narrow rectangular channel 40-mm wide, 350-mm long, with gap sizes of 2.5-mm, 3.3-mm, and 4.1-mm.
Al-Yahia et al. [141], 2018	For constant flowrate and varying heat flux: $q''_{OFI} = q''_{sat}[0.8(\frac{p_H}{p_w})(\frac{P}{1.12})^{0.4}]$ where P is pressure in bar, p_H is heated perimeter, and p_w wetted perimeter. For constant heat flux and varying flowrate: $G_{OFI} = G_{sat}[1.25(\frac{p_w}{p_H})(\frac{1.12}{P})^{0.4}]$	Whittle & Forgan [126], Kennedy et al. [138], Unal et al. [142], Lee et al.[127], Bowring [143], Saha & Zuber [133]. Included modified predictions similar to Wang et al. [140].	Vertical upflow of water in a 566-mm long, 54-mm wide, 2.35-mm tall rectangular channel. Should be noted they define OFI as location where pressure fluctuations become larger with increasing heat flux/flow rate. Declared OSV is a good indicator of OFI, used several OSV correlations (Unal [142], Saha & Zuber [133], Bowring [143]).
Lu et al. [144], 2019	$N_{pch,OFI} = N_{conf}^{-0.24}[4.84 N_{sub}^{0.60} + 1.98 We^{-0.84}(\frac{\rho_f}{\rho_g})^{0.64}],$ $N_{pch} = \frac{Q}{G A_c h_{fg}} \frac{\rho_f - \rho_g}{\rho_g}$, is phase change number, $N_{sub} = \frac{c_{p,f} \Delta T_{sub}}{h_{fg}} \frac{\rho_f - \rho_g}{\rho_g}$, is subcooling number and $We = \frac{\rho_f u_f^2 D_h}{\sigma}$ is Weber number.	Lu et al. [144], Leng [145], Zhou [146]. Original references for Leng [145] and Zhou [146] not accessible.	Define OFI as the point past which significant flow oscillations are observed. Appears (from experimental results) to sometimes correspond to Ledinegg followed by DWO.

The other common method for gaining *Knowledge of Operating Boundaries* involves formulating a detailed model for internal system pressure drop, such as the previously mentioned work by Ishii and Fauske's [128] on natural circulation. One early example of this approach may be found in the work of Achard et al. [147]. Their approach (which follows that established by earlier works in the field, including Ishii [148] and Yadigaroglu [149]) involves formulating equations of motion within the heater, including both single-phase and boiling regions. By non-dimensionalizing these equations, several key dimensionless numbers appear, including:

$$Eu = \frac{\Delta P}{\rho_f U_f^2}, \tag{13}$$

$$Fr = \frac{U_f^2}{g L_H}, \tag{14}$$

$$\Lambda = \frac{f L_H}{2 D_h}, \tag{15}$$

and

$$N_{sub} = \frac{v_{fg}\left(h_f - h_i\right)}{v_f h_{fg}}, \tag{16}$$

where Eu is Euler number, Fr Froude number, Λ friction number, and N_{sub}subcooling number.

By linearizing their equation of motion and applying the D-partition method (determining roots of governing equations as a function of operating parameters, allowing presentation of stability bounds for varying conditions), they generate information on stability of the boiling system for different ranges of operating conditions. This approach is similar to that applied in control theory for determining stability/instability of dynamic system controls.

One of the most common ways this information is utilized is through formulation of 'stability maps'. One of the maps generated by Achard et al. [147] is shown in Fig. 4(d), consisting of a plot of friction number versus subcooling number, and including boundaries showing what combinations of conditions will lead to stable or unstable operating conditions. They explicitly identify the region pertaining to Ledinegg instability, which, for the system they modeled, corresponds to very high friction numbers. Other unstable regions identified (D_2, D_3, D_4) likely correspond to the onset of Density Wave Oscillations (DWOs); these will be discussed in more detail in Section 3.1, but for now it should be mentioned other researchers analytically show Ledinegg instability as the 0-frequency limit of DWOs [148,149].

Key to note when attempting to formulate and/or use existing stability maps is the 2-D nature of the maps, while the problem depends on four dimensionless groups (commonly Eqs. (13)-(16), although sometimes more depending on model formulation). This means stability maps formulated for a specific test fluid, test section, and operating conditions rarely offer utility when any of these parameters is changed. Because of this, stability maps are not generally applicable design tools. Rather, it is the modeling and stability analysis approach that may be broadly applied, resulting in specific stability boundaries for individual systems.

This analytic approach to determine stability limits is very prolific in existing literature. Many works have taken a similar approach for conventional macro-channel tubes (modelled using a constant pressure drop assumption to mimic that in banks of tubes) [147,150-161], natural circulation driven systems [128,162-164], systems with supercritical flows where temperature-dependent density variations allow flow to be modelled as pseudo-multiphase [165-170] (recently augmented with CFD predictions [171,172]), natural circulation driven supercritical systems [173], and parallel micro-channel heat sinks [129,132,174-175]. Although comparatively little work has been performed investigating Ledinegg instability in parallel micro-channel heat sinks, their proliferation in recent years warrants a short discussion on their potential differences compared to traditional macro-channel systems (where boiling occurs in tubes designated as macro-channels based on criteria in Section 1.3).

2.2.4. Differences in micro-channel systems

As discussed in Sections 2.2.1 and 2.2.2, Ledinegg instability is a system level instability, meaning it depends on interaction between external and internal system characteristics to manifest. Explanations of internal and external pressure curves and how they may interact to yield Ledinegg instability are applicable to single micro-channels as well as parallel micro-channel heat sinks, and the same approaches for mitigation and avoidance outlined in Section 2.2.3 may be successfully utilized to avoid encountering this instability.

Some recent evidence suggests, however, that determination of external pressure curves for systems using parallel micro-channel heat sinks may not be straightforward. In the case of parallel macro-channel tubes, it is common to use a constant pressure drop assumption across the tube bank, but in the case of parallel micro-channel heat sinks, Zhang et al. [174] found increasing the number of parallel micro-channels increases system susceptibility to Ledinegg instability. They stated that, for a system with a constant displacement pump and a parallel micro-channel heat sink, the external pressure curve will be neither zero (constant pressure drop, case 3 in Fig. 2(d)) nor infinite (positive displacement pump, case 1 in Fig. 2(d)), but somewhere in between depending on heat sink design.

Although only a single source, their experimental evidence is very compelling, and it is recommended future research be performed to address the exact impact of micro-channel heat sink design on external pressure curve definition.

2.2.5. Concluding remarks on Ledinegg instability

The preceding subsections highlight the impressive amount of research work focused on Ledinegg instability available in literature. Both practical guidelines for avoiding the instability (inlet throttling, operating at higher pressure) and advanced predictive tools (OFI correlations, full system models) are available to assist system designers in understanding and mitigating potential adverse effects of Ledinegg instability.

In particular, development of full system models is thought to be the safest way to fully understand and avoid Ledinegg instability in any given system. After review of prior works, three key areas (other than intended application) may be used to distinguish between full system models:

1) *Model Formulation* – When establishing the governing equations, do the models use Homogeneous Equilibrium Model (HEM) assumptions (most common), Drift-Flux model assumptions, take a purely correlation based approach, or use some other method for expressing relevant pressure drop terms?
2) *Method for Evaluation/Determination of Stability* – Do the models linearize the system and undertake stability analysis (frequency domain analysis)?Or, do they directly evaluate steady-state conditions to generate an internal pressure characteristic curve and look for the OFI point (time domain analysis)?
3) *Comparison with Experimental Results* – Were any experimental results used for evaluation?This is arguably the most important aspect to look for, as unverified model predictions do little to reinforce confidence in the model.

Overall, all studies referenced above offer valuable information on modeling approaches for determining system susceptibility to Ledinegg instability, but those that do the best job of including experimental verification are works by Ishii [128], Zhang [174], and Shin [129].

Finally, to conclude this section dealing with Ledinegg instability, many of the studies referenced here include findings either not reported in most literature or in direct contradiction with statements made in other places. These are outlined in Table 4.

2.3. Boiling Curve Hysteresis and Vapor Burst

Unlike the prior section, which was concerned primarily with OFI, Boiling Curve Hysteresis and Vapor Burst are both boiling instability modes which occur at the ONB point of the curve shown in Fig. 2(a). As vapor burst is (when it manifests) a byproduct of boiling curve hysteresis, boiling curve hysteresis will be discussed first.

Boiling curve hysteresis commonly occurs with low contact angle combinations of fluid and heated surface in a variety of boiling configurations [176-188], and may be simply described as resulting from difference in wall superheat required for nucleation to begin versus that at which it ends (it takes a higher wall superheat to start nucleation than the heat flux wall superheat at which nucleation ends). The main culprit for hysteresis is flooding of surface cavities by low contact angle fluids, which deprives the cavities from viable vapor embryos capable of initiating the bubble nucleation. Overcoming this would require increasing the wall superheat further to ultimately initiate properly sized embryos and commence nucleation. But, once the nucleation occurs, it propagates violently across the wall, greatly improving heat transfer and resulting in a sharp decrease in the wall superheat. This process

Table 4
Uncommon findings related to Ledinegg instability.

Finding	Implications/Relevance	Relevant References
Ledinegg instability may occur on the positive slope portion of the internal pressure characteristic curve for sufficiently high subcooling.	This is in contradiction to the common understanding of how Ledinegg instability occurs (outlined in Section 2.2.2). No experimental verification of this has been found in literature by the present authors.	Fowler [151], 1978
Care must be taken when determining an external pressure curve to apply. In the case of a bank of parallel tubes, a constant pressure drop assumption may be applied and behavior in the tube analyzed. In the case of natural circulation, flowrate and pressure drop will depend on pressure drop throughout the loop, and the entire system (including boiling and condensation lengths) must be included in analysis. Systems driven by centrifugal pumps also must be analyzed in their entirety. Systems driven by constant-displacement pumps may be assumed not to experience Ledinegg instability, except in the case of parallel micro-channel heat sinks, where behavior becomes more complicated (see next row).	It is important to understand how any specific system is similar to / different from those present in other studies. Valid modeling applied on an incorrectly defined system may lead to incorrect predictions of stable or unstable behavior.	Ishii & Fauske [128], 1983 Lahey & Podowski [122], 1989 Zhang et al.[174], 2009
Ledinegg instability in parallel micro-channel heat sinks may require analysis different from that for traditional boiling systems. Stability boundaries clearly depend on the number of parallel channels, and the external pressure curve (as seen by the micro-channel heat sink) is thought to depend on specific heat-sink operating conditions.	As micro-channel heat sinks are increasingly becoming the go-to solution for evaporation in a variety of applications, additional experimental investigation of Ledinegg instability in these systems is necessary. Internal pressure curve modeling is understood, but the dependence of the external curve (as seen by the heat sink) on heat sink geometry must be studied.	Zhang et al.[174], 2009 Genglei et al.[132], 2012 Shin et al. [129], 2017
Commonly accepted theory indicates it is possible for Ledinegg instability to lead to a higher flowrate (trending back towards single-phase liquid flow) or a lower flowrate (often leading to premature CHF). Experimental sources seem to indicate a decrease in flowrate is much more common than an increase.	This is likely related to the location on the internal pressure curve where the instability manifests. If the external pressure curve is flat, Ledinegg instability may occur at the OFI point, and only one stable solution exists (lower flowrate). Additional exploration is needed for cases with external pressure curves of intermediate slope (which may yield two stable solutions after flow excursion) to see if a bias still exists.	Theory: Ruspini et al.[159], 2010 Experiments: Whittle & Forgan [126], 1967 Mishima et al. [125], 1985 others

leads to a 'hysteresis' in boiling curves traced with ascending versus descending heat fluxes, manifest near the incipience point. An example of this from Heindel et al. [176] (who investigated flow boiling of FC-72) is shown in Fig. 5(a).

In the case of a well de-gassed low contact angle fluid with a relatively low heat flux applied over a large area, it is possible to encounter Vapor Burst. In this case, suppression of nucleation associated with boiling curve hysteresis leads to 'liquid superheat', where bulk fluid significantly exceeds saturation temperature at local pressure. Incipient boiling is now accompanied by violent flashing of a large fraction of liquid to vapor, which can significantly affect system pressure. Although not as common as boiling curve hysteresis, documented accounts of this phenomenon do exist [189-191], and an example is shown in Fig. 5(b) corresponding to flow boiling of FC-72 through a circulation heater [92,192-193]. Vapor burst manifestation in quenching and nuclear fuel cooling represent a field of study on their own [194,195].

Both boiling curve hysteresis and vapor burst are commonly treated with practical solutions for two-phase system design and operation, both through awareness of their potential to occur and operation away from conditions that may cause them to impact operation. Unlike Ledinegg instability, detailed design tools are not available for these two phenomena, and more information on fundamentals of boiling incipience is warranted for development of reliable predictive models for both.

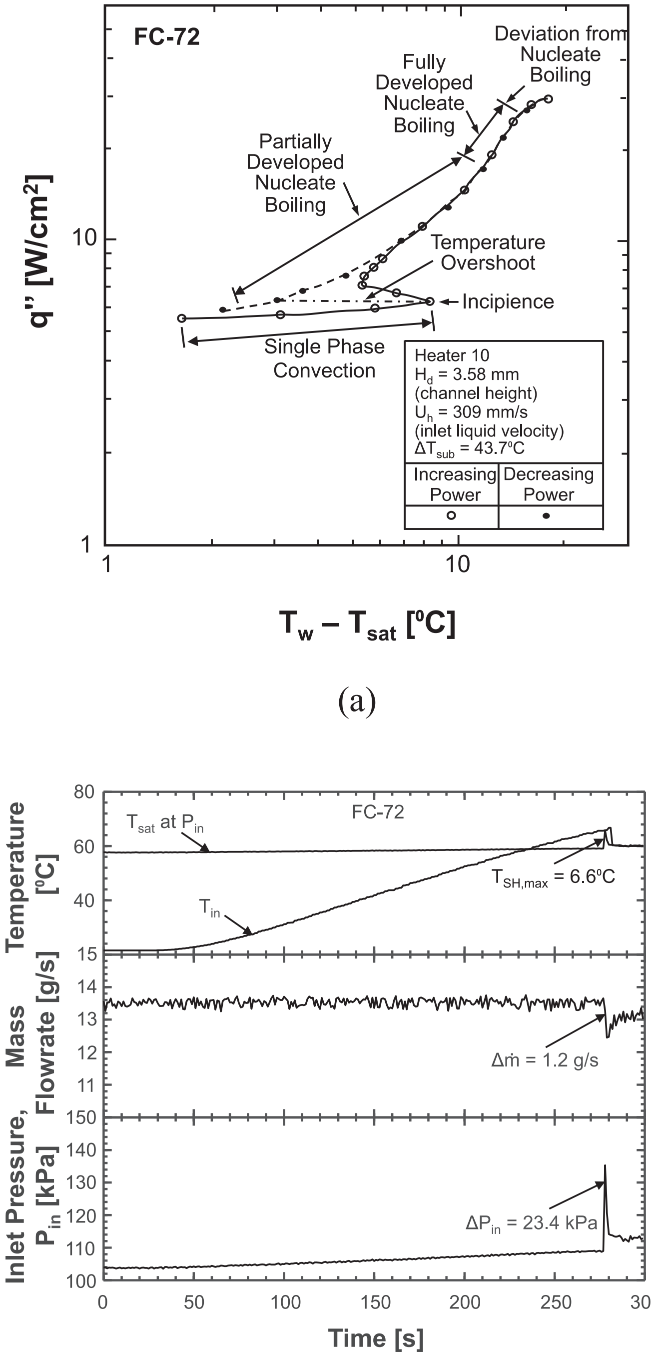
2.4. Flow regime transition instability

Mention of flow regime transition instability is often a source of confusion in two-phase instability literature due to three key reasons: 1) the ability for it to manifest as either a static or dynamic instability mode, 2) the differences present between flow regimes in macro- versus micro-channels, and 3) whether it is a unique, self-sustaining oscillatory mode, or a byproduct of other instability(s). Following are key observations concerning each:

Static versus Dynamic: Flow regimes are an inherent part of two-phase flow that distinguish it from traditional single-phase flows. Depending on geometry, working fluid, phase velocities, mass fractions of vapor and liquid, and other factors, distribution of liquid and vapor phases can differ greatly. For example, a small increase in heat flux may lead to slightly larger quality, transitioning flow from *slug* to *annular* (thus a small perturbation in operating conditions leads to a large change in flow behavior), the latter having distinctly different pressure drop and heat transfer coefficient than the former. This static-type instability is fairly well predicted by existing flow regime maps available in literature.

In the dynamic type manifestation, changes in operating state may lead to a self-sustaining oscillation between operating points. Nayak et al. [196] provided a compelling description for this, but the majority of literature indicates dynamic changes in flow regime are in fact a response to other instability modes [48,197-199]. An example of this would be pressure and flowrate variations brought on by DWOs leading to a cyclical transition between slug and annular flow.

Macro- versus Micro-Channels: Due to confinement effects described in Section 1.3, it is possible for single bubbles to occupy the entire cross-section in micro-channels, leading to abrupt transitions between flow regimes due not to bulk-flow changes, but to single-bubble formation and expansion. A recent series of studies by Chinnov et al. [200-203] used advanced optical measurements to quantitatively describe transient changes in flow regime within a single micro-channel, and Lee et al. [204] provided similar analysis for a large parallel channel heat sink. Other authors have also addressed these transient changes for micro-channels [205,206], but it appears these changes in flow regime are largely attributable to Density Wave Oscillations in micro-channels (to be discussed in a later section).



(a)

(b)

Fig. 5. Examples highlighting key features of boiling curve hysteresis. (a) Differences in ascending and descending boiling curves for flow boiling of FC-72 (adapted from Heindel et al. [176]). (b) 'Vapor Burst' phenomenon associated with flow boiling of FC-72 [92,192,193]). The sharp pressure increase in (b) due to rapid vaporization of a significant mass of liquid is observable in most boiling configurations with well de-gassed, low contact angle working fluids.

Unique Instability versus Byproduct of Other Dynamic Instability(s): This item has been touched on in the preceding two points, and while conclusive proof is not available in literature, most studies indicate transient changes in flow regime are attributable to other dynamic instabilities. This means flow regime transition should not be considered a unique dynamic instability type, although changes in flow regime will be discussed along with other dynamic instabilities in the next section.

3. Dynamic instabilities

Unlike *Static Instabilities*, which involve a one-time excursion from an unstable operating point to a new, stable condition, *Dynamic Instabilities* are best characterized by continuous cycling between marginally unstable operating points. In their seminal review, Boure et al. [48] used frequency ranges to help classify *Dynamic Instabilities* into different classes. Frequency information is one of the most important pieces of information (along with amplitude) for evaluating potential impact of different dynamic instability modes, but is not a reliable method for classifying different instability modes. In fact, 46 years of continued scientific investigation since the publication of Boure et al.'s review has shown frequency of *Density Wave Oscillations* in one system may be similar to *Pressure Drop Oscillations* in another, which in turn may be similar to *Parallel Channel Instability* in a third system. Complicating matters is the potential for mechanically-induced vibrations (by fluid machinery, external factors, or otherwise) appearing alongside physical oscillatory phenomena.

The present section aims to provide physical descriptions of the underlying mechanisms behind common *Dynamic Instabilities*, allowing for classification based on cause (physical mechanisms) rather than effect (i.e., frequency of oscillations). A summary of relevant experimental and analytic works on each instability mode will also be provided, and subsections will conclude with summaries of key findings and recommendations for new/continuing work.

3.1. Density wave oscillations

Commonly reported as the first dynamic instability mode investigated in two-phase flow literature [207], *Density Wave Oscillations* (DWOs), or *Density Wave Instability,* are sometimes referred to as *Flow-void Feedback Instabilities* [208] for reasons that will be explained shortly. Good discussions on the physical mechanisms for *Density Wave Oscillations* may be found in the works of Boure et al. [48] and Lahey and Podowski [122], but the present work will provide a slightly more descriptive approach to better illustrate how this oscillatory mode manifests.

Also, tying in with the discussion of flow regime transition instability in Section 2.4, clear mechanistic differences have been observed for DWOs in macro-channels versus micro-channels, as well as for parallel- versus single-channel systems. Parallel-channel systems will be addressed in a separate section on Parallel Channel Instability, while the present section will split study of DWOs in macro- and micro-channels into separate subsections.

3.1.1. Existence and characteristics of density wave oscillations in macro-channels

Fig. 6(a) and (b) provide schematics and plots, respectively, outlining how DWOs occur in a simplified boiling system. A single channel subjected to constant pressure drop and constant heat flux boundary conditions is considered. Flow at the inlet has some constant subcooling level, meaning flow along the channel may be divided into single-phase and two-phase lengths ($L_{1\Phi}$and $L_{2\Phi}$). At time $t = t_0$, the inlet velocity ($U_{1\Phi,in}$) is slightly perturbed (by δ_U), as shown in Fig. 6(a). The perturbation in velocity causes formation of a low-enthalpy (heat flux remains the same as velocity is increased, meaning local enthalpy has to decrease) wave that propagates downstream. At time $t = t_1$, this wave reaches the 'boiling boundary' separating the single-phase and two-phase regions. Due to its reduced enthalpy, the passage of this wave serves to move the boiling boundary downstream within the channel. As this wave

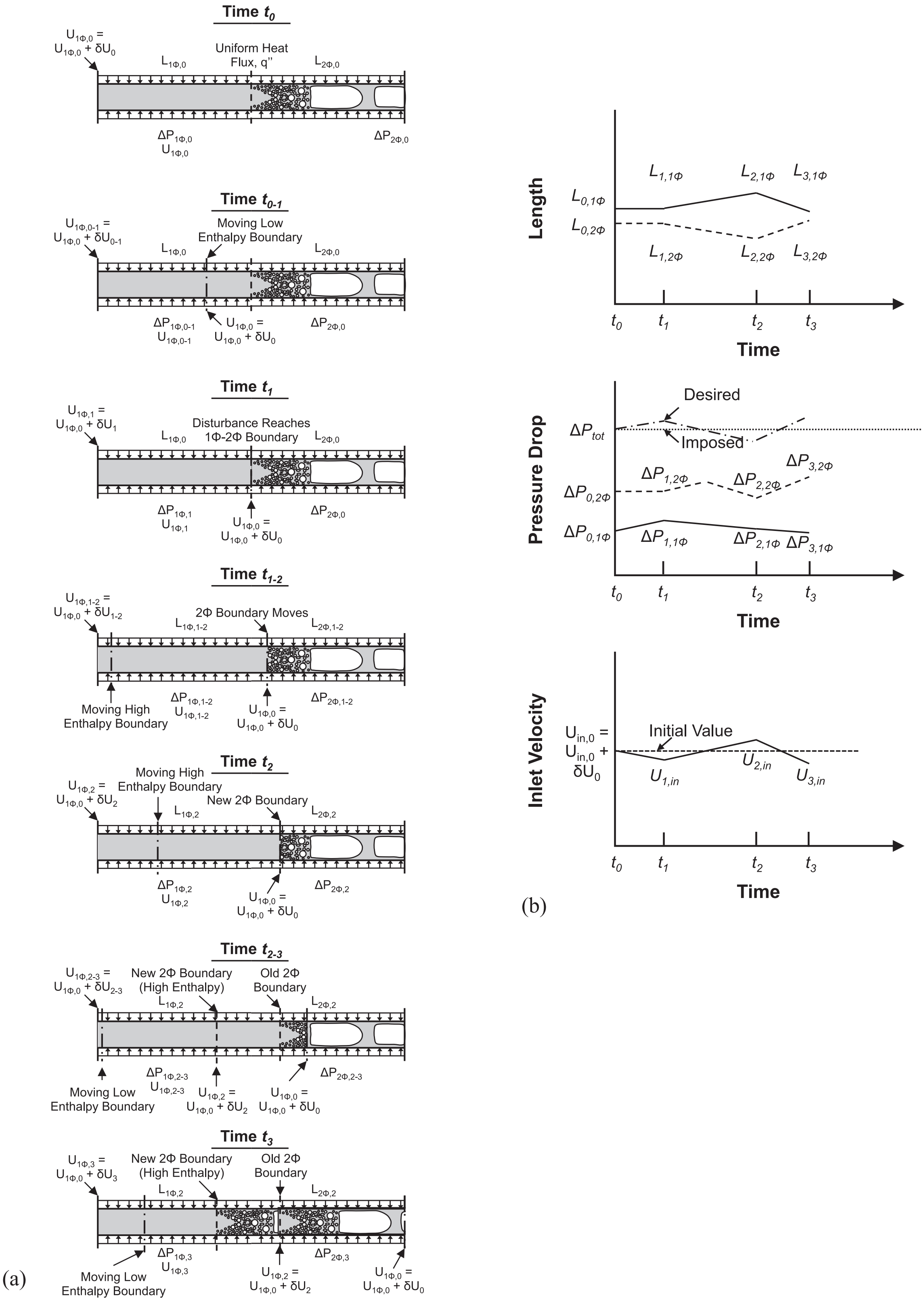


Fig. 6. Illustration of simplified Density Wave Oscillation (DWO) process. Information corresponds to a half-cycle of the instability, and includes (a) schematics and (b) plots of representative parameters.

continues through the channel, a new boiling boundary is established (time $t = t_2$) and local void fraction is altered in its wake. This continues until the low-enthalpy wave exits the channel at time $t = t_3$.

At the same time, due to the significant delay in decrease of pressure drop in $L_{2\Phi}$ due to the delay in propagation of the low-enthalpy front, a high-enthalpy front is formed and moves along the channel (between $t_1$and t_2) due to the now reduced velocity. As the initial low-enthalpy front moves out of the channel between $t_2$and t_3, the high-enthalpy front now causes the boiling boundary to shift upstream towards the channel inlet, and, at time $t = t_3$, the two-phase length is larger than it was initially (while another low-enthalpy front forms and begins moving along the channel).

Fig. 6(a) clearly captures the motion of these high/low-enthalpy fronts and their impact on boiling within the flow channel. In a single-phase, adiabatic case with constant pressure drop, any perturbation in velocity would be met by an increase in pressure drop, driving velocity back to its nominal value. In the present case, however, this reduction in inlet flow velocity occurs along with the low enthalpy wave reducing the boiling length $L_{2\Phi}$ and associated pressure drop $\Delta P_{2\Phi}$. This, in turn, causes flow rate to attempt to increase, however, reduction in flowrate around time $t = t_1$ causes the formation of a high enthalpy wave, which propagates through the channel and causes the two-phase length to increase once again, leading to the cycle repeating itself.

Schematics in Fig. 6(b) show these changes in important flow-field parameters corresponding to the schematics shown in Fig. 6(a), including 'Desired' and 'Imposed' pressure drop, which indicate how the fixed pressure drop channel will respond to changes in flowrate (i.e., the increase in flow velocity at t_0 causes desired pressure drop to increase as this will lead to a new stable condition, but the difference between desired and imposed means inlet velocity will decrease towards its nominal stable value). Only the first half of the entire oscillatory phenomenon is shown, spanning $t_0 - t_3$. These steps are followed by the inverse process mentioned above (the formation and motion of another low enthalpy wave through the system, leading to a shift in the boiling boundary upstream and associated changes in pressure drop components and flowrate).

The motion of these high and low enthalpy fronts through the channel occur at a wave-speed c_k. For single-phase flow, this is equal to the speed of sound within the fluid, but,for two-phase flow, it is difficult to define. This difference in propagation speed (exemplified in the differences between $t_1 - t_2$ and $t_2 - t_3$) is what allows DWOs to occur, and, for the two-phase portion of flow, c_k is commonly approximated as 1 – 1.5 times bulk liquid velocity. Because of this, the period (inverse of frequency) of DWOs is commonly 1.5 – 2 times liquid transport time (based on liquid inlet velocity) through the channel [122].

To expand on this, it is often said DWOs occur due to perturbations being amplified and resulting in oscillatory phenomena due to the two-phase portion responding out of phase with the single-phase portion of the channel (due to the differences in propagation speed). This requires $\Delta P_{2\Phi}$ to be of the same order as $\Delta P_{1\Phi}$, as otherwise their changes will become closer to in-phase with one another and any perturbation will decay back to the initial value. Thermal inertia of heated surfaces, inlet/exit restrictions, local phase non-equilibrium (manifest differently for subcooled boiling versus saturated boiling), and a variety of other factors also influence whether a given operating point is stable to perturbations. These effects will be discussed further in the following subsections.

Finally, it should be noted here that the 'flow-void' feedback depicted in Fig. 6(b) is only one feedback mechanism capable of leading to *Density Wave Oscillations*. In their classic experimental and analytic work, Fukuda and Kobori [209] reported five separate types of DWOs in their system, distinguished by the terms leading to instability. Their system included vertical and horizontal, adiabatic and diabatic sections, and they found acceleration in the heated section, friction in the heated section, friction in the riser section, gravity in the heated section and inertia of single-phase fluid, and gravity in the riser section all could lead to unstable feedback mechanisms (DWOs).

Many authors choose to classify DWOs into 'Type-I' and 'Type-II', stating Type-I DWOs occur at low exit qualities (high flowrates for a fixed heat flux) and Type-II at high exit qualities (low flowrates for a fixed heat flux). The frequency with which this classification is used (particularly in nuclear-oriented investigations) warrants their acknowledgement, but in reality there are more than two types of Density Wave Oscillations. Contemporary literature provides mention of three fundamental types of DWOs [53], as well as several other atypical feedback mechanisms (including rapid growth of confined vapor in micro-channels) best characterized as DWOs.

This concept will be revisited in subsections below, as the potential for complicated, atypical DWOs will be shown to relate to unique opportunities for unstable feedback mechanisms. For now, however, it is relevant to present standard experimental examples of DWOs taken from literature to help provide an understanding of key instability characteristics.

3.1.2. Studies investigating density wave oscillations in macro-channel systems

Having provided a mechanistic basis for the existence of DWOs in classic macro-channels, examples of experimentally captured occurrences of DWO are provided in Fig. 7. Fig. 7(a) shows DWO induced fluctuations in heater inlet pressure and flowrate captured by Dogan et al. [210] for vertical upflow of Freon-11. DWOs in their system had a period of 1–2 s (frequency of 0.5 – 1 Hz) depending on operating conditions.

It is also possible for DWOs to occur in response to other oscillatory modes. Fig. 7(b), adapted from Yuncu [211], shows DWOs (high frequency mode) superimposed on *Pressure Drop Oscillations* (PDOs, low frequency mode). These will be discussed in more detail in following subsections, but, for now, it is sufficient to note they serve to shift operation from the negative-slope portion of the system pressure drop curve (stable for DWOs, unstable for PDOs) to the low-flowrate, positive slope portion (potentially unstable for DWOs). This behavior is characterized in Fig. 7(c), also taken from Yuncu [211].

Fig. 7(d), adapted from Mishima et al. [125], shows DWOs occurring after a Ledinegg excursion (again shifting system operation to the low flowrate, positive slope portion of the system characteristic curve). Amplitude of DWO-induced flowrate oscillations is seen to increase with increasing heat flux until CHF (burnout) is encountered.

Across the examples shown in Fig. 7(a) – 7(d), it is important to note (1) the relative consistency of frequency and amplitude of DWOs for a given set of operating conditions, (2) the changes of frequency and amplitude of DWOs in response to changes in system operating conditions, and (3) the ability of DWOs to interact with other instability modes. These are all key facets of DWOs that will be explored further.

Unlike Ledinegg instability, where the problem may be avoided by modifying the system to eliminate the negative slope portion of the internal characteristic curve, *Knowledge of Operating Boundaries* is the only option available for DWOs. Further, there are no simple correlations available for DWO stability boundaries (as were presented for OFI point associated with Ledinegg instability), as DWOs appear only for specific combinations of operating conditions dependent on a wider variety of factors. The only viable option for design tools capable of determining whether a system will experience DWOs are full system models (as discussed alongside the sta-

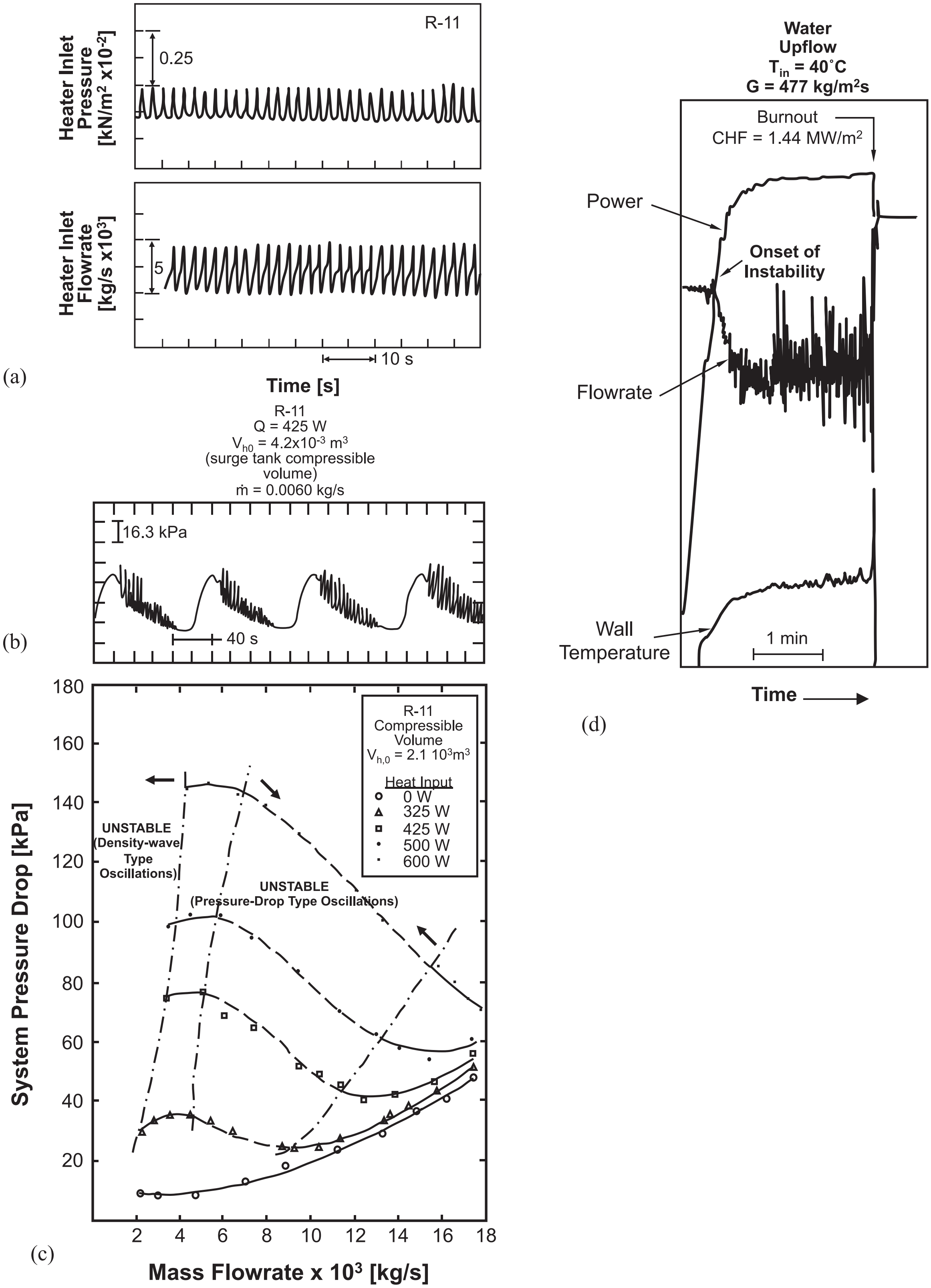


Fig. 7. Experimental examples of Density Wave Oscillations (DWOs), including (a) isolated DWOs, adapted from Dogan et al. [210], (b) DWOs induced by PDOs, adapted from Yuncu [211] with (c) superposition of PDO and DWO conditions on system pressure curves, also from Yuncu [211], and (d) DWO following Ledinegg instability, adapted from Mishima et al. [125].

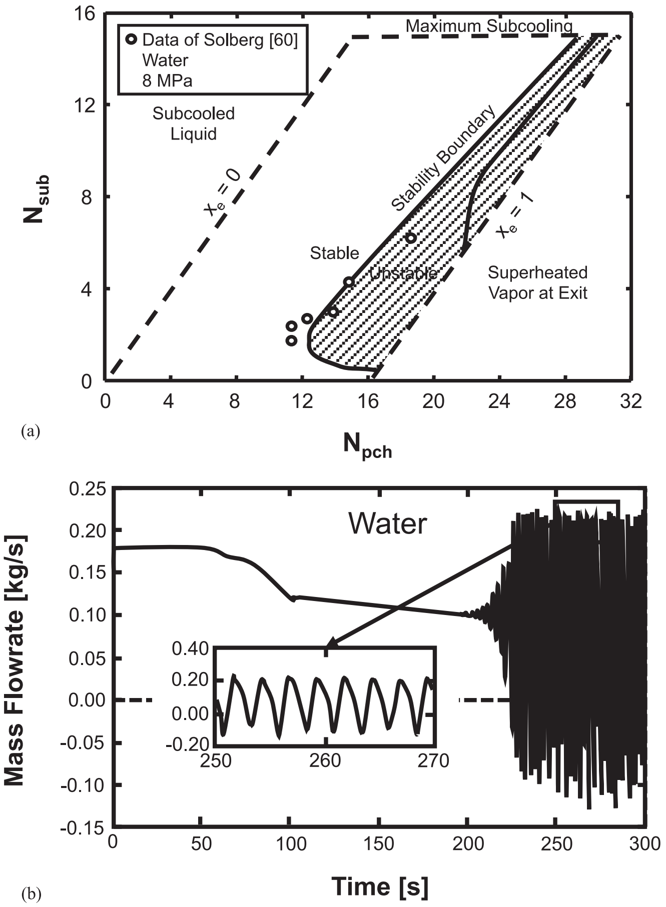


Fig. 8. Examples of results from analytic models used to determine under what conditions Density Wave Oscillations will occur in a given system: (a) stability map of Ishii and Zuber [212] and (b) transient model results of Colombo et al. [214].

bility map of Achard et al. [147] in Fig. 4(d)). These are developed in exactly the same way as described for prediction of Ledinegg instability in Section 2.2, only now they are concerned not with what operating conditions fall on the negative slope portion of the boiling curve, but with what combinations of conditions will lead to unstable feedback mechanisms on the positive slope regions. This is typically determined in two ways: 1) transforming the governing equations into frequency domain and performing stability analysis (D-partition, Nyquist plots, *etc.*), or 2) directly solving the governing equations in time domain and determining for which operating conditions unstable oscillatory phenomena is observed.

One of the earliest works outlining an analytic approach to determining DWO stability boundaries for a given boiling system was provided by Ishii [148]. He presented his results in the form of a stability map [212], shown here in Fig. 8(a), along with validation using experimental results of Solberg [213]. Ishii's use of phase change number,

$$N_{pch} = \frac{Q}{G A_c h_{fg}} \frac{\rho_f - \rho_g}{\rho_g}, \tag{17}$$

versus subcooling number N_{sub} (provided in Eq. (16)) became very popular as these two groups map possible operating conditions a fixed (meaning constant diameter, length, and working fluid) system may encounter.

Fig. 8(b) provides transient model results adapted from the work of Colombo et al. [214]. For a single boiling channel with a constant pressure drop boundary condition, Fig. 8(b) shows how increases in heating power (leading to reductions in mass flowrate on the y-axis) eventually destabilize the system. By keeping track of which conditions lead to destabilizing the system, Colombo et al. [214] were able to use their transient model predictions to create stability maps similar to those of Ishii and Zuber [212].

It is important to recognize stability maps (and predictions of system stability in general) are only valid for given combinations of working fluid, test section length, diameter, boundary conditions, orientation, and others (typically governed by Froude number, confinement number, Euler number, friction number, *etc.*). Due to 2-D limitations associated with presentation of stability maps and the higher-dimensional nature of DWO stability problems, it is critical to understand individual stability maps are not generalizable design tools; it is the methodology used to develop them that may be applied to other systems to determine their stability.

Having provided some examples of experimental characteristics of DWOs and the main methodology used to model them, it is now useful to provide a full summary of existing literature on DWOs in macro-channels. A multitude of studies on DWOs exist in literature, so these will be grouped by experiment-focused, modeling-focused, and combination experimental-modeling studies, with care taken to point out particularly useful studies in each group. This subsection will conclude with a table outlining influences of different key operating parameters on DWO behavior.

Some of the best literature to begin understanding DWOs provides both high-quality experimental results and detailed analytic modeling of the instability mode. One of the earliest works providing both experimental and analytic results for DWOs comes from Jain et al. [215], who investigated boiling of water in a natural circulation loop. They compared their experimental results with models developed by Jones (frequency domain solution approach) [216,217] and Jahnberg (time domain solution approach) [218], and found that of Jones yielded better agreement with their experimentally determined stability boundaries.

Another early work came from Yadigaroglu and Bergles [149], who investigated flow boiling of Freon-113. Their work is notable for experimental and theoretical evidence of higher-order DWOs, or oscillations whose frequencies are multiples of the fundamental DWO mode.

Yuncu [211] provided another comparison of experimental and analytic instability results for flow boiling of R-11 in a horizontal channel. His work is notable for its inclusion of Pressure Drop Oscillations along with DWOs.

Other relevant works including both experimental and analytic investigation of DWOs include those of Saha et al. [219], Fukuda and Kobori [209], and Dogan et al. [210] for forced flow, Guanhui et al. [220] and Nayak et al. [221] for natural circulation, and Chen et al. [222] for cryogenic flow boiling.

Many other authors choose to focus primarily on experimental evidence of DWOs. These include studies on both forced convection [144,223-234] and natural circulation [235-237]. Of note among these are the studies of Sorum and Dorao [229] and Lu et al. [234] for their experimental evidence of the impact of DWOs on deteriorating heat transfer coefficient and CHF, respectively. Another high-quality experimental work from this group is that of Wang et al. [223], who studied DWOs in vertical upflow boiling of water.

Of practical interest from this group are the works of Karsli [225] and Karagoz [226], who investigate DWOs in flow boiling channels with surface enhancement and inserts, respectively. Both show clear changes in stability boundaries for different surface modifications and inserts, indicating 1) theory must be adapted to accommodate systems with atypical surfaces and/or inserts, and 2) the potential to improve system stability through selective use of modifications and inserts. Additional work in this area is recommended.

Finally, a wealth of analytic work has been performed with the aim of better predicting and modeling DWOs

[152–154,157,160,214,238-247]. These are primarily studies modeling forced convection (often with a constant pressure drop assumption), although a significant amount of analytic work has also been done modeling DWOs in supercritical flows [166-173,248-249] (there is significant overlap with the supercritical Ledinegg instability references provided in Section 2.2).

When investigating analytic studies on DWOs, all approaches have strengths and weaknesses, and distinctions may be drawn between them based on a variety of factors including:

1) Modeling approach taken (e.g., Homogeneous Equilibrium Model, Drift-Flux Model, friction factor correlation(s) used, 1-D, 2-D, *etc.*).
2) Linear or non-linear treatment of governing equations.
3) Solution in time-domain or frequency-domain (as mentioned previously).

Across all the studies on classic DWOs in single macro-channels cited here, it can be seen most DWO literature only reports the fundamental modes for DWO, and contains similar types of information:

1) Experimental results depicting conditions for which DWOs will occur.
2) Analytic modeling for the system, allowing prediction (and comparison with experimental results) of conditions that will lead to DWOs.
3) Parametric analysis of experimental results and/or model(s) to assess the impact of variations in key operating parameters on DWO occurrence and behavior within the system.

Item number three is relevant for system designers, and a summary of key parametric trends taken from studies cited here is provided in Table 5. A discussion of parametric trends is also provided in the work of Boure et al. [48]. Their conclusions match well with those in the present work, indicating much of the relevant understanding for classic DWOs has been in place for decades. Key areas for additional study on classic macro-channel DWOs as identified in the current work include (1) orientation effects (2) heated wall thermal mass effects, and (3) impact of surface enhancements.

Despite the wealth of literature focused on DWOs in boiling channels, recent work has found DWOs resulting from atypical feedback mechanisms not well described by classic theory. Atypical mechanisms in macro-channels are described in the following section.

3.1.3. Atypical density wave oscillations in macro-channels

Extensive use of high-speed imaging during flow boiling testing over the past decades have revealed the existence of atypical feedback mechanisms leading to DWOs during flow boiling.

One example of this is found in the work of Khodabandeh and Furberg [250], who investigated flow boiling of R-134a in a thermosyphon. They used test sections with hydraulic diameters spanning 1.2 – 2.7 mm and observed a transition from macro- to micro-channel behavior. Within their macro-channels, they observed flow oscillations due to backflow of liquid into their vertically oriented evaporator at low heating powers (corresponding to low flowrates as thermosyphons are natural circulation systems). This instability mode is characterized by low intensity nucleate boiling followed by liquid rushing into the channel from the exit (backflow) and collapsing vapor back to single-phase liquid flow. After a short period of time, boiling begins again, and the process repeats.

Similar atypical periodic behavior was reported by Aritomi et al. [276] during their work with flow boiling of water in a parallel channel system. They found that, during downflow boiling, the oscillatory mode was fundamentally different from that for upflow. They termed it 'slug excursion' and characterized it by vapor generation forming a vapor slug that excluded the channel. Buoyancy force caused the slug to stagnate and expand towards the channel inlet, where exposure to subcooled liquid led to its rapid collapse and flow of liquid back into the channel. This periodic process occurred only at low flow velocities (less than 30 cm/s) and is representative of an atypical DWO mode.

Fukuda and Kobori [209] reported in their classic study that DWOs may be brought on by feedback between inertia and gravitational effects but provided no examples or modeling of the case experienced by Khodabandeh and Furberg [250] involving liquid backflow into the channel and vapor collapse (nor that of Aritomi et al. [276]). It is these types of mechanisms that may be classified as DWOs (as they are device-level instability mechanisms with period similar to fluid transport time through the test section) but may be considered atypical compared to classic work in the field.

Another recent example may be found in the work of O'Neill et al. [76,251-253], who investigated vertical upflow boiling of FC-72 in a rectangular channel. They observed a characteristic oscillatory mode with period ~ 1.5–2 times fluid transport time through the channel [76] (characteristic of DWOs [48,122]), but largely independent of heat flux within the channel. Extensive analysis of flow visualization images and oscillatory characteristics [252] allowed a mechanistic description of the phenomenon to be formed, presented here in Fig. 9.

Fig. 9(a) provides flow visualization images captured at 2000 frames per second covering the ~11-cm heated length of their test section. Clearly visible is the alternating passage of liquid-dominant (high-density, optically opaque) and vapor dominant (low-density, optically clear) fronts. These high-density, optically opaque regions were termed High-Density Fronts (HDFs), and by identifying consecutive fronts, single-event frequencies were found and seen to match with peak oscillatory frequency of pressure measurements upstream and downstream of the heated length.

Through extensive analysis [76,252], an understanding of the mechanisms responsible for this oscillatory mode was developed, presented schematically in Fig. 9(b). In essence, separated flow within the entire channel (~33-cm adiabatic developing length and ~11-cm heated length) lead body force to drive liquid accumulation at the channel inlet and vapor to exit the channel. This created an instantaneous imbalance for conservation of mass (with the channel effectively beginning to fill with liquid), driving pressure buildup at the inlet and excursion of a liquid slug through the channel, rewetting the walls and satisfying conservation of mass in a time-averaged fashion.

O'Neill and Mudawar developed a model [253] based on this understanding and found excellent agreement for predictions of frequency and amplitude using their experimental datasets.

The key takeaway for these atypical DWO mechanisms is the inability of classic modeling approaches to properly account for them (primarily due to non-continuum effects, such as liquid accumulation in the inlet region for O'Neill et al. and backflow of subcooled liquid collapsing vapor for Khodabandeh and Furberg [250]. Fukuda and Kobori [209] famously identified numerous different forcing mechanisms for DWOs (depending on orientation and operating conditions), but all of these could be captured using classic modeling approaches.

There clearly exist feedback mechanisms in two-phase flow leading to DWOs that are not well understood using classic analysis discussed in Sections 3.1.1 and 3.1.2. Perhaps no better example of this exists than flow boiling in micro-channels.

3.1.4. Existence and characteristics of density wave oscillations in micro-channels

As discussed in Section 1.3, flow boiling in micro-channels is fundamentally different from that in macro-channels due to the comparable size of bubble and hydraulic diameter in the former.

Table 5
Parametric trends for traditional (macro-channel) Density Wave Oscillations.

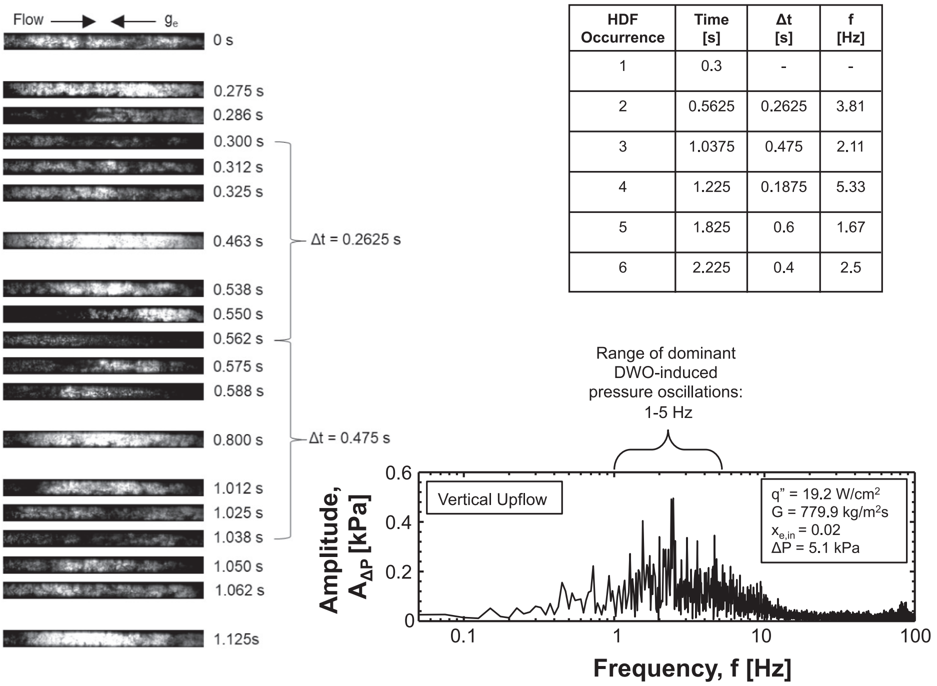
Parameter	Effect	Mechanism	References
Heating Power	Increase in heating power acts to destabilize flow (up to the point where CHF/dryout occurs).	Increasing heating power leads to more vigorous boiling and larger two-phase pressure drop, commonly leading to a negative shift in marginal stability boundary and/or increase in amplitude of oscillations.	Colombo, 2012 [214] Boure et al., 1973 [48]
Inlet Subcooling	Increasing subcooling is often stabilizing for high initial subcooling, destabilizing for low initial subcooling.	The nonlinear effect associated with changes to inlet subcooling may be attributed to changes in the relative lengths of single-phase and two-phase regions.	Wen, 2018 [237] Guanghui, 2002 [220] Comakli, 2002 [224] Colombo, 2012 [214] Boure et al., 1973 [48]
Mass Flowrate	Increasing mass flowrate improves stability. If flow is already unstable, increasing mass flowrate increases amplitude and period of oscillations (may decrease period, depending on DWO mechanism).	For a given heat flux, increasing mass flowrate reduces the two-phase length and may improve stability. However, for conditions already exhibiting DWO, higher mass flowrate means the instability manifests with additional energy (increasing amplitude). Effect on frequency depends on DWO type.	Guanghui, 2002 [220] Comakli, 2002 [224] Boure et al., 1973 [48]
Operating Pressure	Increasing operating pressure has a stabilizing effect. Once the instability manifests, increasing pressure leads to increased period.	Increasing operating pressure leads to a slight positive shift in marginal stability boundary due to the reduction in density difference between phases and reduction in void fraction (for a constant heating power).	Guanghui, 2002 [220] Furuya, 2005 [235] Colombo, 2012 [214] Dorao, 2015 [228] Boure et al., 1973 [48]
Inlet Throttling	Increasing inlet throttling has a stabilizing effect.	Increasing the single-phase pressure drop (relative to the two-phase) improves stability of the channel.	Colombo, 2012 [214] Boure et al., 1973 [48]
Outlet Throttling	Increasing exit throttling has a destabilizing effect.	Increasing the two-phase pressure drop (relative to the single-phase) reduces stability of the channel.	Colombo, 2012 [214] Boure et al., 1973 [48]
Orientation	Changes in orientation may be stabilizing or destabilizing, depending on other factors.	Changes in orientation often lead to changes in dominant feedback mechanism(s) causing DWO. This may be a positive or negative depending on specifics. Additional study necessary.	Fukuda & Kobori, 1979 [209]
Channel Length	There exists a critical channel length, prior to which increases in length destabilize flow, after which increases to length stabilize flow.	Deals with relative contribution of single-phase and two-phase lengths. This needs experimental verification.	Liu et al., 2018 [249] Comakli et al., 2002 [224] Paruya et al., 2012 [243] Boure et al., 1973 [48]
Heated Wall Thermal Mass	Changes in thermal mass of heated wall(s) will alter stability characteristics of a given channel.	Numerical results show stability increasing with wall thermal mass, but experimental results show non-linear trend (first decreases, then increases). Needs additional verification.	Liu et al., 2018 [249] Zhang et al., 2018 [230]
Channel Hydraulic Diameter	Hydraulic diameter affects stability in the sense increases or decreases will require more or less heater power to establish similar single-phase and two-phase lengths. Once it becomes a micro-channel, however, DWOs exhibit very different characteristics.	Diameter does not directly impact channel stability, only in conjunction with other operating conditions.	Nayak et al., 2006 [221]
Compressible Volume	Typically important for occurrence of Pressure Drop Oscillations, some results indicate it may increase DWO amplitude.	Resonance of compressible volume with DWO acts to increase amplitude (in the absence of PDO). Needs additional verification.	Park et al., 2018 [232]
Surface Enhancement/Modification	Stability boundaries may be positively or negatively affected. Oscillatory characteristics also impacted.	Result depends on relative impact to single-phase and two-phase portions of boiling channel. Additional study necessary.	Karsli et al., 2002 [225] Karagoz et al., 2009 [226]

This leads to a distinctly different mechanism for DWOs in micro-channels.

Fig. 10(a) provides a set of schematics illustrating key concepts behind the dominant mechanism for DWOs in micro-channels. This description draws largely from the work of He et al. [254], who developed a model for bubble growth leading to flow reversal and pressure fluctuations in a micro-channel (DWOs).

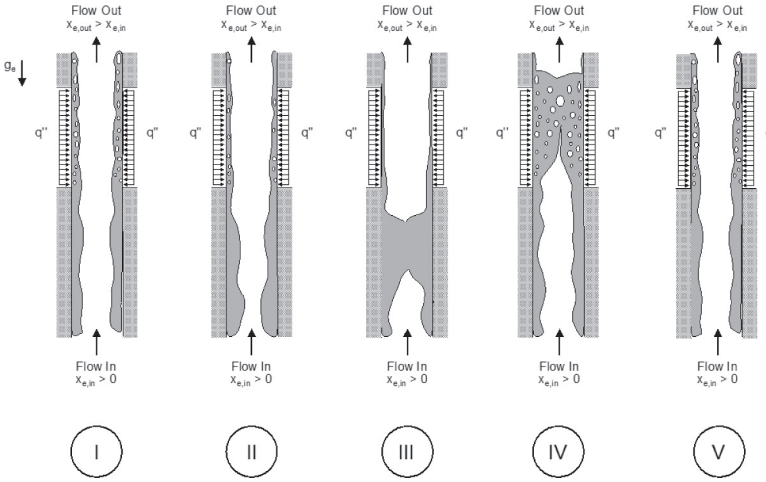
He et al. describe bubble growth in a micro-channel occurring in three stages or states:

1) *Free growth*, where the bubble is unconstrained and expands in a spherical fashion (as it would in a macro-channel).
2) *Partially confined growth*, where the bubble growth becomes inhibited by the channel cross-section along one dimension (the width in Fig. 10(a)).
3) Fully confined growth, where the bubble occupies the entire cross-section of the channel and must expand axially in response to any additional phase change.



HDF Occurrence	Time [s]	Δt [s]	f [Hz]
1	0.3	-	-
2	0.5625	0.2625	3.81
3	1.0375	0.475	2.11
4	1.225	0.1875	5.33
5	1.825	0.6	1.67
6	2.225	0.4	2.5

(a)



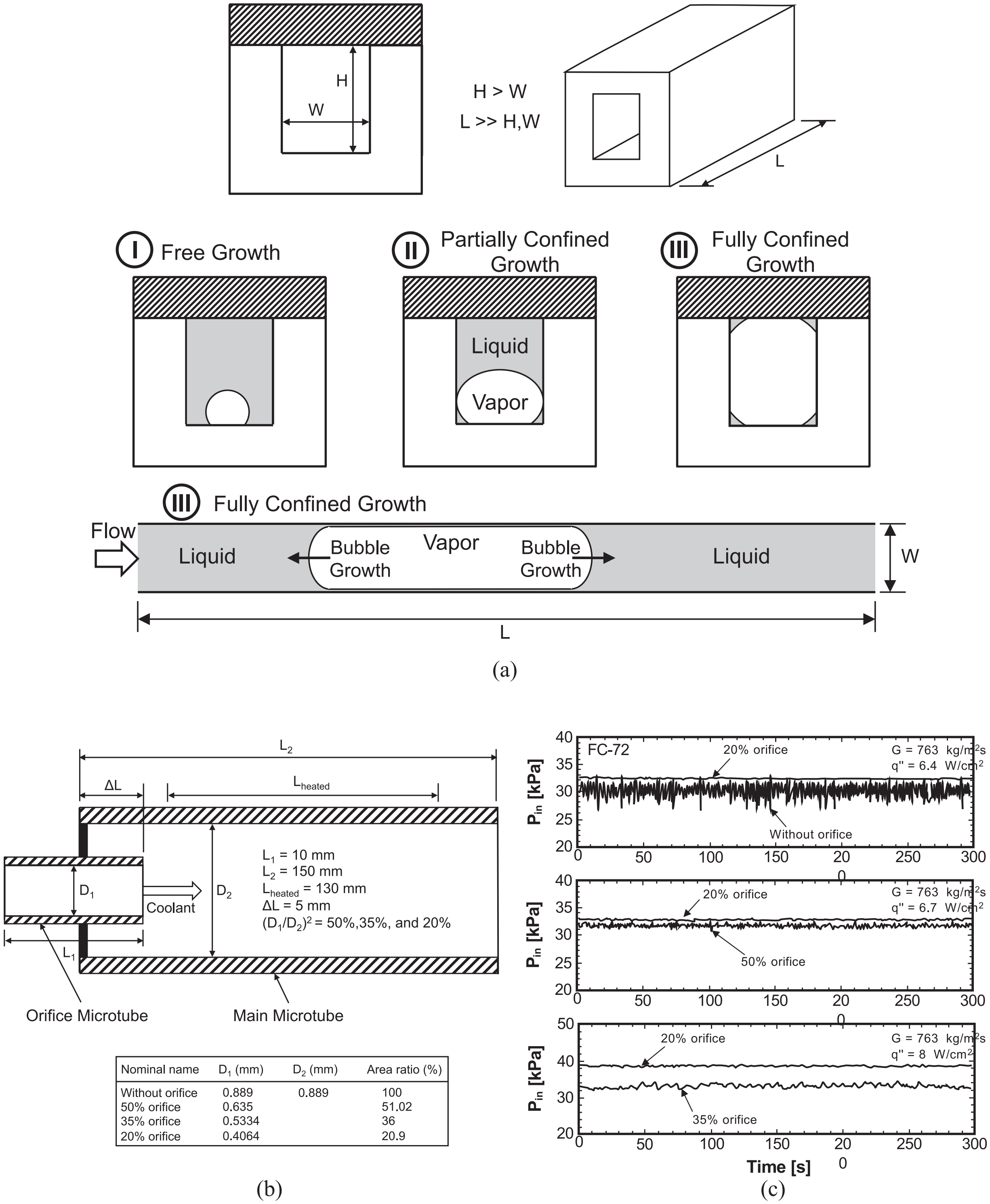
Stage	Description
I	In its initial state, annular co-current flow dominates throughout the length of the channel. Phase change occurs along the heated length due to energy provided by two sets of electric heaters mounted on opposite walls.
II	Due to the significant influence of body force on the liquid film compared to that on the vapor core, liquid film flow along the channel stagnates, and liquid begins accumulating towards the entrance region of the channel. This leads to reduced liquid content in the downstream portion of the channel, causing the liquid film along the heated length to begin to dry out.
III	As the liquid film thickness increases in the region upstream of the heated length, mass is no longer conserved within the channel. This is due to a disproportionate ratio of vapor to liquid exiting the channel, versus that entering the channel. In an effort to rectify the situation, the momentum of the accumulated liquid is increased by the difference in momentum flux between upstream and downstream regions, and it begins to move along the channel, re-wetting the walls in its wake. In this manner, the high density front (HDF) moves along the channel to ensure conservation of mass (on a time-averaged basis), re-wetting the liquid film in its wake. Just prior to the HDF reaching the heated length, the liquid film within the heated length is at its minimum thickness, and flow exiting the channel is almost entirely vapor.
IV	As the HDF passes through the heated length of the channel, re-wetting the heated walls, nucleation boiling is re-established. In the wake of the HDF liquid film, thickness is returned to nominal value and annular, co-current flow is reestablished. Flow exiting the channel is still mostly vapor, but the accumulated liquid (HDF) will soon pass, satisfying the hitherto violated conservation of mass.
V	HDF having exited the channel, the flow returns to its initial state of parallel, co-current annular flow throughout the channel length. Body force effects soon begin to dominate once more, however, and the cyclical formation of high density fronts continues. This cyclical process is how Density Wave Oscillations (DWOs) manifest within two-phase flow in mini/macro channels.

(b)

Fig. 9. (a) Experimental evidence for and (b) explanation of an atypical DWO mechanism investigated in a series of studies by O'Neill et al. [76,251–253].

It is important to recognize these three states correspond to both (i) the nucleation process of a single bubble at high heat flux and low flowrate (continuing to expand from state 1 through 3) and (ii) changes in nucleation behavior at a single location in response to increasing heat flux (at low heat flux, the bubble may depart during free growth and be advected through the channel, while increasing heat flux will lead to partial or full confinement before exiting the channel).

The final schematic in Fig. 10(a) shows an axial view of the fully confined growth case, illustrating how, for high heat fluxes,



Nominal name	D_1 (mm)	D_2 (mm)	Area ratio (%)
Without orifice	0.889	0.889	100
50% orifice	0.635		51.02
35% orifice	0.5334		36
20% orifice	0.4064		20.9

Fig. 10. (a) Schematic illustrating the key condition for Density Wave Oscillation in a micro-channel (presence of fully confined vapor growth) based on the work of He et al. [254]. (b) Illustration of orifice use at inlet to micro-channel, and (c) experimental results depicting impact of inlet orifice on damping/elimination of DWOs in the micro-channel, adapted from Fan and Hassan [260].

phase change will cause the bubble to expand towards the channel exit as well as inlet. It is this case (and specifically the bubble expansion towards the channel inlet) which leads to DWOs in micro-channels. Fully confined bubble growth towards the channel inlet reduces flowrate (potentially leading to backflow). This leads to further bubble expansion towards the inlet, causing inlet pressure to build. Eventually inlet pressure reaches a level sufficient to overcome the fully-confined bubble, and liquid rushes back into the channel, advecting the bubble out of the micro-channel. High frictional pressure drop associated with this liquid surge causes flowrate in the channel to decrease back to a nominal level, bubble growth begins again, and the process repeats.

This phenomenon is undoubtedly a DWO, although fundamentally different than that observed in single macro-channels. The following subsection will provide a summary of literature investigating DWOs in single micro-channels. It should be mentioned, however, that most work on DWOs in micro-channels corresponds to parallel micro-channel heat sinks and will be addressed separately in a section on Parallel Channel Instability (PCI).

3.1.5. Studies investigating density wave oscillations in micro-channels

One of the earliest investigations of flow instability in a single micro-channel was done by Brutin et al. [255,256]. They studied flow boiling of n-pentane in a channel with hydraulic diameter D_h = 0.889 mm and observed significant inlet pressure fluctuations corresponding to confined-growth phenomena similar to those described in Fig. 10(a). They also showed clearly how confined growth could lead to a rapid transition from bubbly flow to annular flow and near-dryout prior to liquid rushing back into the channel, something Mudawar [69] also identified as a key concern when utilizing micro-channel heat sinks as it may lead to premature CHF.

Another important early work is that of Wang et al. [257], who studied flow boiling of water in both single and 8 parallel trapezoidal micro-channels with D_h = 0.186 mm. They also reported a similar mechanism of confined vapor growth leading to instability and backflow towards the inlet in unstable cases, while stable cases showed isolated bubbles being generated and advected out of the channel.

Wang and Cheng [258] investigated flow boiling of water in a channel with D_h = 0.155 mm. They attributed oscillations in their system to Pressure Drop Oscillations (PDOs) with superimposed DWO.

Barber et al. [259] studied flow boiling of n-pentane in a channel with D_h = 0.727 mm. Their work included the interesting observation that deformation of the liquid-vapor interface in the case of confined bubble growth could play a significant role in high-frequency pressure oscillations observed in micro-channel flow boiling.

Relevant in the context of Section 2.4 (dealing with flow regime transition instability) is the work of Celata et al. [72], who found that, while a variety of flow regimes occurred in their channel (FC-72, D_h = 0.48 mm), changes in flow regime did not necessarily correspond to instability. This further reinforces the idea presented in Section 2.4 that most fluctuations in flow regime are a result of other instability modes, and though they may act to amplify pressure/flowrate/temperature fluctuations, they are not a fundamental instability.

One of the most interesting works on flow boiling in a single micro-channel comes from Fan and Hassan [260]. They studied flow boiling of FC-72 in a single micro-channel with D_h = 0.889 mm and included inserts to provide inlet orifices for their test section. This is shown schematically in Fig. 10(b), with Fig. 10(c) illustrating how these orifices act to damp out or even eliminate DWOs depending on percent inlet restriction. This is a very important practical conclusion as it provides a way to avoid the adverse impact of DWOs in micro-channels (although coming at the expense of heightened pressure drop). This method shows clear parallels with the tactic of adding a throttling valve at the channel inlet for macro-channels, which extensive literature in Section 3.1.3 showed to have a stabilizing effect on DWOs (and also to help prevent Ledinegg and PDO).

Theoretical approaches to predicting onset of DWOs in micro-channels are limited compared to those for DWOs in macro-channels. He et al. [254] developed their model for expansion of a single bubble, but did not adapt it to account for the realistic effects often encountered in micro-channels (e.g., bubble merger prior to confined expansion [255-257]).

Li and Hrnjak [261] also undertook modeling based on a mechanistic definition similar to that of He et al. [254] and provided some comparison with flow visualization images. Additional work is recommended, however, with efforts focused on matching qualitatively (vapor fraction and distribution) and quantitatively (inlet and exit pressure, interface speed) with experimental results.

This and the preceding section provided the fundamental basis for DWOs in a single micro-channel. Results discussed here will become relevant again when discussing parallel channel instability in micro-channel heat sinks (for which work has been far more prolific), where feedback effects between DWOs in individual micro-channels act to further destabilize the system.

3.1.6. Density wave oscillations in flow condensation

Thus far in the present review, flow condensation has been mentioned only in the section discussing flow regime transition instability. As shown in Fig. 2(b), condensing flows cannot manifest a negative slope portion of their internal characteristic curve, meaning they are not subject to Ledinegg instability (or Pressure Drop Oscillations, as will be explained in a later section). They also do not possess many of the local instabilities associated with boiling, such as CHF, vapor burst, or rapid bubble growth, meaning condensation is generally much more stable than boiling.

Despite this, one instability mode condensing flows manifest is DWOs. Although receiving far less attention than boiling DWOs, their existence has been confirmed through several experimental and theoretical studies.

In the 1960′s, Westendorf and Brown [262] observed high and low frequency oscillatory modes present in direct condensation of saturated water vapor and subcooled liquid and found the modes could be related to liquid subcooling.

Goodykoontz and Dorsch [263] studied flow condensation in a traditional tube-in-tube configuration and observed pressure oscillations with frequencies in the 1–10 Hz range, although only for what they termed moderate condensation lengths (1.7 – 3.7 feet). This restriction to a specific length range corresponds well to the theoretical understand of DWOs in macro-channels presented in Section 3.1.1, with DWOs only manifesting for cases where single-phase and two-phase lengths were comparable and provided pressure drop contributes which oscillate out-of-phase.

Around this time, Soliman and Berenson [264] investigated flow condensation of R-113 in a multi-tube condenser in vertical upflow, vertical downflow, and horizontal flow orientations. They observed two distinct oscillatory modes, one for vertical upflow and another for horizontal and vertical downflow orientations, and noted amplitude of pressure oscillations always remained below 5% of nominal inlet pressure for horizontal and vertical downflow orientations, and below 10% for vertical upflow.

These conclusions are similar to those from a recent study by O'Neill et al. [192], who performed flow condensation testing using FC-72 in a circular tube in vertical upflow, downflow, and horizontal orientations. Clear differences were seen between oscillatory mode in vertical upflow with those in horizontal and vertical downflow. In a follow up study, O'Neill et al. [193] were able to leverage the differences in oscillatory mode in vertical upflow to develop a criterion for determining whether flow is *co-current* or *counter-current*, which is of great practical relevance in situations when flow regime may not be determined optically.

A variety of other studies have investigated transient flow condensation behavior, including in U-tube condensers [265], flow through an annulus [266], multi-tube condensers [267], and micro-channels [95]. Some analytic work has also been performed, including standard stability models [268,269], and those seeking to assess the impact of classic hydrodynamic instability present in condensing flows [42] on system pressure fluctuations and flow regime transition [267,270-271].

Across these works, key takeaways are the existence of DWOs in condensing flows and the impact of flow orientation on instability characteristics. It is also important to note DWOs in condensing flows are typically considered far less dangerous than those in boiling flows as there is no potential for them to trigger burnout or any other catastrophic system failure.

3.1.7. Summary of findings relating to density wave oscillations

The current section is by far the longest in the present work, reflecting both the pervasive nature of DWOs in boiling systems and the complexity in determining exactly which factors may lead to their occurrence. Key conclusions from this section are:

1) DWOs occur in macro-channels due to out-of-phase oscillations of pressure drop in single-phase and two-phase portions of the channel. These may occur in both boiling and condensing flows.
2) Theoretical modeling of DWOs is a well-developed field, and a variety of approaches exist to determining stability boundaries for classic DWOs in macro-channels. Parametric influences are also well understood, with information summarized in Table 5.
3) Atypical DWOs exist and are commonly related to backflow and pseudo-compressibility effects in macro-channels. In micro-channels, these are related to rapid expansion of confined bubbles towards the channel inlet.

Further highlighting their importance as a fundamental two-phase flow instability, DWOs will feature prominently in the following section dealing with Parallel Channel Instability. Here, feedback effects between out-of-phase DWOs occurring in parallel boiling channels will be seen to lead to significant adverse effects in two-phase flow systems.

3.2. Parallel channel instability

Similar to Flow Pattern Transition Instability discussed in Section 2.4, Parallel Channel Instability (PCI) may refer to either static or dynamic phenomenon. The following subsection provides a brief description of the fundamental mechanisms behind these instability modes.

3.2.1. Existence and characteristics of parallel channel instability

Instability modes in parallel channels are identical in mechanism to those in single channels, but with interactions across multiple channels adding complexity. Fig. 11(a) provides a schematic of

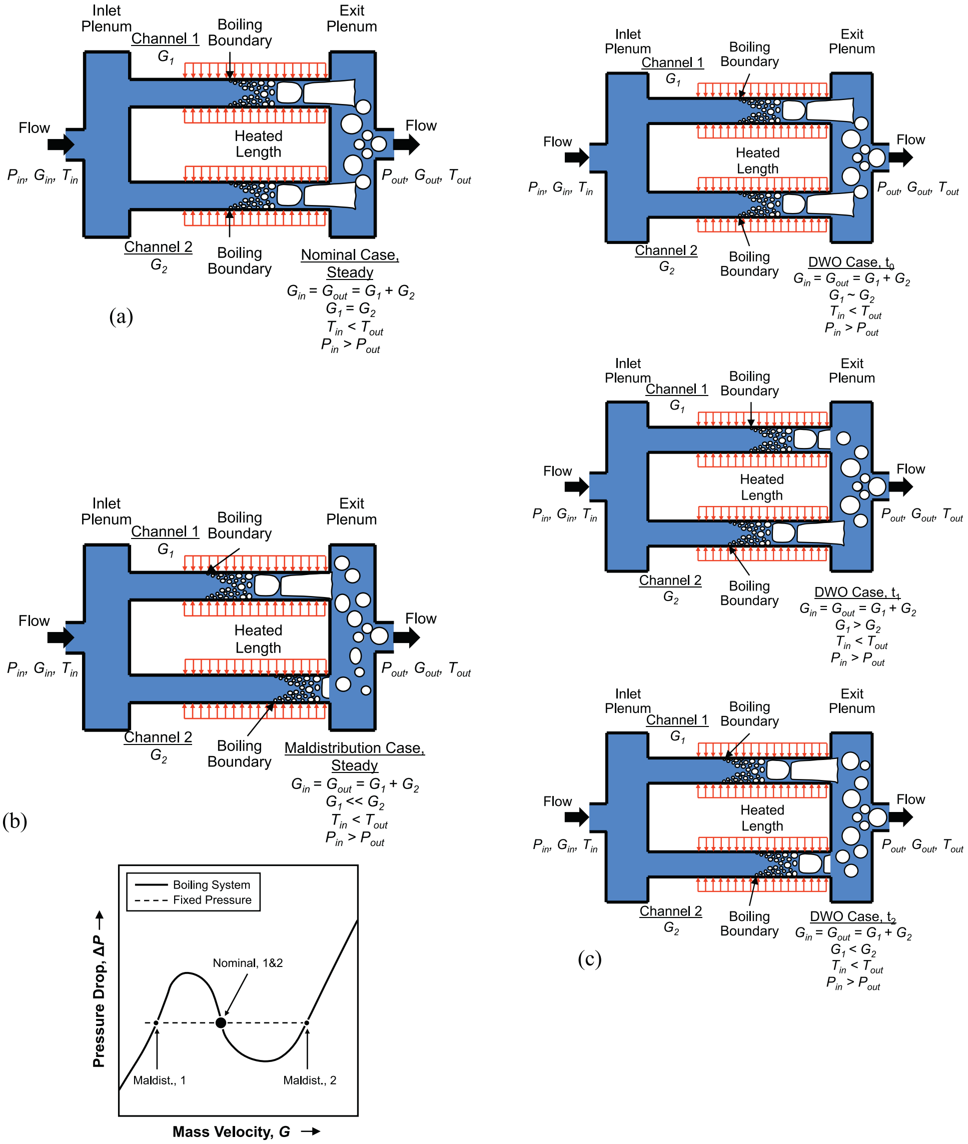


Fig. 11. Schematics depicting (a) nominal operation of two parallel boiling channels, (b) parallel boiling channels experiencing Flow Maldistribution (Ledinegg instability), and (c) parallel channels exhibiting out-of-phase Density Wave Oscillations (DWOs), referred to as Parallel Channel Instability (PCI).

a sample case with boiling in two parallel channels connected by inlet and exit plenums. For nominal, stable operating conditions, Fig. 11(a) shows how flow is split evenly between the two boiling channels, with equal vapor generation and flowrate in each.

For operation on the negative slope portion of the internal characteristic curve with a constant pressure drop boundary condition (characteristic of many parallel channel systems, as discussed in Section 2.2), a perturbation in one or more boiling channels will lead to Ledinegg instability. In a single-tube system this would mean the entire system departs to either a lower- or higher-flowrate condition, after which burnout may be encountered. Fig. 11(b), however, shows how, in parallel channel systems, this is not the only possible outcome: The presence of multiple flow paths means total flowrate may be maintained, while flow distribution across the two channels becomes drastically different (as indicated by $G_1 << G_2$ in Fig. 11(b)). This stable state (unless CHF is encountered) is often termed 'Flow Maldistribution' in literature, and its mechanism is identical to Ledinegg instability (covered in Section 2.2 of the present review).

The final (and most relevant) case is that of boiling in a parallel channel system where Density Wave Oscillations (DWOs) may occur. Interaction between parallel channels may lead to either 1) total flowrate held constant while flowrates in individual channels oscillate out-of-phase, or 2) total flowrate oscillating as individual channel flowrates remain equal but oscillate in-phase. Fig. 11(c) presents schematics corresponding to the first case, showing how boiling boundary position oscillates out-of-phase between the two channels.

It is this dynamic, oscillatory mode depicted in Fig. 11(c) which is commonly termed *Parallel Channel Instability* (PCI), and which will be addressed at length in the current section. Its dependence on DWOs as the fundamental mechanism means much of the modeling approach and theoretical analysis have already been presented in Section 3.1, but the interactions between parallel channels, in-phase versus out-of-phase behavior, and, in particular, its manifestation in micro-channel heat sinks (where it may lead to premature CHF) mean PCI warrants separate analysis from that provided for DWOs in the prior section.

3.2.2. Studies on parallel channel instability in macro-channel systems

Similar to Density Wave Oscillations (in fact, *because* of DWOs), Parallel Channel Instability (PCI) manifests differently in macro- and micro-channel systems. The present section aims to provide an overview of relevant literature dealing with PCI in macro-channel systems. As mentioned in the preceding subsection, the 'Flow Maldistribution' instance of PCI is a static instability, and literature regarding it is covered in Section 2.2 [129,135,147,151,162,175]. Recent analytic work on this topic specific to micro-channels is also available from Oevelen et al. [272,273].

One of the earliest works dealing with PCI is that of Hayama in 1967 [274]. Analytic modeling in his study established that, for a system of N parallel channels, there will be N possible modes of oscillatory flow, one with oscillations in-phase between all channels, and $N-1$ with different phases and amplitudes across channels.

This concept was reinforced in a series of studies by Aritomi et al. [275-279]. They studied flow boiling of water in parallel channels both experimentally and analytically. Fig. 12(a) provides a sample of their experimental results, highlighting how flowrates in parallel channels oscillate 180° out-of-phase, maintaining a constant combined flowrate.

Similar work was carried out by Fukuda and Hasegawa [280,281]. Their 1984 work in particular [277] does an excellent job of comparing analytic and experimental results, focusing discussion on initial difficulties in capturing DWO characteristics in parallel channel systems.

Additional refinement to analytic modeling of PCI occurred over recent decades, including the works of Guido et al. [282], Nayak et al. [162], Lee and Pan [283], Zhang et al. [284], and Zhang et al. [285]. Fig. 12(b) provides a sample of results from Lee and Pan [283] showing oscillatory modes for a simulated 5-channel system. Interesting to note is four of the five channels (2 – 5) oscillate in-phase, while the fifth (channel 1) oscillates 180° out-of-phase while maintaining amplitude equal to that of the first four combined.

Experimental verification of this predicted behavior is found in the work of Jain et al. [286] who studied natural circulation flow boiling of water through four parallel channels. They saw similar behavior in their system, with different cases showing different combinations of channels oscillating in-phase versus out-of-phase. They also noted phase difference(s) between channels could change slightly over the duration of experiments.

Other works on macro-channel PCI include those of Ozawa et al. on adiabatic gas-liquid two phase flow [287], Xiong et al. [288] and Xie et al. [289] on PCI in supercritical flows (Xiong et al. in particular do an excellent job of presenting experimental evidence of PCI), Papini et al. [290] in parallel vertical helically-coiled tubes, and Ma et al. [291] on the effects of heat flux profile (generated by counterflow of liquid sodium) on PCI. It is also worth recognizing the significant work on PCI including the effect of neutron-kinetics, relevant for nuclear reactor design [292-297]. These will not be analyzed here as they represent a specific subcase of PCI, but recognition of their existence is important for engineers working in the nuclear field.

Across all works on PCI in macro-channels, parametric trends for onset of PCI and oscillatory characteristics (amplitude, frequency) resemble those for DWOs in solitary channels. This makes intuitive sense, as DWOs are the fundamental mechanism leading to the onset of PCI. Because of this, Table 5 contains relevant information for trends relating to PCI.

One interesting addition is repeated mention of intentional differences to channel characteristics leading to improved system stability [277] (or in the case of Zhang et al. [285] the ability to use flow-control to suppress PCI). In their early work, Aritomi et al. [277] showed that different heat flux and/or inlet throttling values applied to parallel channels led to a new stability boundary roughly equivalent to that of the average values applied to both channels.

One area that remains somewhat unclear is the impact of increasing channel number on marginal stability boundary (MSB, combination of conditions for which the system will transition from stable to unstable operation) of the system. The analytic work of Lee and Pan [283] showed complex, non-monotonous changes to stability boundary as the number of parallel channels increased, but this has not been rigorously verified by experimental results. This trend will be discussed further in the following subsection dealing with PCI in micro-channels.

3.2.3. Studies on parallel channel instability in micro-channel systems

Prior to discussing literature investigating PCI in micro-channels, it is necessary to mention proper identification of PCI in micro-channels. Unlike macro-channel systems, it is currently impossible to include independent flow meters and/or pressure measurements in parallel channels for micro-channel heat sinks. Because of this, common measurements used for identifying instabilities in micro-channel heat sinks are inlet and exit plenum pressure measurements (as well as direct optical access, although these are rarely used in a quantitative fashion).

Fig. 12(c) provides plots of inlet and exit plenum pressure versus time adapted from the work of Qu and Mudawar [298], who

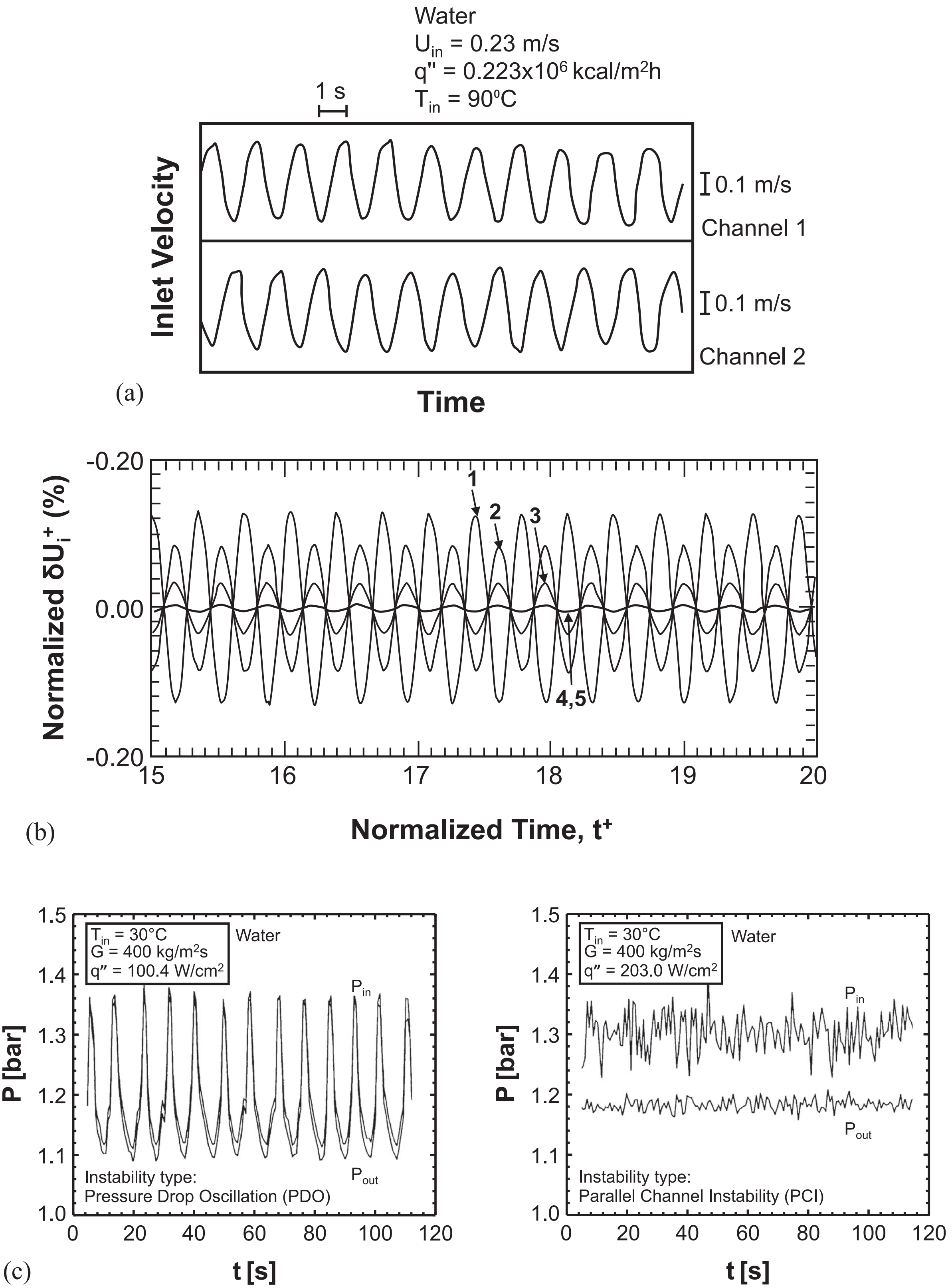


Fig. 12. Plots of (a) inlet velocity versus time showing Parallel Channel Instability 180° out-of-phase between two channels, adapted from Aritomi et al. [275–279], (b) fluctuations in non-dimensional inlet velocity versus non-dimensional time showing PCI in a five-channel system, adapted from analytic work of Lee and Pan [283], and (c) experimental results highlighting the difference between Pressure Drop Oscillations (left) and PCI (right) in parallel micro-channel heat sinks, adapted from Qu and Mudawar [298].

investigated flow boiling of water in a micro-channel heat sink with $N = 21$ channels of $D_h = 0.349$ mm. The first plot clearly shows both inlet and exit pressure oscillating with high amplitude and low pressure, and corresponds to Pressure Drop Oscillations (PDOs, to be discussed in detail in the following section). The second plot represents similar flowrate and inlet temperature, now with a throttling valve upstream of the test section to eliminate PDOs (by eliminating the negative slope region on the internal pressure curve). In this case, inlet pressure oscillates with moderate amplitude while exit pressure hardly oscillates at all. This is similar to behavior observed for DWOs in single micro-channels discussed in Section 3.1.5 and is representative of PCI occurring in a micro-channel heat sink. It is this type of inlet pressure oscillation that is commonly used to identify the presence of PCI in micro-channels.

The early work of Qu and Mudawar [298] is joined by studies from Wu and Cheng [299] and Peles [300], who presented evidence of PCI in micro-channel heat sinks around the same time. The ability of parallel micro-channel heat sinks to offer greatly improved heat transfer performance for small surface areas meant the amount of literature on the topic proliferated in the following years with many authors showing 1) the advantages of micro-channel heat sinks from a heat transfer standpoint, and 2) the limiting effects of PCI in these heat sinks.

Notable experimental works characterizing PCI in micro-channels include those by Cheng and co-authors [257,301-303], Mudawar and co-authors [75,82,304-306], Hetsroni et al. [307], Chang and Pan [308], Bogojevic et al. [309], and Lee et al. [310]. From these works, many of the dominant trends relating to onset of PCI as well as PCI characteristics are summarized as:

1) Decreasing mass velocity and/or increasing heat flux (i.e., increasing exit quality) leads to onset of PCI in micro-channel heat sinks.
2) Frequency and amplitude of oscillations are dominated by heat flux (increasing as heat flux increases), although mass velocity also plays a non-linear role on amplitude [306].
3) Generally, frequency and amplitude are governed by the length of liquid upstream of confined bubble growth, with longer liquid lengths yielding lower frequencies and amplitudes [306].
4) Vapor backflow into the inlet occurs primarily for very high heat fluxes [304], and significantly affects dynamics of inlet plenum [306].

Many of the authors listed above present criteria and/or stability maps for detailing the onset of PCI. Several of these are expressed as transition criteria using a ratio of heat flux to mass velocity (q''/G) [309] or exit quality [303], both of which involve the dominant parameters of flowrate and heat flux. These are not expected to generalize well, however, due to their omission of differences in surface tension and diameter effects critical to the onset and characteristics of DWOs in micro-channels (see Section 3.1.5) which in turn cause PCI in parallel micro-channel heat sinks.

A more sophisticated approach is that recommended by Lee et al. [310], who introduced a parameter R defined as the ratio of force terms acting backwards (towards the inlet) to the force terms acting forwards (including expansion and inlet orificing components). Formally, this was expressed as

$$R = \sqrt{\frac{F_{back}}{F_{forward} + F_{\exp} + F_{orf}}}, \tag{18}$$

with individual terms defined as

$$F_{back} = \frac{1}{4\rho_g A_c}\left(\frac{Q}{h_{fg}}\right)^2, \tag{19}$$

where $A_c$is the channel cross-sectional area and Q total heat input in a channel,

$$F_{forward} = \frac{G^2 A_c}{\rho_f}, \tag{20}$$

$$F_{\exp} = \sigma\left(\frac{1}{W_1} - \frac{1}{W_2}\right)A_{c,1}, \tag{21}$$

where $W_1$and W_2 represent changing widths of the micro-channel and $A_{c,1}$ is cross-sectional area in the upstream portion (Eq. (21) deals with expanding microchannels, discussed further in Section 3.2.4), and

$$F_{orf} = \frac{1}{2\rho_f}\left(\frac{GA_{c,1}}{A_{c,orf}}\right)^2 K_{orf} A_{c,1}, \tag{22}$$

where $A_{c,orf}$ is the cross-sectional area of an inlet orifice (such as that shown in Fig. 10(b)) and K_{orf} the inlet orifice loss coefficient. More information on defining and evaluating these terms may be found in the original work [310].

Lee et al. [310] used this parameter to predict whether PCI would occur (if $R > 1$, forces acting to drive backflow are greater than those for forward motion and DWOs should occur) in straight micro-channels, expanding micro-channels, and micro-channels with inlet orifices, and showed excellent agreement with their experimental results. More than this agreement, however, is the relatively simple yet comprehensive modelling approach adopted: By capturing important effects relating to channel flow area, inlet restriction, surface tension, and vapor generation rate, they provided fundamental groundwork for researchers seeking to begin optimizing parallel micro-channel heat sink design to provide stable flow while minimizing pressure drop through inclusion of geometry modifications.

Unlike PCI in macro-channels (and almost all other instability modes discussed in this study), PCI in micro-channel heat sinks has received relatively little analytic focus in literature. Instead, researchers have focused on exploring practical modifications to heat sink geometry to reduce and/or eliminate PCI.

3.2.4. Geometry modifications to suppress/eliminate PCI in parallel micro-channel heat sinks

Despite the (comparative) lack of theoretical work related to PCI in micro-channel heat sinks, extensive mitigation methods are available in the form of geometry modifications. These are summarized in a recent review by Liang and Mudawar [116] and presented at length in the work of Prajapati and Bhandari [59]. Specifically, Table 3 in the work of Prajapati and Bhandari [59] does an excellent job of providing a summary of proposed mitigation techniques and the studies investigating them. For the sake of the current work, two of the more common configurations will be discussed, and their respective impact on PCI assessed.

Continuing with the fundamental understanding of forces developed by Lee et al. [310], it is clear the purpose of geometric modifications to micro-channel heat sinks is to increase the resistance to vapor expansion towards the channel inlet (which leads to flow reduction or backflow depending on intensity of vapor generation as discussed in Section 3.1.5). The most commonly used schemes for this purpose are inlet restriction/orificing and diverging channels. An early study by Wang et al. [303] showed the ability of added orifices at individual channel inlets to suppress PCI (and thus backflow). They also came to the interesting conclusion that flow into the inlet plenum and leaving the exit plenum affect stability characteristics significantly, with flow entering parallel to channels (e.g., that in Fig. 11) exhibiting greater stability than that entering/leaving plenums at a 90° angle to channel direction (from the bottom of the inlet plenum).

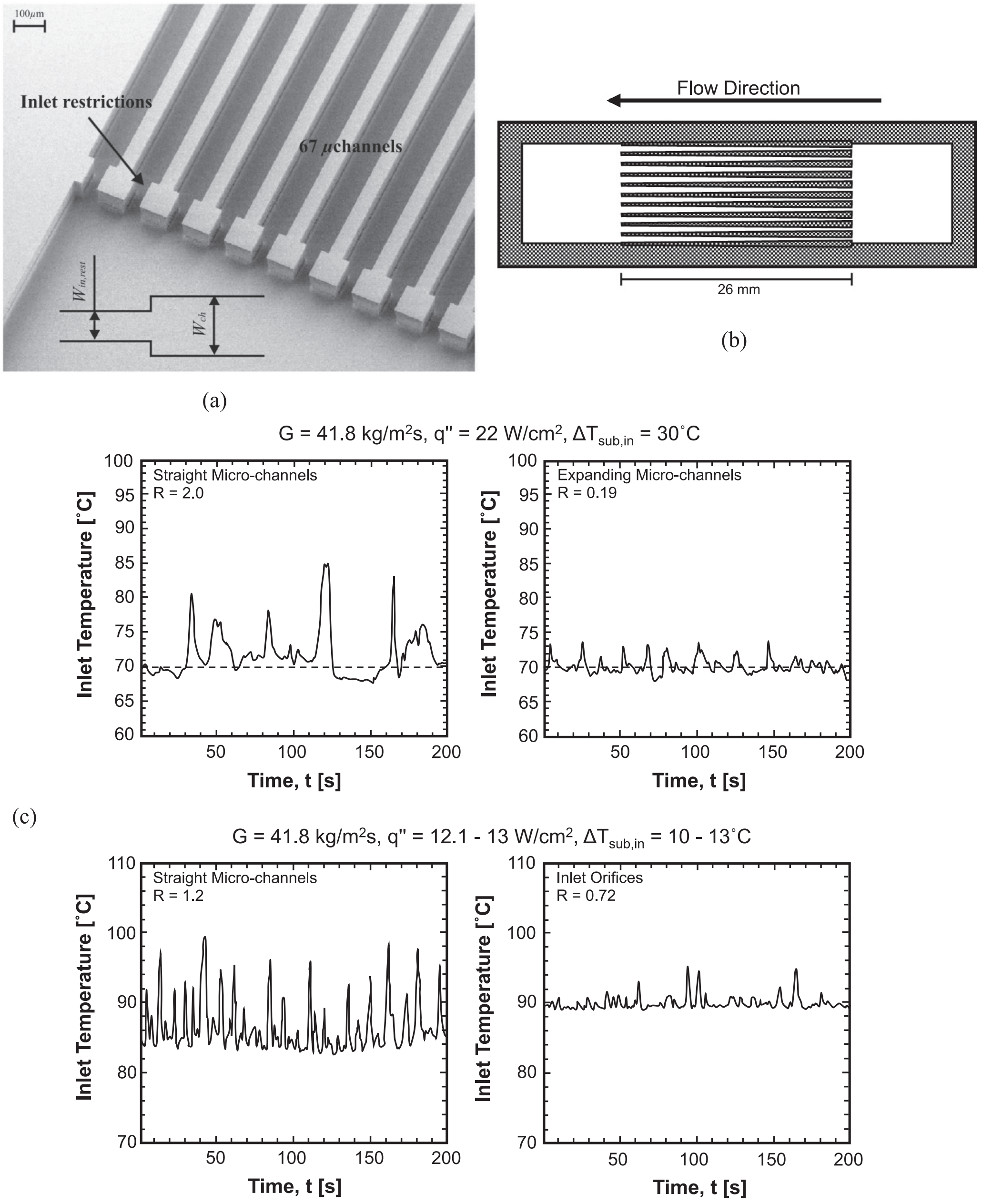


Fig. 13. Image of (a) parallel micro-channels with inlet restrictions adapted from Szczukiewicz et al. [312], (b) schematic of expanding parallel micro-channels adapted from Lu and Pan [317], and (c) comparison of results for straight micro-channels with expanding micro-channels (top) and those with inlet orificing (bottom), adapted from Lee et al. [310].

Other studies involving inlet orificing include those of Kosar et al. [311], Szcukiewicz et al. [312,313] and Kaya et al. [314]. Fig. 13(a) provides an image of micro-channel inlet restrictions implemented by Szcukiewicz et al. [312,313] for their work and representative of those included in other works. The impact of these restrictions on flow stability is similar to that shown for the work of Fan and Hassan [260] in Figs. 10(b) and 10(c), which showed fluctuations eliminated by aggressive inlet orificing. Kaya et al. [314] went further and illustrated how, for high heat flux values in micro-channel heat sinks, CHF values increased exponentially with increased inlet restriction ratio due to inlet orificing preventing backflow (which commonly causes premature CHF in micro-channel heat sinks).

Many additional studies exist detailing advantages of inlet orificing for suppressing PCI, but, for the scope of the current work, it is sufficient to understand the following: Increasing inlet orificing for individual micro-channels in parallel micro-channel heat sinks suppresses PCI at the cost of increased pressure drop. More detailed modeling on DWO formation and characteristics in micro-channels (which manifest as PCI in parallel micro-channel systems) is needed to optimize this trade-off.

The second commonly used modification is that of expanding channels. These serve to bias vapor expansion towards the downstream portion of the test section, and often have less adverse impact on pressure drop than inlet orificing. However, due to the increase in flow area downstream, flow velocity is reduced, which may impact heat transfer coefficients (this is largely speculative, and some work has shown heat transfer to improve due to increased flow stability [315]).

One early study to incorporate expanding flow in the downstream region is that of Lee and Pan [316]. They compared straight to expanding channels in a single micro-channel flow boiling configuration and saw significantly reduced inlet temperature oscillations in the expanding channel case (attributed to the absence of backflow into the inlet plenum).

Other studies investigating the impact of diverging micro-channels on heat sink stability include those of Prajapati et al. [177] and Lu and Pan [317], both of whom found advantages to using expanding microchannels. Fig. 13(b) shows a schematic of a micro-channel heat sink with diverging channels, adapted from Lu and Pan [317].

Overall, the standard for studies dealing with impact of inlet restriction and expanding channels on PCI is that of Lee et al. [310]. In addition to their mechanistic modeling mentioned previously, they provide excellent comparison of results for plain channels, diverging channels, and those with inlet restrictions, clearly showing the tradeoffs between each configuration in Fig. 13(c). Their work is strongly recommended as an entry-point for researchers looking to apply inlet restrictions and/or channel expansion to help stabilize flow.

Many other modification techniques exist to help suppress and/or eliminate PCI in micro-channel heat sinks. These include the use of reentrant cavities [318–322], interconnected micro-channels [323-325], and a plethora of direct surface-enhancement (e.g., nanotubes) studies. Those interested in further reading on these topics should consult the reviews of Liang and Mudawar [116] and Prajapati and Bhandari [59].

3.2.5. Summary of key information related to parallel channel instability

Parallel Channel Instability has been shown to refer to both static (flow maldistribution) and dynamic type instabilities in the preceding subsections. Analysis here focused on the dynamic type instability, as Section 2.2 (Ledinegg instability) covered studies dealing with static type. Key conclusions are listed below:

1) DWOs interacting across parallel channels were discussed as the mechanism leading to PCI. Many classic experimental and analytic studies were referenced, with key trends relating to onset of PCI and oscillatory characteristics found to be near-identical to those for DWOs in single macro-channels.
2) Like DWOs, PCI is mechanistically different in micro-channel systems, but is again attributable to DWOs acting in parallel channels (this time with the dominant DWO mechanism related to rapid confined bubble growth).
3) Dominant parameters influencing PCI onset and characteristics in parallel micro-channel heat sinks are heat flux and mass velocity. Some mechanistic modeling is provided (from the work of Lee et al. [310]) showing the different parameters influencing whether bubble growth will expand towards the channel inlet (destabilizing flow), and the effects of geometric modifications on these.
4) A brief overview of common geometry modifications for suppressing PCI was provided, with inclusion of inlet orificing and expanding channels identified as promising solutions.
5) Additional modeling work is needed to optimize the tradeoffs between increased pressure drop and improved stability associated with common geometry modifications.

3.3. Pressure drop oscillations

Pressure drop oscillations (PDOs) are another pervasive two-phase flow instability. First reported in the 1960's [326-328], PDOs are a system-level instability (as opposed to device level instabilities such as DWOs and PCI). Similar to Ledinegg instability, it requires the system to be operating on the negative slope portion of the internal characteristic curve and have an external pressure curve with higher (less-negative) slope than the internal curve. Additional details on these conditions can be found in Sections 2.2.1 and 2.2.2.

Unlike Ledinegg instability, which is a static instability characterized by a one-time excursion in operating conditions to a new stable state, the presence of compressible volume (typically a surge tank, accumulator, or equivalent) within the system causes PDOs to manifest as a dynamic instability mode. As compressible volumes are necessary for closed systems that undergo phase change (in order to accommodate the increased volume of fluid present without prohibitive increases to operating pressure), this instability mode is very common in two-phase literature. A detailed description (again drawing heavily on the explanation of Lahey and Podowski [122]) of the mechanisms behind it is provided in the following subsection.

3.3.1. Existence and characteristics of pressure drop oscillations

A brief sample case outlining the mechanisms behind PDOs is captured in Fig. 14. Fig. 14(a) shows the nominal operating conditions under consideration: The system is driven by a centrifugal pump (case 2 in Fig. 2(d)), currently operating in the middle of the negative slope region of the boiling curve (point **A**), liquid level in the surge tank (closed reservoir or accumulator) is constant, and pressure in the tank is in equilibrium with that along the flow path. Fig. 14(b) shows the system experiencing a perturbation (slight increase) in mass velocity, which destabilizes the operating condition (as was discussed with case 2 in Fig. 2(d), Section 2.2.2). The increase in flowrate reduces pump pressure head, meaning pressure inside the tank is now higher than that along the flowpath, and liquid flows out of the tank.

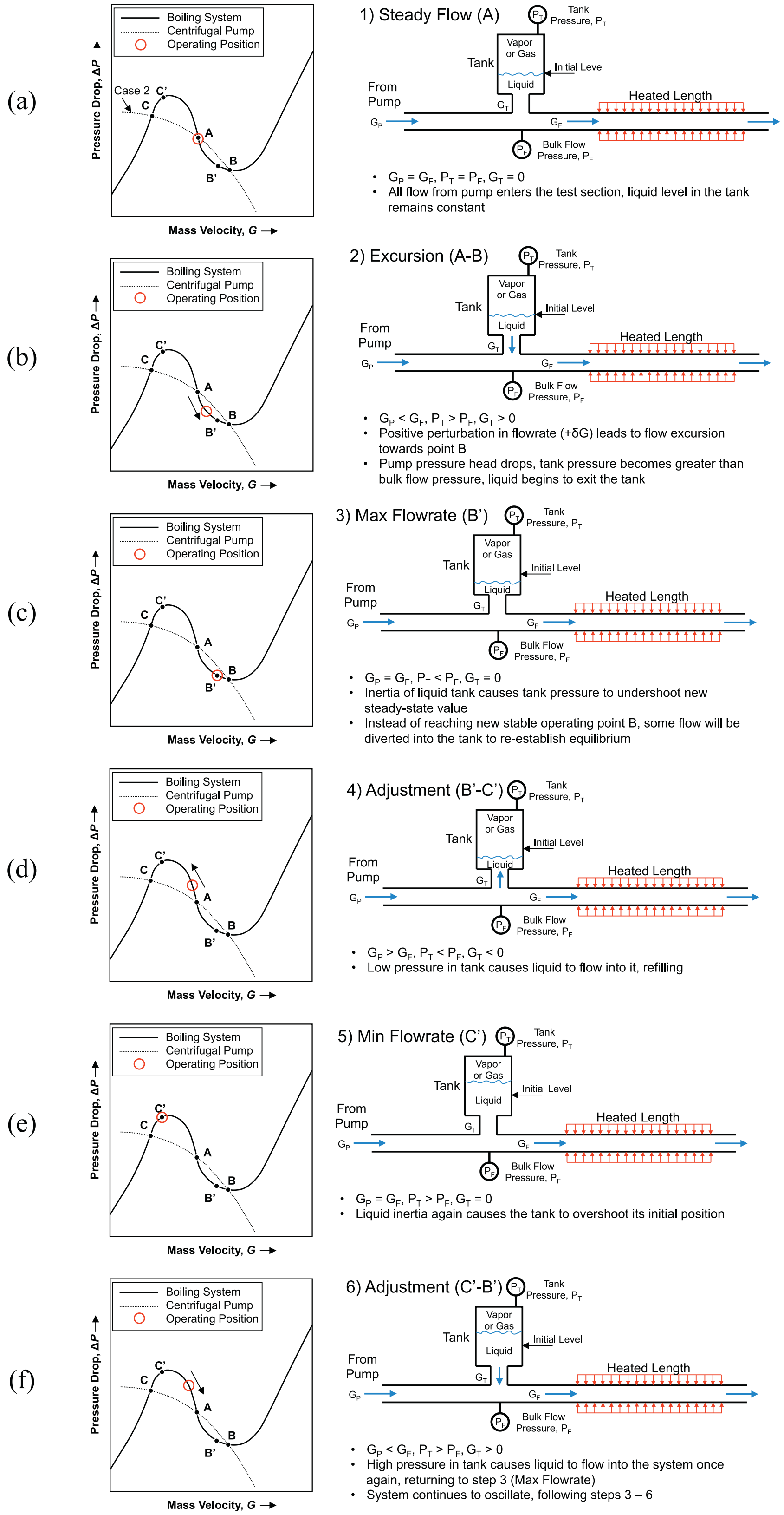
Due to the inertia of liquid within the tank, however, tank pressure undershoots what would be a new stable value. Fig. 14(c) shows how, at its maximum flowrate condition (**B'**, where **B** is the stable post-Ledinegg-excursion point from case 2 in Fig. 2(d)), tank pressure is now less than bulk flow pressure, meaning flow will be diverted back into the tank. Fig. 14(d) illustrates this process, with flow diverted back into the tank and operating condition moving back towards lower flowrate and higher pressure.

Once again due to inertial effects associated with liquid motion, tank fill level overshoots its stable value, and Fig. 14(e) shows tank pressure once again exceeding bulk flow pressure (point **C'**, where **C** is the stable post-Ledinegg-excursion point from case 2 in Fig. 2(d)). This leads to outflow from the tank (Fig. 14(f)), driving system flowrate up and pressure down, causing the system to continue its cycle between points **C'** and **B'**.

It is worth noting here that the present explanation for PDOs depends on the system's predilection for Ledinegg instability in the absence of a compressible volume. This is not totally confirmed within literature: In fact, one early analytic work asserted the external pressure curve *must* be steeper than internal (Case 1 in Fig. 2(d)) for PDOs to occur [155]. This has been disproved by experimental work showing PDO occurring for conditions that yielded Ledinegg prior to the inclusion of a compressible volume [125], but conclusive proof that PDOs will *only* occur under conditions that would have led to Ledinegg instability is absent in existing literature.

3.3.2. Comments on Ledinegg instability versus pressure drop oscillations

The mechanistic description of PDOs in the preceding subsection can be summarized as 'the system attempts to undergo Ledinegg instability, but the presence of an underdamped compressible volume causes it to experience limit cycle oscillations instead'. This implies the presence of a compressible volume in the



- $G_P = G_F$, $P_T = P_F$, $G_T = 0$
- All flow from pump enters the test section, liquid level in the tank remains constant

- $G_P < G_F$, $P_T > P_F$, $G_T > 0$
- Positive perturbation in flowrate (+δG) leads to flow excursion towards point B
- Pump pressure head drops, tank pressure becomes greater than bulk flow pressure, liquid begins to exit the tank

- $G_P = G_F$, $P_T < P_F$, $G_T = 0$
- Inertia of liquid tank causes tank pressure to undershoot new steady-state value
- Instead of reaching new stable operating point B, some flow will be diverted into the tank to re-establish equilibrium

- $G_P > G_F$, $P_T < P_F$, $G_T < 0$
- Low pressure in tank causes liquid to flow into it, refilling

- $G_P = G_F$, $P_T > P_F$, $G_T = 0$
- Liquid inertia again causes the tank to overshoot its initial position

- $G_P < G_F$, $P_T > P_F$, $G_T > 0$
- High pressure in tank causes liquid to flow into the system once again, returning to step 3 (Max Flowrate)
- System continues to oscillate, following steps 3 – 6

Fig. 14. Series of schematics presenting the process of Pressure Drop Oscillations, from (a) nominal operation, (b) attempting flow excursion, (c) max flowrate condition, (d) reduction in flowrate, (e) minimum flowrate condition, and (f) continuation of the cycle.

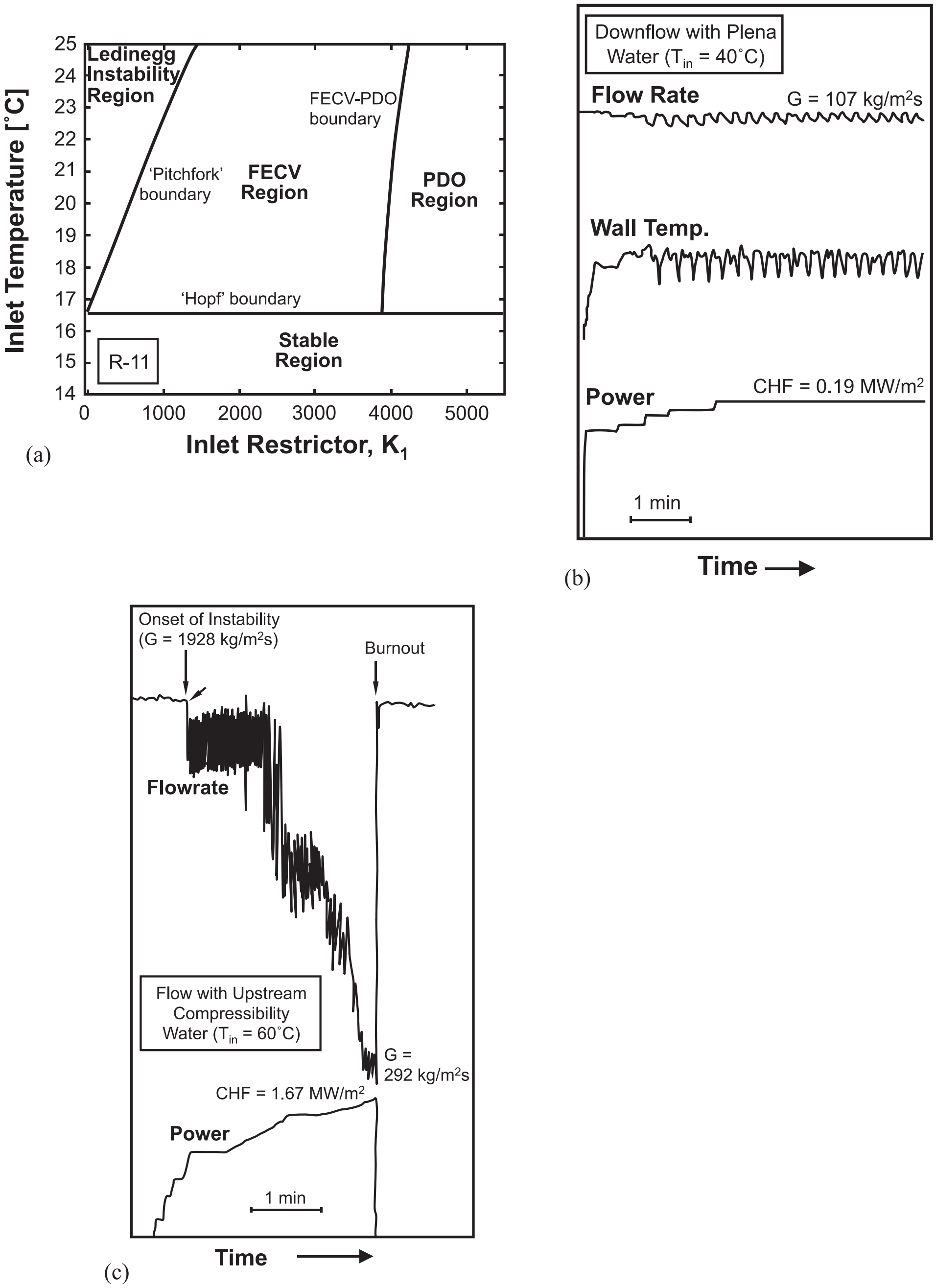


Fig. 15. (a) Sability map (for fixed mass flowrate, pressure, and heat flux) showing conditions for which Ledinegg instability, Flow Excursion with Compressible Volume (FECV), and Pressure Drop Oscillations will occur (adapted from Rahman and Singh [329]). (b) Operating conditions exhibiting PDOs, and (c) operating conditions showing FECV, adapted from Mishima et al. [125].

system precludes the existence of Ledinegg instability and means operating conditions that would have led to Ledinegg now yield PDOs (in the system pressure curves shown in Fig. 14, Ledinegg instability would cause the system to shift from A to **B** or **C**, but the inclusion of a compressible volume leads to oscillations between intermediate points **B'** and **C'** instead). This is true in most cases, but it is necessary to point out cases for which it does not hold and explain the conditions that may lead to a middle ground between Ledinegg and PDOs.

Recent analytic work by Rahman and Singh [329] discussed the existence of Flow Excursion with Compressible Volume (FECV). These are cases where a Ledinegg-like flow excursion takes place despite the presence of a compressible volume in the system. Fig. 15(a) shows a stability map generated from their work, illustrating how changes to an inlet restriction value K_1 (resistance located between their supply tank and surge tank just upstream of a vertical test section) lead to manifestation of different instability types resulting from interplay between flow excursion and compressible volume.

Little experimental evidence of this phenomenon is available, but one study where it seems to appear (although not identified as such) is the work of Mishima et al. [125]. Fig. 15(b) and (c) present results from their work, with Fig. 15(b) showing PDOs encountered during vertical downflow boiling. In this case, their large inlet plenum (despite only using a single boiling channel) acts as the compressible volume resulting in PDOs.

Fig. 15(c), however, shows more complex behavior. It corresponds to a case with vertical upflow boiling and a significant compressible volume located just upstream of the test section. For this case, the point they identify as 'Onset of Instability' exhibits a flow excursion followed by DWOs. As they continue to increase heat flux, 4–5 additional flow excursions are identifiable (each followed by unsteady boiling exhibiting DWOs), until CHF (burnout) finally occurs. In their work, Mishima et al. postulate these multiple small flow excursions are a result of the compressible volume: increasing heat flux triggers Ledinegg instability (shown here in Fig. 3(b)), but the presence of the large compressible volume stabilizes the system prior to full excursion. Referring to the mechanistic description provided in the prior subsection, this corresponds to a case where the compressible volume is overdamped (as opposed to the underdamped case that leads to PDOs).

The potential for compressible volume to interact with the system in an overdamped fashion receives virtually no attention in two-phase literature. Some experimental works on PDOs vary compressible volume (as will be discussed in the following section), but none identify a boundary between PDO and FECV as depicted in Fig. 15.

Analytically, Padki et al. [155] first mention the potential for Ledinegg-type excursive behavior to occur even in the presence of a compressible volume, but only for very high heat fluxes (based on their model and system). Srinivas and Pushpavanam [330] discuss infinitely large compressible volumes resulting in order-of-magnitude larger periods for PDO compared to finite tanks; it is possible this relates to the occurrence of FECV, but additional work is necessary on the topic. For the sake of the current review section, the remainder of discussion will focus on works where the inclusion of a compressible volume results in PDOs.

3.3.3. *Studies investigating pressure drop oscillations*

PDOs have been investigated extensively. Since their initial presentation in 1960's [326-328], numerous studies on two-phase flow instabilities and dynamic behavior have analyzed them, often alongside Ledinegg instability (refs. [125,155,160,167] from Section 2.2), DWOs (refs. [210-211,222-224,227,231-233,242,256,258,260] from Section 3.1), and PCI (ref. [298] from Section 3.2).

Experimental examples of PDOs are provided in Figs. 7(b) and 7(c) (adapted from the work of Yuncu [211]), Fig. 12(c) (adapted from the work of Qu and Mudawar [298]), and Fig. 15(b) (adapted from the work of Mishima et al. [125]). Relative to DWOs and PCI, they are best characterized by their low frequency and high amplitude of oscillation.

Unlike DWOs and PCI in the prior sections, PDOs do not require mechanistic distinction between occurrence in macro- and micro-channel systems. As discussed for Ledinegg, they are 'system-level' instabilities, meaning they are dependent on interplay between system components (in this case test section and compressible volume). Works such as those by Qu and Mudawar [298], Fan and Hassan [260], Kuo and Peles [331], and Grzybowski and Mosdorf [332] illustrate how PDOs in microchannel systems are mechanistically identical to those in macro-channels. The one potential difference, however, is the impact of parallel micro-channel heat sinks on external pressure curves discussed in Section 2.2 [174]. More investigation on this is needed.

When discussing parametric trends leading to the onset of PDOs, key conclusions resemble those drawn for Ledinegg instability (as presence of a negative slope region on the internal pressure curve is necessary for the existence of PDOs). Increased inlet throttling and increased system pressure [260,331,333] act to stabilize the system against PDOs, increased heat flux is destabilizing [233,333].

Assuming PDOs have manifested within a system, guidance exists on how changes to operating conditions will affect PDO characteristics. In their recent review on PDOs, Chiapero et al. [54] summarized important experimental trends from the works of Yuncu et al. [334], Comakli et al. [224], and Ding et al. [335] for horizontal channels, and Kakac et al. [336], Liu and Kakac [337], and Padki et al. [338] for vertical channels. These changes are minor compared to existence versus non-existence of PDOs, however, and most studies focus on avoiding them entirely.

One factor affecting PDOs that is under-explored in literature is the size and position of compressible volume on the impact of PDOs. Cheng et al. [339] recently showed that moving the compressible volume downstream of the test section (as opposed to placing it just upstream as in Fig. 14) can significantly increase system stability to PDOs. More rigorous investigation on this is necessary, however, to fully understand the impact of compressible volume position on PDOs.

Similarly, it has long been known inclusion of even a very small compressible volume may trigger PDOs in boiling systems [340], but extended experimental analysis of compressible volume magnitude on PDO characteristics (frequency and amplitude) is lacking. A related area needing clarification is the statement of Maulbetsch and Griffith in their early works [341,342] that test sections with large length-to-diameter ratios ($L/D > 150$) may act as their own compressible volumes. This statement is often repeated in literature, but has not been verified by other researchers.

Other underexplored areas include the effects of nano-fluids and surface enhancements on PDOs. Yu et al. [343] studied Al_2O_3 nanoparticles in water and showed their ability to delay the occurrence of PDOs. This was accomplished by filling of nucleation sites with nano-particles (delaying ONB and OFI), meaning it is debatable whether it is advantageous or not. Kakac and Cao [344] used both coated and uncoated test sections in their work, but did not provide any extended analysis on the impact on PDO characteristics.

Analytic tools for prediction of PDOs are very robust. For occurrence of PDOs, it is possible to use OFI correlations outlined in Table 3 (as they occur on the negative slope portion of the internal boiling curve). More common, however, is the development of full transient system models for PDOs (similar to that done for DWOs and sometimes Ledinegg). These models necessarily include transient equations governing mass storage (and associated pressure) within the loop compressible volume, and key points of differentiation between modeling approaches again include HEM versus Drift-flux formulation, linear versus non-linear approach, inclusion of thermal non-equilibrium effects, *etc.*

Model results for one of the earliest works is shown in Fig. 16(a), adapted from Ozawa et al. [345]. Their work was clearly able to capture general behavior of PDOs but misses somewhat on oscillation period.

Over the ensuing decades, many other researchers presented analytic models for PDOs. Notable works include those of Yuncu [211], Padki et al. [155], Cao [346] (who used experimental results from Liu [347]), Schlichting et al. [160] and Kakac and Cao [344]. One of the best recent examples of PDO modeling comes from the work of Zhang et al. [348]. Fig. 16(b) shows a sample of their model predictions alongside experimental results, indicating a near-perfect match between the two.

Despite the wealth of works that exist dealing with PDOs, researchers continue to discover new, atypical interactions between compressible volumes and two-phase flow systems that lead to unstable operation.

3.3.4. *Atypical interactions between boiling systems and compressible volume(s)*

In a recent study, Lee et al. [349] clearly showed how the presence of a closed liquid reservoir just downstream of the condenser in their two-phase pumped loop flow boiling (micro-channel heat sink) test facility could trigger what they term *Charge Transition*

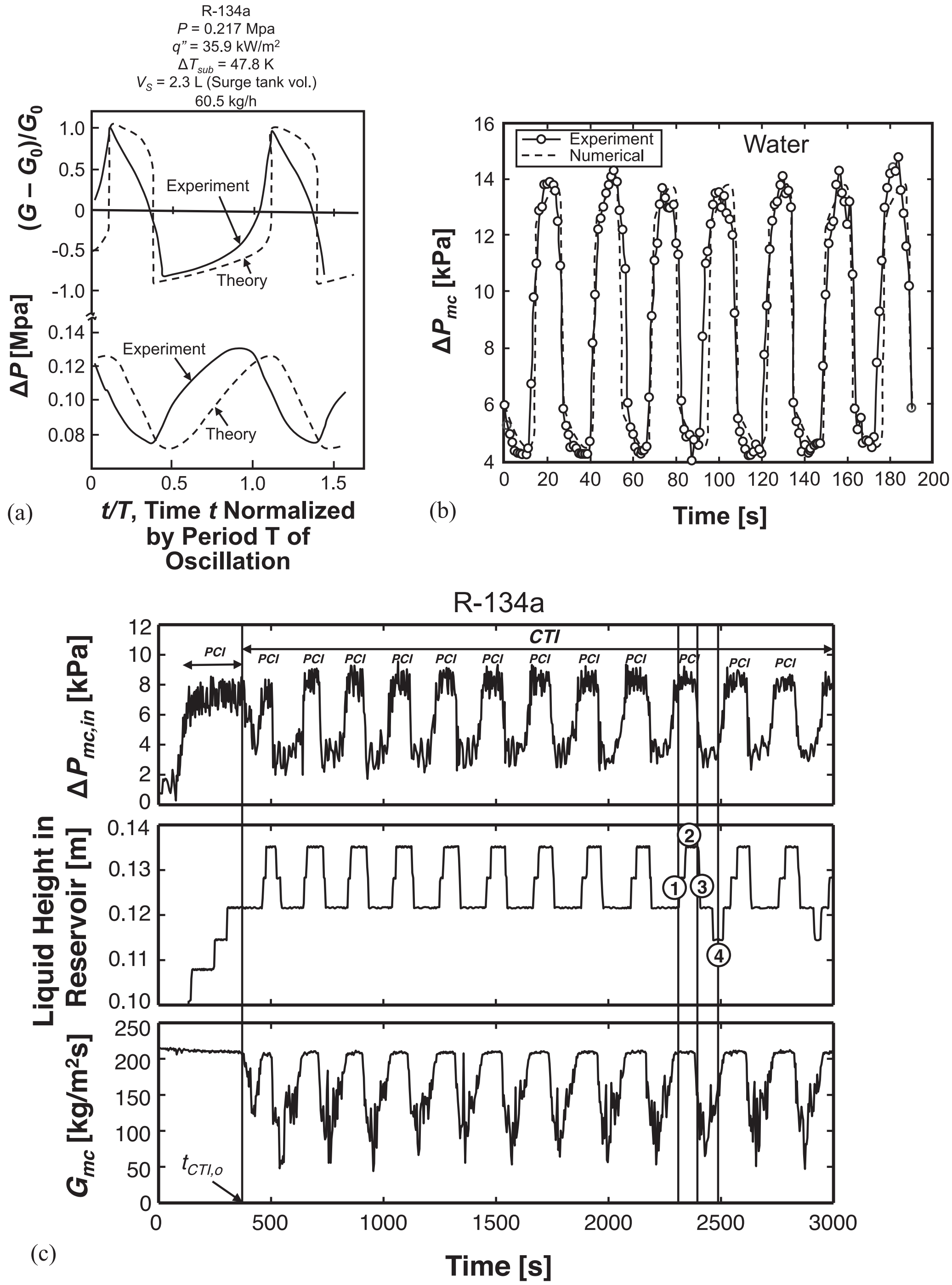


Fig. 16. Examples of analytic model results for Pressure Drop Oscillations adapted from (a) Ozawa et al. [345] and (b) Zhang et al. [348]. Also, (c) example of atypical interaction between compressible volume and system dynamic behavior resulting in a new instability mode termed Charge Transition Instability (CTI), adapted from Lee et al. [349].

Instability (CTI). They systematically prove this is a fundamentally different instability from PDOs (their system has no negative slope region on the internal pressure curve, and pressure drop and mass velocity oscillate in phase during CTI) and show it is related to transient fluctuations in the liquid level in their closed liquid reservoir. Full details on their mathematical modeling approach may be found in the original work [349]. Fig. 16(c) shows sample experimental results from their study, highlighting how pressure drop across the micro-channel test section (ΔP_{mc}), reservoir height (H_{res}) and system mass flowrate (G_{mc}) behave during CTI.

Fig. 16(c) also clearly highlights the existence of Parallel Channel Instability (PCI) during peaks and troughs of CTI. CTI clearly occurs on a much longer timescale than PCI (similar to PDO), but, due to the aforementioned characteristics, it is inherently different from PDOs. Lee et al. included analysis of experimental results and analytic modeling for charge distribution within their system and showed occurrence of CTI is associated with vapor pockets at the exit of their condenser interacting with the compressible volume.

The work of Lee et al. [349] is particularly important as it highlights the need for more thorough investigation of the influence of compressible volume position on two-phase loop dynamics. Based on current (limited) investigation, changes in compressible volume position have been shown to delay the onset of PDOs [339] or lead to a fundamentally different system-level instability mode [349].

3.3.5. Summary of important findings related to PDOs

Having analyzed literature relating to PDOs in flow boiling systems, several key conclusions may be drawn:

1) The existence of PDOs requires a compressible volume within the system and a negative-slope portion of the internal pressure curve. Some disagreement exists as to the exact relationship between Ledinegg instability and PDOs, but, if a system possesses a compressible volume and operates on the negative slope region, it is safe to assume PDOs will manifest.
2) Numerous experimental and analytic investigations into PDOs have established a detailed understanding of the effect of changes to mass velocity, inlet temperature, heat flux, and operating pressure on the existence and characteristics of PDOs.
3) The primary recommendation for future work on PDOs involves parametric analysis of changes to position and size of compressible volume(s) used within flow boiling systems.

3.4. Acoustic oscillations

Used as a general term for most oscillatory phenomena observed at frequencies above ~20 Hz (depending on specific source), *Acoustic Oscillations* are one of the most pervasive and least impactful dynamic instability modes in two-phase flow. One of the earliest works on the topic by Firstenberg [350] investigated oscillations in the range from 1000 – 10,000 Hz (leading him to term them 'boiling songs'). He saw these oscillations were occasionally accompanied by vibrations of the flow channel.

Generally speaking, most oscillatory modes present in two phase flow fall in the range of 0 Hz (static type) to ~20 Hz (for DWO, PCI, or PDO, depending on system geometry and operating conditions), and any observed oscillatory modes above this frequency are described as 'acoustic oscillations'. One of the most common causes for these high-frequency modes is bubble collapse during subcooled boiling. Bubble collapse has long been known to release energy in the form of acoustic pressure waves in the surrounding fluid [351,352] (this is a field of study on its own), and, depending on the level of subcooling and intensity of nucleate boiling, this may manifest in traditional macro-channel systems as a high-frequency oscillatory mode. Evidence for this mechanism has been provided in several macro-channel works [76,353-355]. Its impact on micro-channels (and small-scale systems in general) is potentially larger due to the relative size of bubbles to the flow channel and remains under investigation [356,357].

Other sources for acoustic oscillations include those originating from rotating machinery within the flow loop [251] as well as droplet impact on liquid films due to liquid film breakup, entrainment, and deposition mechanisms during annular flow [192,358].

Overall, acoustic oscillations can be described as a catch-all category for high-frequency oscillatory modes having little impact on bulk fluid behavior (with the possible exception of Bergles et al. [353] who observed a high-frequency, high-amplitude mode on the negative slope portion of the internal curve; additional verification of the causes contributing to this is required). These high-frequency oscillations are commonly related to (1) manifestation of micro-scale phenomenon (bubble growth, collapse, film breakup, droplet impingement) in macro-channels and/or (2) mechanically-induced vibrations within the system.

3.5. Other reported two-phase dynamic instabilities

Other dynamic type instabilities are occasionally reported in literature, falling under topics such as *Bumping, Geysering, Chugging, Flashing,* and *Thermal Oscillations*. Boure et al. [48] provided a brief discussion on the first four (under the common header *Compound Relaxation Instability*), the general takeaway being they are resultant from combinations of other commonly reported static and/or dynamic instabilities, primarily vapor burst and flow regime transition. *Thermal Oscillations* are slightly more complex and are only self-sustaining under certain conditions (primarily in pool boiling and natural circulation). A brief description of each and a short summary of relevant works is provided below.

Bumping is an oscillatory (although not necessarily periodic) fluctuation between natural convection and boiling. Boure et al. [48] highlighted the work of Deane and Rohsenow [359] with boiling of liquid metals. For low operating pressures and a narrow heat flux range, they observed a self-sustaining oscillation between natural convection and nucleate boiling, possessing associated variations in temperature and pressure depending on heat transfer mode. Although not referred to as *bumping*, this is very similar in nature to self-sustaining oscillations observed for transition (between nucleate and film) pool boiling [360,361]. These oscillatory modes will be discussed again alongside *thermal oscillations*.

Geysering is one of the more well-understood two-phase instabilities, occurring only in closed-end, vertical tubes heated at the bottom [48]. Once boiling initiates in the bottom of the tube, liquid is displaced from the top of the tube. This reduces the hydrostatic head, lowering pressure in the bottom of the tube and causing phase change to occur faster, leading to rapid liquid expulsion from the top of the channel. Subcooled liquid then returns to the tube, allowing for the process to begin again.

The work of Griffith [362] is commonly cited as an early investigation on *geysering*. The subject has received some analysis for forced flows and natural circulation [363] (key takeaways being it occurs for low flowrates and during startup, respectively), but in recent years it has been most relevant to analysis of thermosyphon design and operation [364-369].

Many of the two-phase thermosyphon references listed above [364-369] performed parametric analysis on factors leading to geysering in thermosyphons. Key takeaways are that, for a given geometry, geysering only occurs for relatively low heat fluxes and is strongly dependent on fill ratio and operating pressure.

Chugging is largely a misnomer in two-phase flow literature. One of the earliest uses of the term comes from the work of Wallis and Heasley [370]. They use the term extensively to refer to two-phase flow instability, which, based on their modeling approach, seems to be DWOs. By the time of Boure et al.'s seminal review [48], the term was commonly used to denote periodic expulsion of coolant from a flow channel. In a later work, Boure [371] attributed this primarily to vapor burst, describing a mechanism of rapid bubble growth pushing liquid from a channel similar to that of geysering.

Herein lies the issue with use of the term *chugging*: It refers to two-phase flow conditions where coolant is expelled from the channel in a periodic fashion, but this expulsion could be due to a wide variety of different causes (DWOs [370], geysering [371], counterflow configurations [372], *etc.*). Any of the instability modes described in this study that could lead to variations in mass flowrate may be technically described as causing chugging. The term is still used in some contemporary studies dealing with two-phase flow oscillations and instabilities [373,374], but it is the recommendation of the current authors that its use be avoided when possible and observed oscillatory phenomenon be classified as more fundamental instability modes.

Flashing in the fundamental sense is not an instability at all, but a known phenomenon in liquid-vapor flow whereby sharp pressure drop causes a significant fraction of saturated liquid to convert to vapor (a near-vertical movement on a *P-h* diagram). *Flashing* has been shown to impact oscillatory characteristics of DWOs

Table 6
Overview of strengths and weaknesses of current instability literature.

Instability	Understanding of Fundamental Mechanism	Experi- mental Evidence	Predictive Tools for Onset of Instability	Predictive Tools for Instability Characteristics	Differences Between Macro- and Micro-channels	Key Area(s) for Future Study
Critical Heat Flux (Device Level)	Mechanisms behind CHF are well understood.	Extensive experimental evidence exists.	Many different empirical, semi-empirical, and analytic tools exist for prediction of CHF.	Instability characteristics are usually not a focus of analysis for CHF, as burnout usually occurs before the system reaches a new stable operating state.	Phenomenon is similar in macro- and micro-channels.	CHF is largely considered a separate field of study. Consult Section 2.1 for dedicated reviews which may better inform areas for future study.
Ledinegg Instability (System Level)	Mechanisms behind Ledinegg instability are well understood.	Experimental evidence exists.	Extensive predictive tools exist for determining onset of Ledinegg instability.	Few predictive tools exist for predicting/quantifying the magnitude and rate of flow excursion due to Ledinegg instability.	Phenomenon is similar in macro- and micro-channels.	The impact of parallel channels on external pressure curve (discussed in Section 2.2) needs further investigation.
Boiling Curve Hysteresis (Device Level)	Mechanisms behind Boiling Curve Hysteresis are well understood.	Experimental evidence exists.	Few predictive tools exist — Boiling curve hysteresis is treated practically rather than theoretically.		Phenomenon is similar in macro- and micro-channels.	Better understanding of nucleate boiling incipience is necessary for modeling of Boiling Curve Hysteresis.
Vapor Burst (Device Level)	Mechanisms are well understood.	Limited experimental evidence exists.	Few predictive tools exist. Like boiling curve hysteresis, vapor burst is treated practically rather than theoretically.		Phenomenon is similar in macro- and micro- channels.	Extended experimental investigation is necessary to determine parametric trends and begin modeling.
Flow Regime Transition Instability (Device Level)	Mechanisms are disputed, with many believing dynamic flow regime transition instability to be the result of other instability modes (DWOs, PDOs).	Experimental evidence exists.	Many predictive tools (flow regime maps) exists for prediction of relevant operating boundaries.	As these are often the result of other dynamic instabilities, few predictive tools exist expressly for flow regime transition instability.	Phenomenon is clearly different in macro- versus micro-channels. This is due to confinement effects in micro-channels.	Sophisticated experiment design is needed to determine whether flow regime transition is a self-sustaining instability or is a result of other dynamic instabilities as commonly hypothesized.
Density Wave Oscillations (Device Level)	Mechanisms behind DWOs are well understood, although some atypical configurations require additional investigation.	Extensive experimental evidence exists.	Many predictive tools exist for onset of classic (i.e., 'Flow-void feedback') DWOs. Additional work needed for atypical and micro-channel DWOs.	Instability characteristics are well predicted in the classic case. Atypical and micro-channel DWOs need additional study.	Phenomenon is fundamentally different in macro-channels versus micro-channels. In macro-channels, instability is commonly associated with oscillation of the boiling boundary, while in micro-channels, rapid confined bubble expansion towards the inlet is the key mechanism.	Additional modeling of DWOs in micro-channels is needed to provide useful design tools.

(*continued on next page*)

Table 6 (*continued*)

Instability	Understanding of Fundamental Mechanism	Experi- mental Evidence	Predictive Tools for Onset of Instability	Predictive Tools for Instability Characteristics	Differences Between Macro- and Micro-channels	Key Area(s) for Future Study
Parallel Channel Instability (Device Level)	Mechanisms behind PCI are well understood, both in the static (Flow Maldistribution, due to Ledinegg) and dynamic (due to interacting DWOs across channels) modes.	Extensive experimental evidence exists.	Many tools exist for macro-channels, and some limited tools exist for micro-channels.	Similar to DWOs, instability characteristics are well predicted in the classic case, but micro-channel PCI needs additional modeling.	Phenomenon is fundamentally different due to the difference between DWOs in macro- versus micro-channels discussed above.	Additional modeling of PCI in micro-channels is necessary. Also, further experimental study on effect of channel number on stability boundaries is recommended.
Pressure Drop Oscillations (System Level)	Broad concepts behind PDOs are well understood (presence of compressible volume, operation on the negative-slope portion of the boiling curve), but specifics regarding the influence of external pressure curve are lacking.	Extensive experimental evidence exists.	Many tools exist for predicting onset of PDOs.	Modeling approaches exist for determining PDO characteristics.	Mechanisms are similar in macro- and micro-channel systems.	Experimental work is needed to determine the exact influence of external pressure curve on the occurrence of PDOs. Also, like Ledinegg instability, potential for parallel micro-channels to alter this external characteristic must be studied. Exact influence of size and position of compressible volume is also uncertain, including potential to incite atypical instability modes such as CTI.
Acoustic Oscillations (Device or System Level)	Various mechanisms are known to result in observed Acoustic Oscillations.	Experimental evidence exists.	Predictive tools are not commonly used for acoustic oscillations. These occur for a variety of reasons (Section 3.4) and are largely unavoidable in two-phase flows.		No differences between macro- and micro-channel systems.	These have little impact on system performance, and as such additional investigation is not a priority.
Other Dynamic Behavior	This refers to a range of other reported instability modes. These are discussed at length in Section 3.5, and it is believed further study may be necessary for specific subfields of research (e.g., investigation on *geysering* by researchers studying thermosyphons) but generally additional work is not a priority.					

[235,236], however, so despite it not being a unique instability mode, its potential impact should be considered when modeling other dynamic instabilities.

Finally, *thermal oscillations* are reported in a wide variety of two-phase flow literature included in the current section on dynamic instabilities. A common misconception is that they are a unique instability mode, when they are actually either 1) a result of hydrodynamic instability or 2) intrinsic parts of other instabilities.

Thermal oscillations are important to consider when designing devices for thermal control and are an interesting coupling of heat transfer and hydrodynamics. Similar to the impact of heated wall thermal mass on DWO characteristics discussed in Section 3.1 [230,249], thermal mass has the potential to significantly affect manifestation of *thermal oscillations*. O'Neill et al. [76] provided evidence of thermal oscillations only manifesting alongside DWOs for cases with high heat flux, and they attribute this to the thermal mass of their heated walls.

Although not an independent mode of two-phase flow instability, *thermal oscillations* warrant further investigation, particularly on the affects of heated wall thermal mass on their manifestation.

4. Current state of instability literature

This study has presented key mechanisms behind two-phase instabilities and provided summaries of existing literature on each, including mention of topics for future study where they become apparent. Due to the length of this work, however, it is beneficial to consolidate these in the present section to better help inform researchers working in the field.

Table 6 provides an overview of the current state of instability literature. This includes assessment of fundamental understanding for the mechanisms leading to each instability mode, predictive tools available for system designers, differences between macro- and micro-channels, and key areas for future study. To expand on items for future study, several topics are discussed in depth below:

Ability of parallel micro-channels to influence external pressure curve – As discussed in Section 2.2, results in literature indicate the ability of parallel micro-channel heat sinks to impact the external pressure curve, with increasing number of channels decreasing stability. This requires additional experimental investigation as it impacts both Ledinegg and PDO instabilities.

Mechanisms behind/leading-to Flow Regime Transition Instability – Much existing literature indicates dynamic flow regime transition instability to be a result of DWOs (and not a fundamental instability on its own), but some disagreement exists on this.

Identification of atypical DWOs – As discussed in Section 3.1, understanding of classic DWOs in macro-channels is fairly complete, but work remains necessary on proper identification of feedback mechanisms leading to DWOs in atypical configurations.

Impact of parallel channels on stability boundaries – While mechanisms for PCI are relatively well understood (as they result from DWOs interacting across multiple channels), exact influence of number of parallel channels on stability boundaries needs additional investigation, particularly in parallel micro-channels where some evidence exists increasing number of parallel channels destabilizes the system.

Position and size of compressible volume in system – Presence of a compressible volume is recognized as requisite for occurrence of PDOs, but exact influence of its size and position is poorly understood. Further parametric study is recommended on size and position of compressible volume to determine 1) relationship between Ledinegg instability and PDOs and the influence compressible volume has on this, 2) optimal size and positioning of compressible volume to increase system stability, and 3) potential for placement of compressible volume to initiate atypical instability modes such as *Charge Transition Instability* (CTI). The current authors recommend identical tests with compressible volume located 1) in the single-phase region on the pump discharge side, 2) in the two-phase region, and 3) in the single-phase region on the pump suction side. Additional positions should be investigated if multiple evaporators and/or condensers are present.

5. Conclusion

This study provided a systematic overview of dominant instability modes occurring during boiling (and to a lesser extent condensation) in a variety of configurations. Key emphasis was placed on distinguishing between macro- and micro-channel flows, as this difference was shown to impact mechanisms behind commonly observed instabilities.

Instabilities were grouped into static and dynamic types, and key experimental and analytic works were discussed for each instability mode. Overall, extensive work was shown to exist for all key two-phase instability modes, although some gaps in understanding remain. Conclusions for each subsection typically included recommendations for future work, which were further highlighted in Section 4. Key conclusions from the present study are:

1) Strategies for classification of flow boiling and condensation into macro- or micro-channel flow were provided. This distinction is important as it impacts the mechanism behind observed instability modes.
2) Internal and external pressure curves remain the best method for assessing potential for system-level instabilities (*i.e.*, those involving interaction between test section and driving head), primarily Ledinegg instability and Pressure Drop Oscillations. Parallel micro-channels with inlet plenums have shown some potential to affect shape of external pressure curve; additional study on this is strongly recommended.
3) Device-level instabilities (i.e., those occurring within a boiling/condensing channel due to inherent two-phase mechanisms) are shown to occur for a variety of reasons in many different two-phase configurations. Some show strong differences for macro- versus micro-channels (Density Wave Oscillations, Parallel Channel Instability), while others do not (Boiling Curve Hysteresis, Vapor Burst).
4) Density Wave Oscillations in micro-channels (and associated Parallel Channel Instability in micro-channel heat sinks) are a key topic of study. Further analytic/mechanistic modeling is recommended to better optimize trade-offs between their mitigation (commonly achieved through inlet throttling and/or expanding channels) and system performance.
5) Pressure Drop Oscillations require additional investigation on the influence of size and position of compressible volume on their occurrence. Section 3.3 discusses these issues at length, as well as the potential for placement of compressible volume to initiate other atypical oscillatory modes such as *Charge Transition Instability* (CTI) [349].
6) While impressive volume and quality of work already exists on two-phase flow instabilities, key areas for future study have been identified. Completion of these will provide appreciable value for system designers looking to leverage phase change heat transfer technologies.

Declaration of Competing Interest

None.

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Supplementary materials

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