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Review

Two-phase flow instabilities: A review

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ABSTRACT

An updated review of two-phase flow instabilities including experimental and analytical results regarding density-wave and pressure-drop oscillations, as well as Ledinegg excursions, is presented. The latest findings about the main mechanisms involved in the occurrence of these phenomena are introduced. This work complements previous reviews, putting all two-phase flow instabilities in the same context and updating the information including coherently the data accumulated in recent years. The review is concluded with a discussion of the current research state and recommendations for future works.

Contents

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Nomenclature

Abbreviations and acronyms

BWR	boiling water reactor
CHF	critical heat flux
DFM	drift-flux model
DSG	direct steam generator
DWO	density wave oscillations
DWO_I	DWO – due to gravity
DWO_{III}	DWO – due to momentum
DWO_{II}	DWO – due to friction
FDF	frequency domain formulation
FDI	flow distribution instability
FNS	fixed nodes scheme
FPT	flow pattern transition
FSH	flashing induced instability
GES	geysering
HEM	homogeneous equation model
LED	Ledinegg instability
MNS	moving nodes scheme
NBO	natural boiling oscillations
OFB	onset of nucleate boiling
OFI	onset of flow instability
OSB	onset of significant boiling
PDO	pressure drop oscillations
TAO	thermo-acoustic oscillations
TDF	time domain formulation
TFM	two-fluid model
ThO	thermal oscillations

Non-dimensional numbers

Fr	Froude number
Λ	friction number
N_{Pch}	phase change number
Re	Reynolds number
N_{Sub}	subcooling number
N_{Zu}	Zuber number, N_{Pch}

Variables and parameters

A	area
ρ	density
D	diameter
G	mass flow rate
K	valve constant
L	length
ΔP	pressure drop
P	pressure
q''	heat flux
T	temperature

Subscripts

ext	external
int	internal
in	inlet
out	outlet

1. Introduction

Historically, the study of two-phase flow instabilities started with the pioneering article of Ledinegg [1]. Several decades later, around 1960, the development of industrial high-power-density boilers and boiling water reactors (BWR) turned the attention of many researchers into this kind of phenomena occurring in two-phase flow systems. During those years, several experimental studies described different kinds of phenomena occurring in boiling channels. As described by Yadigaroglu [2, chap. 17], "a period of relative confusion followed, with many authors attempting to explain various widely different observations". Thus, it is not until late 1960s that the main instability mechanisms were understood, especially due to the development of analytical and computational tools, namely, Bouré and Mihaila [3]; Zuber [4]; Ishii and Zuber [5]; Ishii [6]. During the 70's and early 80's, several analytical works made a significant contribution on the understanding basis of thermo-hydraulic instabilities like that from Fukuda and Kobori [7]. With the development of computational tools, the study of transient phenomena related with accident analysis in nuclear reactors started to grow rapidly; most of these efforts were applied to thermal hydraulic instabilities. Nowadays, the different scenarios where these phenomena can take place are fairly well understood in the nuclear industry. Today more than 90% of thermo-hydraulic research in nuclear reactors belongs to the field of nuclear safety, as observed by Mayinger [8]. Regarding other industries where two-phase flow components are important, like oil and chemical industries, the understanding of the two-phase flow instability phenomena is still limited. In the last 50 years, several works reported the occurrence of this kind of phenomena in components such as heat-exchangers, re-boilers, economisers, steam-generators, condensers, petroleum well components, thermo-syphons, etc. Several excellent related reviews of experimental and analytical research have been published, such as Bouré et al. [9], Ishii [10], Bergles [11], Yadigaroglu [2], Lahey and Drew [12], Nakanishi [13], and Lahey and Podowski [14]. More recently, some reviews describe some particular aspects of two-phase flow instabilities Belblidia and Bratianu [15], Prasad et al. [16], Tadrist [17], Nayak and Vijayan [18] and Kakac and Bon [19].

The objective of this work is to review the main kinds of instabilities occurring in two-phase flows. It complements previous reviews, putting all two-phase flow instabilities in the same context and updating the information including coherently the data accumulated in recent years. In the first section, a description of the main mechanisms involved in the occurrence of two-phase flow instabilities is made. In Sections 3 and 4, some of the most important experimental and analytical investigations are described. Moreover, a critical discussion of some relevant aspects of the current state-of-art and future needs are presented in Section 5.

2. Two-phase flow instability mechanisms

In order to get a clear picture of the phenomena taking place in two-phase flow systems it is necessary to introduce some common terms used in this field. The first distinction should be made between *microscopic* and *macroscopic* instabilities. The term *microscopic* instabilities is used for the phenomena occurring locally at the liquid–gas interface; for example, the Helmholtz and Taylor instabilities, bubble collapse, etc. The treatment of this kind of instabilities is out of the scope of this work. On the other hand, the macroscopic instabilities involve the entire two-phase flow system. In this review, the main focus is kept on macroscopic phenomena.

The most popular classification, introduced in Bouré et al. [9], divides two-phase flow instabilities in *static* and *dynamic*. In the first case, the threshold of the unstable behaviour can be predicted from the steady-state conservation laws. On the other hand, to describe the behaviour of *dynamic* instabilities it is necessary to take into account different dynamic effects, such as the propagation time, the inertia, compressibility, etc. In addition, the term compound instability is normally used when several of the basic mechanisms, described later, interact with each other. In more recent reviews, the distinction between natural and forced convection instabilities is made by Nayak and Vijayan [18], Prasad et al. [16], albeit the nature of the involved phenomena in the different cases is the same. In the present work a classification similar to the one presented in Yadigaroglu [2] is used. Moreover, this classification is extended by the one presented in Fukuda and Kobori [7] and more recent investigations.

In the following sections, the main mechanisms related with the occurrence of two-phase flow instabilities are described.

2.1. Characteristic pressure drop vs. flow rate instabilities

The static methodology for boiling channel stability analysis comes from considering two different steady-state systems, external and internal. Thus, the intersecting points give the steady-state operational points. It is well-know that under certain conditions the pressure-drop vs. flow-rate characteristic curve of a boiling system (internal curve) may exhibit a N-shape (or S-shape). Depending on the corresponding characteristic curve of the external system the operational points can be stable or unstable. An operational point is thus stable when the slope of the internal characteristic curve is smaller than the slope of the external characteristic curve Ledinegg [1]. This is

$$\left.\frac{\partial \Delta P}{\partial G} int\right|_w > \left.\frac{\partial \Delta P}{\partial G} ext\right|_w \quad \text{stability condition.} \tag{1}$$

In Fig. 1 the typical N-shape curve for a boiling system together with possible scenarios of several external curves are plotted. In addition, the total pressure drop for the theoretical cases of *all*

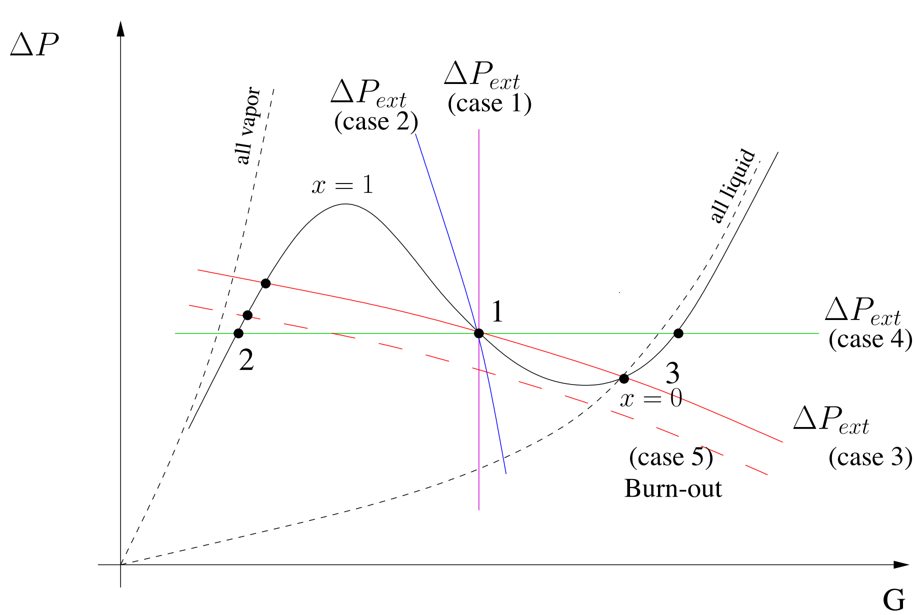


Fig. 1. Internal pressure-drop vs. flow-rate characteristic curve for a boiling system. Five different external characteristic curves (cases) are presented.

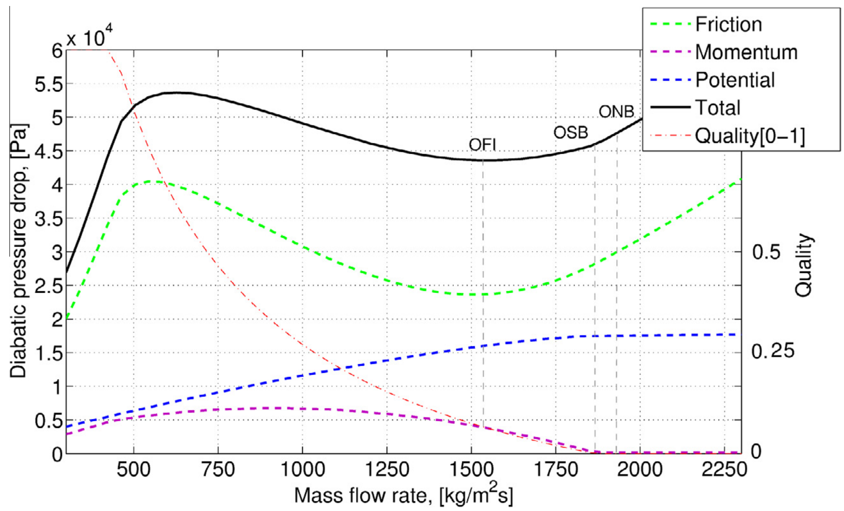


Fig. 2. Decomposition of the different pressure drop components in the characteristic pressure-drop vs. flow-rate curve of an upward flow boiling system.

vapor and *all liquid* (dotted lines) are also shown. These two curves correspond to the limit cases for the two-phase pressure drop. As can be seen, the external curves of the *case 1* and *case 2* intersect the internal curve in only one point (1). As the internal curve slope is larger than the external curve slope, then this point is stable. An opposite behaviour is observed when the external curves of *case 3* and *case 4* intersect the same point. In these two cases the point (1) becomes unstable. Furthermore, two new stable operation points are fulfilling the steady-state operation condition, points (2) and (3).

Before continuing, it is interesting to analyse the different sources of the pressure-drop vs. flow-rate characteristic curve.

2.1.1. The characteristic pressure-drop vs. flow-curve

In a general steady-state case, this curve has three main components; momentum, frictional and potential pressure drops. According to the stability criteria, Eq. (1), the influence of the different terms stabilises or destabilises the system depending on the measure of how much they increase or decrease the characteristic curve slope. Fig. 2 shows the different components for an upward boiling channel. In this case, the potential term is stabilising the system, while the momentum and frictional terms are destabilising the system in some flow regions. Note that in the case of downward flow, the potential term will also destabilise the system. Fukuda and Kobori [7] propose to classify the instabilities depending on which of the terms is dominant. Even if according to the steady-state analysis this distinction is not strictly necessary, it is still not clear if there is any difference in how the different source terms influence the dynamic evolution of the system as it will be discussed in the following sections.

For the particular case of subcooled flow boiling in conventional-sized channels, three different physical points are distinguished in literature. They are named; Onset of Nucleate Boiling (ONB), the Onset of Significant Boiling (OSB) or Net Vapor Generation (NVG) and the Onset of Flow Instability (OFI). The location of ONB and OSV points can be obtained through the void fraction distribution in the heated channel. Yadigaroglu [20] defines the OSB or NVG point as the point where the subcooled boiling void fraction starts growing appreciably. For most practical purposes the region between ONB and OSB is not analysed individually. Furthermore, the OFI denotes the minimum point of the total pressure drop characteristic curve. Normally, this last point is used to indicate the beginning of the unstable region, even when it is not a sufficient condition to assure an unstable behaviour.

On the other hand it should also be mentioned that the N-shape curve is not only particular of boiling systems but it is also reported in general gas–liquid mixtures, see Ozawa et al. [21], Jovic et al. [22], Hu [23]. There are several instabilities triggered by this mechanism. In the following sections some of them are explained.

2.1.2. Ledinegg instability

Ledinegg instability or flow excursion is one of the most analysed instabilities in literature. It is classified as a static instability by Bouréet al. [9]. It was first introduced by Ledinegg [1] and later named as *Ledinegg* instability. It is necessary to remark that the term *Ledinegg* instability is used in literature in a general way to denote the unstable region.

Ledinegg instability is the basic phenomena associated with the characteristic pressure drop vs. flow curve. It is said that the system experiments a flow excursion when it turns from an unstable to a stable operational point. In most practical cases this situation will never happen, since in operation conditions it is not possible to achieve a static unstable point. Conversely, the modification of the external (or internal) characteristic curve can change the stability of an operation point. This effect is shown as *case 5* in Fig. 1. If the external characteristic of a system, having initially three operation points (*case 3*), is for some reason modified to *case 5*, then the system will experiment a flow excursion from point 3 to point 2. When the flow is decreasing from the single-phase liquid region (point 3), the system suddenly turns into a two-phase state with a high vapor generation rate. On the contrary, the same phenomenon can occur from an operation point in the two-phase region to a point in the fully liquid zone. In Ruspini et al. [24] it is shown that from an unstable point the system can evolve in both directions, increasing or decreasing the flow with the same probability. Several examples describing the occurrence of this and other related phenomena, and their interaction, are included in the following sections.

2.1.3. Flow distribution instability

In this section, the flow distribution instability in parallel channels due to negative characteristic slope is analysed. Firstly, it is convenient to distinguish between single and parallel channel boundary conditions. In the case of a parallel array of tubes, connected by an inlet and exit plenum, whenever the conditions at the channel limits are sufficiently specified at all times, the problem reduces to a single-channel instability. Furthermore, the term “parallel channel” has been frequently used to recall

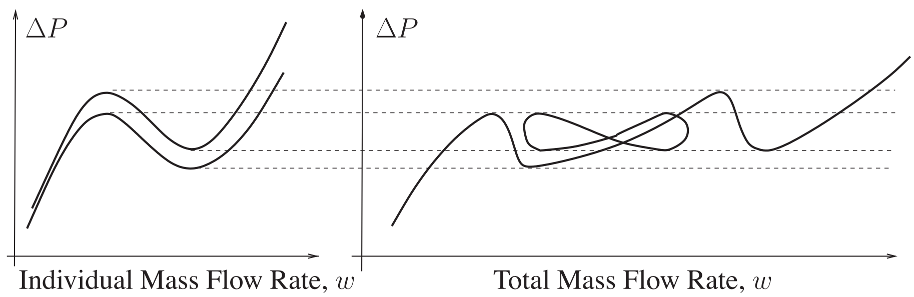


Fig. 3. Characteristic pressure-drop vs. flow-rate for two parallel channels with different individual characteristics.

a *constant pressure drop* boundary condition, while it might have been used more properly to denote flow distribution phenomena.

In the case of multiple channels, flow redistribution between the different channels may result when some of the channels operate in the negative slope region. In Fig. 3 the case of two parallel channels with different characteristic curves is shown. As can be seen, there are several regions of multiple solutions. Thus according to the external characteristic curve intersecting this curve, the system may have several possible operational points. In the case of a horizontal external characteristic curve (constant pressure difference) then the system can intersect up to nine operational points.[1] It is easy to see that when the amount of channels grows, the complexity of the multiple solution region increases.

This phenomenon was first systematically analysed by Akagawa and Sakaguchi [25]. In this last work, several two-phase phenomena are analysed in an array of long parallel tubes. It is found that under the negative slope condition, the flow rate in the different tubes is not only ill-distributed but also flow excursions between channels are observed.

2.1.4. Flow pattern transition

This kind of instability has been described in the literature for the first time in 1970s. Nevertheless, this phenomenon is not reported in industrial systems as an important issue. The main mechanism can be explained through the static characteristic curve in the same way as for the *Ledinegg* flow excursion. In the proximity of a flow pattern transition (normally considered as bubbly to annular, or slug), the pressure drop vs. flow rate will exhibit a transition point due to the different local pressure drop of the different regimes. When the characteristic curve has a negative slope, then any perturbation to the initial state can cause an excursion to a new operational point. This would be the main mechanism of the flow pattern transition. In some particular cases, the new operational point can produce a change in the main variables (void fraction) and the boundary conditions. Hence, the system will evolve again to the initial state, through another flow excursion. Under very specific conditions, this process can be repeated producing periodic oscillations.

In recent years, some works have attempted to explain this phenomenon analytically. Nayak et al. [26] analyse the internal characteristic curve of a natural circulation pipe, using different pressure drop models for the different flow patterns, based on the maps of Taitel and Dukler [27]. The characteristic curves show a multiple solution region for the flow pattern transition between annular and slug flow. Although this phenomenon can produce a flow excursion, the amplitude in this case is typically smaller than the amplitude of the *Ledinegg* flow excursion in the same system. Very brief experimental examples of this phenomenon can be found in Jeglic and Yang [28], Ünal [29], Buyevich and Natalukha [30].

[1] Number of Operation Points $\leqslant 3^{(NumberTubes)}$.

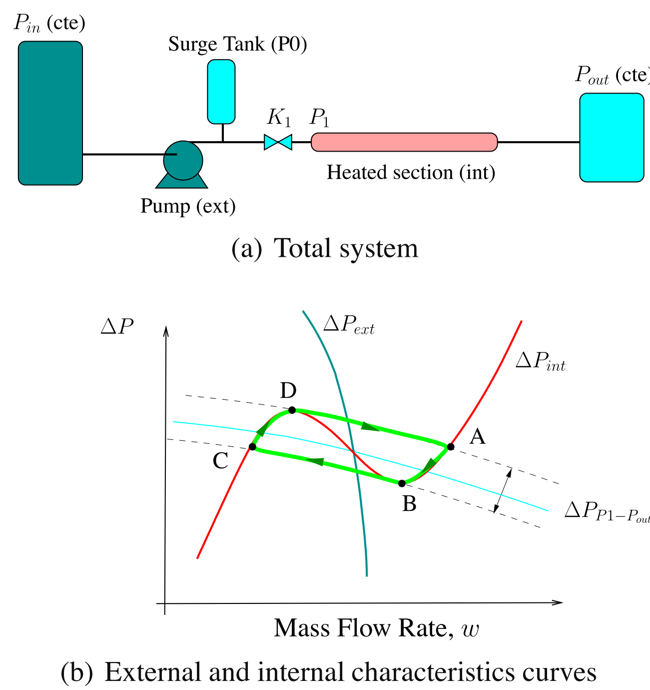


Fig. 4. Mechanism of pressure drop oscillation: (a) system capable of sustaining oscillations, (b) characteristic curves of the different parts of the system.

2.1.5. Pressure drop oscillations (PDO)

Considering a boiling system with an N-shape characteristic curve, such as the one presented in Fig. 4(b), a flow oscillation will be induced if a sufficiently large amount of compressible volume is placed upstream from the heated section. This kind of phenomena is mainly due to the interaction between the flow excursion phenomenon and the surge tank compressibility. It was introduced and systematically analysed in the pioneer studies of Stenning [31], and Stenning and Veziroglu [32], Maulbetsch and Griffith [33,34].

Consider the system shown in Fig. 4(a), where a surge tank (with a compressible volume) is situated upstream from a boiling channel. In accordance with this figure, the internal characteristic curve exhibits the N-shape curve. Consequently, the boundary conditions of the heated section would correspond at each time to the curve given by the valve K_1 and the constant pressures P_0 and P_{out} (dotted line in Fig. 4((b)). When the intersection of this boundary condition curve and the boiling channel does not satisfy the stability condition of Eq. (1), then the system may experience a dynamic phenomenon called *pressure drop oscillations*. Considering a fully developed oscillation, this mechanism is composed by: a compression in the surge tank, CD; a flow excursion from a two-phase state to a liquid state, DA; a decompression in the surge tank, AB; and a flow excursion from a low quality to a high quality two-phase state, BC. In Maulbetsch and Griffith [33], it is proved that for high power density systems, the amount of compressible volume needed to sustain the oscillation is very low. In case of no interference with other phenomena, the frequency of the oscillations is mainly controlled by the compressible volume dynamics and the fluid inertia. Nevertheless, the occurrence of this phenomenon is usually associated with other kind of instabilities, as it will be discussed in the following sections.

2.2. Density-wave oscillations (DWO)

This is by far the most studied kind of two-phase flow instability. A thermo-hydraulic system and its associated boundary conditions constitute a complex dynamic system. The main two mechanisms related with the generation and propagation of this phenomenon are the delay in the propagation of disturbances and the feedback processes conditioning the inlet parameters. While delay effects are the product of transport phenomenon within the channel, feedback effects are related with the characteristics of the boundary conditions. In the classical description, the time period of these phenomena is considered to be between 1.5 and 2 times the time required for the fluid to travel through the system.

In general the name density-wave instability was used in literature to denominate one particular phenomenon occurring at high outlet qualities (DWO_{II}). Fukuda and Kobori [7] presented a classification of different types of density-wave instabilities. These authors classified the different kinds of phenomena according to the main mechanisms involved in their occurrence. In their model a heated channel with an adiabatic chimney section is considered. All in all, they found five different kinds of DWO: due to gravity in the heated section, $D_{I,H}$; due to gravity in the chimney section, $D_{I,R}$; due to friction in the heated section, $D_{II,H}$; due to friction in the chimney section, $D_{II,R}$; and due to inertia-momentum in the heated section, $D_{III,H}$.

The present classification, based in Fukuda's results, and taking into account experimental and analytical evidence, is divided in three types of *density-wave* instabilities, corresponding to the three main mechanisms that cause them: due to gravity DWO_I; due to friction DWO_{II}; and due to momentum DWO_{III}. This last classification is in agreement with the analysis carried out by Bouré and Mihaila [3].

2.2.1. Type I: Due to gravity, DWO_I

This kind of instability is experimentally observed in upward vertical systems with a long adiabatic chimney section downstream from the heated section. It was reported and systematically analysed in Fukuda and Kobori [7]. At low quality conditions, any disturbance can cause a significant change in the void fraction and in the flow conditions. At low pressures the hydrostatic head (heated section and chimney) is very sensitive to flow rate variations. Consequently, the feedback between flow, void fraction, and head can lead into oscillatory scenarios. In particular, this phenomenon is very important in natural convection loops, but it was also reported in forced convection systems, Collins and Gacesa [35]. It plays an important role in nuclear reactors safety analysis, as described in the experimental and analytical studies presented in the following sections.

2.2.2. Type II: Due to friction, DWO_{II}

This type of density-wave phenomenon is the most common *density-wave* instability described in literature. The theoretical basis and dimensionless analysis, used to analyse this phenomenon, were introduced in Stenning et al. [36], Bouré and Mihaila [3], Zuber [4], Ishii [6]. The main cause of this phenomenon is the different propagation speed of the flow perturbations in the single-phase and the two-phase region. Changes in flow or void fraction in the two phase region results in pressure-drop variations. Since the perturbation propagates rather slowly along the two phase region, a significant delay marks the onset of perturbations in the two phase region. Hence, the two-phase pressure drop and the single-phase pressure drop oscillate out-of-phase. A discussion of the complex interaction between the mechanisms taking place during the occurrence of this phenomenon will be presented in Section 4.4.

2.2.3. Type III: Due to momentum, DWO_{III}

This type of *density-wave* instability has received very little attention. It was first presented as high-order instabilities in the experimental study of Yadigaroglu and Bergles [37]. Moreover, in Achard et al. [38] the term "stability islands" was used to describe the parameter region where this phenomenon makes the system unstable. As described in Fukuda and Kobori [7], the basic cause of this phenomenon is the interaction between the inertia and momentum pressure-drop terms and the thermo-hydraulic propagation delays.

2.3. Compound density-wave phenomena

In this section, several phenomena related with the basic forms of the *density-wave* instabilities are presented.

2.3.1. Density-wave oscillations in parallel channels

Several investigations regarding the occurrence of *density-wave* oscillations in parallel boiling channels have been published. Different aspects of this complex phenomenon have been introduced in Gerliga and Dulevskiy [39] and Fukuda and Hasegawa [40]. The basic *density wave* mechanisms, explained before, also occur in parallel channel systems. As concluded by Fukuda and Hasegawa [40], the system stability depends on the local stability for each channel. Moreover, different oscillatory modes are possible according to the different characteristics of the channels. In general terms, out-of-phase and in-phase oscillations are reported and they are the result of the interaction between different channels. Several experimental and analytical investigations are analysed in the following sections.

2.3.2. Coupled neutronic thermo-hydraulic instabilities

During the 80's, several nuclear power plant events (BWR) have triggered the attention of thermo-hydraulic researchers and nuclear reactors vendors, Gialdi [41]; NRC [42]. As described before, *density-wave* instabilities are the consequence of feedback between the propagation phenomena and the different pressure-drop terms in the single- and two-phase regions. In BWRs, since water is used as a coolant as well as moderator, the neutron flux (and thus the power) depends strongly on the void fraction. Therefore, there is a feedback effect between the void fraction and the neutronic flux called *void reactivity feedback*. When this new feedback effect is coupled with the system thermo-hydraulics the whole system can become unstable, leading to the phenomenon named as neutronic-coupled *density-wave* instability. Reactivity feedbacks caused by temperature variations are also present during instabilities. In addition, the thermal inertia of the fuel influences the heat flux delivered to the coolant during power variations, affecting significantly the system dynamics and stability. An excellent review of the state-of-art regarding neutronic-coupled instabilities was presented by March-Leuba and Rey [43]. In general, two different modes are described in the literature: *Core wide*, when the whole core behaves as one (in the sense of the neutron flux); *Out-of-*

phase, when the neutron flux oscillates azimuthally in the core of the reactor. In the last decades, considerable effort was done in order to understand and predict the occurrence of this phenomenon in nuclear reactors.

2.4. Flashing induced instability (FSH)

This phenomenon is generally described in natural convection systems, in which an unheated section (chimney) is placed downstream from the boiler. As described by Furuya [44], the flashing-induced mechanism can be resumed in the following steps:

(a) The fluid heated in the core flows into the chimney.
(b) Boiling is initiated at a location where the liquid temperature exceeds the local saturation temperature.
(c) A decrease in the static head promotes further evaporation (flashing).
(d) The natural circulation flow rate increases due to an enlarged vapor volume, resulting in an outflow of vapor bubbles. The temperature at the chimney inlet decreases due to the higher flow.
(e) After the chimney is filled with subcooled liquid, the flow rate decreases and the process repeat itself from point (a).

It is found that the oscillation period agrees with the time required for the single-phase liquid to pass through the unheated section region (chimney). For this reason it is considered in some works as a *density-wave* phenomenon.

2.5. Thermal oscillations (ThO)

The name *thermal oscillation* is associated with the large fluctuations of the heated channel wall temperature. It was first presented by Stenning and Veziroglu [45]. This phenomenon is considered as a compound dynamic instability in the classification presented in Bouré et al. [9], since it is observed as a result of other thermo-hydraulic instabilities. In the original study Stenning and Veziroglu [45], this phenomenon is triggered by *density-wave* oscillations (DWO_{II}).

It was found that this phenomenon is associated with the movement of the dryout and nucleate boiling boundaries [46]. When the instability is triggered by low frequency oscillations (PDO), as described in Kakac et al. [47,19], the temperature fluctuations are simply the result of the boiling boundary movement. In these cases the oscillation frequency is equivalent to that of the primary phenomenon, as any other thermo-hydraulic variable in the system. In contrast, when this phenomenon is triggered by high frequency oscillations (DWO), then the temperature fluctuations have two distinct modes: a high frequency and small amplitude mode (corresponding to the DWO); and a low frequency and large amplitude mode. The high frequency mode is simply due to the boiling boundary movement, similar to the case of PDO. The low frequency mode is found to be a system mode which depends on the heater wall capacity, axial conduction and transition boiling characteristics, as described by Liu et al. [46]. Strictly speaking, this last mode is the only phenomenon that can be considered apart from the primary phenomena and received the name of *thermal oscillations*. According to the experimental evidence from Stenning and Veziroglu [45], Kakac et al. [47], Liu et al. [46], Ding et al. [48], this last mode occurs only as a result of *density-wave* oscillations.

2.6. Geysering (GES)

Geysering phenomenon has been observed in upward vertical boilers with a long unheated section downstream from the heated section. This phenomenon occurs for low power and low flow rates. It has been reported for natural and forced convection systems and in single and parallel channels. It was first reported by Griffith [49] for a vertical heated section with no circulation.

The mechanism triggering this instability mode was first presented in Ozawa et al. [50]. The whole process is explained as occurring in three different parts: boiling delay, condensation (or expulsion of vapor) and liquid returning. Fig. 5 shows a representation of the geysering phenomenon. The main mechanism, as explained by Aritomi et al. [51], can be summarised as follows: in vertical channels with high inlet subcooling, voids are generated and a large slug of bubbles is formed, which grows due to the decrease in the hydrostatic pressure head as it moves towards the exit; when the vapor mixes with the subcooled liquid in the upper

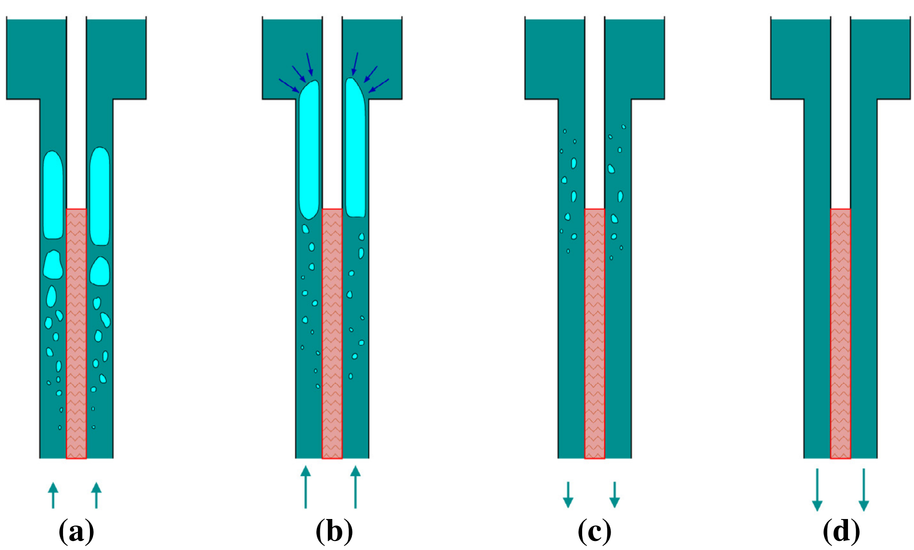


Fig. 5. Mechanism of geysering (Aritomi et al. [52]): (a) Boiling starts in the heated section and a large slug of bubbles is formed. As the hydrostatic head decrease the flow gets accelerated. (b) When the large slug of bubbles reaches the subcooled liquid in the outlet plenum, it gets condensed. (c) Void condensation causes the buoyancy to decrease and decelerates the flow. Flow reversal therefore occurs. (d) The system turns into a subcooled liquid state. The liquid is heated in the bottom part, so it turns again the direction and the process repeats from (a).

plenum, then the large slug of bubbles is suddenly condensed; due to the bubbles collapse the subcooled liquid reenters the channels and restores the non-boiling condition; the heating of the liquid increases again the void in the heater and the whole process repeats. This phenomenon is generally reported in interaction with DWO_I and FSH.

Several experimental investigations have shown that the period of flow oscillation is proportional to the boiling delay time t_{bd}, since it is considered that the boiling delay time is much longer than the condensation and liquid return times. The boiling delay time is defined as the time required for the subcooled liquid to be heated until the saturation temperature. As shown in Ozawa et al. [50], it can be expressed by the following equation,

$$t_{bd} = \frac{\rho_l Cp_l \Delta T_{sub} A_{xs} L_{HS}}{q''}, \tag{2}$$

where ρ_l is the density of the subcooled liquid; Cp_l the heat capacity; ΔT_{sub} the liquid subcooling temperature; A_{xs} the cross section; L_{HS} the length of the heated section; and q'' the heat flux.

2.7. Natural boiling oscillations (NBO)

Chiang et al. [53] described a new kind of flow instabilities in natural convection systems called *natural circulation instability*. This phenomenon is caused by the accumulation of vapor downstream from the heated section. The main mechanism occurring during this transient phenomenon is described as:

(a) Under low vaporisation rate conditions, the vapor may accumulate in an adiabatic section downstream from the heated section (e.g. in Chiang et al. [53] the vapor accumulates in the pipes connecting the outlet plenum with the separation tank). As a consequence, the hydrostatic head decreases and the circulation rate increases.
(b) Due to the flow rate increase, the accumulated vapor flows out and water fills the adiabatic section. Thus, the hydrostatic head increases again and the circulating rate decreases. The process then repeats from (a).

This phenomenon is characterised by a phase shift of about 180 degrees between the flow rate and the pressure drop oscillation in the region where the vapor accumulates (between the outlet plenum and the separator). The period of *natural circulation oscillation* is much longer than the corresponding to the transit time of a fluid particle (*density-wave*) through the adiabatic section.

2.8. Thermo-acoustic oscillations (TAO)

This phenomenon has received very little attention. According to Bergles et al. [54], one of the first survey regarding the occurrence of acoustic phenomena in boiling systems was presented by Firstenberg et al. [55] under the title “Boiling songs and mechanical vibrations”. This last term was used in reference to the high frequency sounds (1000–10,000 Hz) occurring under boiling conditions. These sounds are mostly produced by bubbles collapse, which depends on the subcooling temperature and heat flux. On the other hand, the terms *acoustic oscillation* or *thermo-acoustic oscillations* are used in reference to a lower frequency phenomenon (5–100 Hz). According to Smirnov et al. [56], the main mechanism triggering this kind of instability is the acoustic coupling of the vapor–liquid media with the existence of a forced oscillation source. The resonance occurs when the frequency of the nucleation centers coincides with the natural acoustic frequencies of the vapor–liquid flows, which depends on the pressure, flow patterns, channel geometry and the boundary conditions (open-end, closed-end, U-shape tube or valves).

Cornelius [57] presented one of the first systematic studies describing the occurrence of TAO in forced and natural convection systems. In this investigation, a closed loop using Freon-114 is used to study flow instabilities at supercritical conditions. TAO and what seems to be DWO_I and geysering phenomena are reported. It is worth noting that in some cases the TAO are observed together with other phenomena (in particular with*geysering* and DWO_I). Nevertheless, the interaction between this high frequency phenomena and the other oscillatory phenomena is not investigated. Acoustic oscillations of around 10 Hz are observed in boiling heat transfer studies in Gouse and Andrysiak [58]. This phenomenon seems to be caused by small bubbles which appear to “blink” (i.e., rapidly collapse and then expand) in the high-speed photographs system. Bergles et al. [54] described some experimental results in a boiler under subcritical conditions. In these experiments water was used as a coolant. The reported oscillation frequencies in this case were higher than 35 Hz. The setup boundary conditions neither are closed-end nor open-end but valves are used and it seems to influence the period of the oscillations since it differs from the theoretical one.

The oscillatory behaviour found during heat transfer to a fluid appears to be similar, regardless of whether the fluid is at a subcritical or supercritical pressure. Several investigations report the occurrence of TAO in supercritical systems using helium, hydrogen, nitrogen and other fluids, Yazaki et al. [59], Dmitrevskiy and Mel’nik[60], Krishnan and Friedly [61], Friedly [62]. In the studies Thurston and Rogers [63], Edeskuty and Thurston [64], this phenomenon is reported in a cryogenic boiler using dense hydrogen. A non-dimensional analysis is presented in order to understand the existing similarity with phenomena occurring in other systems. According to these investigations the *thermo-acoustic* phenomenon is excited by film oscillations.

Steward et al. [65] studied TAO in a supercritical pressured water system, which are found together with high frequency audio oscillations (500–2000 Hz). The modes of oscillation are identified as Helmholtz and open-open pipe resonance. During almost 30 years, very few investigations analysed this phenomenon. Smirnov et al. [56] presented one of the most complete studies in the field. Several test sections with different shapes and sizes are used. The main mechanism explained in the previous paragraphs was proposed in this last study. Nevertheless, it is still not clear if this phenomenon is the result of the bubbles collapse or the interaction with microscopic instabilities in the boiling film, as described for supercritical fluids.

2.9. Instabilities in narrow channels

In the last years, considerable research has been done on bounds of the heat extraction in micro- and nano-systems, encouraging the development of two-phase components for practical high-power applications in many fields such as space, communication, biology and electronics. Even though boiling and condensing in narrow channels have been intensively studied, it is not until recent years that two-phase flow instabilities have become the focus of some researchers, named Kennedy et al. [66], Kandlikar [67], Qu and Mudawar [68], Brutin et al. [69], Hetsroni et al. [70], Bergles et al. [71]. A very complete review of two-phase flow instabilities in narrow channels can be found in Tadrist [17].

Several instability modes observed in micro-channels are similar to those occurring in conventional channels, such as Ledinegg instability (LED), Pressure Drop Oscillations (PDO) and Density Wave Oscillations (DWO_{II}). Oscillating pressure drops and wall temperatures, and visualizations showing cyclical backflow, were encountered in many experiments. Due to the particular character-

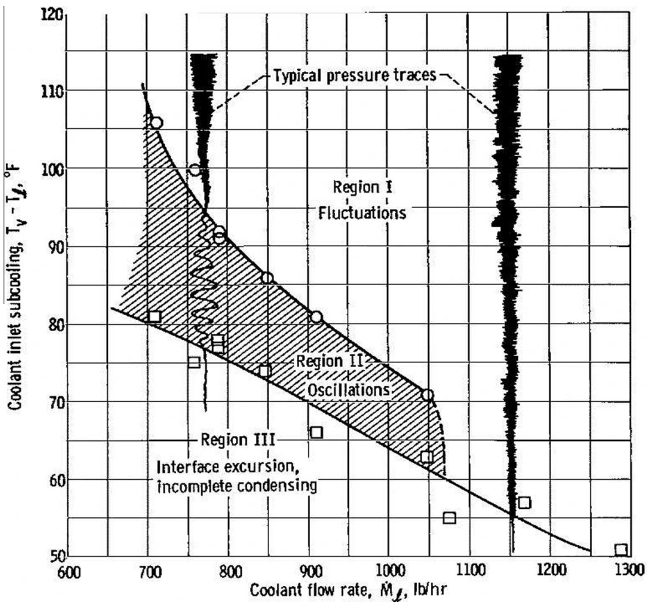


Fig. 6. Stability map for a condensing system (Reprinted from Westendorf and Brown [75]).

istics of these micro-systems the influence of the channel walls (velocity and temperature gradients) are much more significant than in conventional cases. As described in Bergles et al. [71] flashing could also play an important role in micro-channels as a cause of the large frictional pressure drop. In several cases as CHF is approached, flow instabilities induce vapor backflow into the heater inlet plenum, resulting in mixing vapor with the incoming subcooled liquid. This phenomenon produces a virtual independence of the CHF and the stability limits from the inlet subcooling. In addition, in channels where the hydraulic diameter is below the capillary length the surface tension has an important effect in the flow dynamics and, consequently, in the system stability. A very good description of the capillarity-forces effects in the stability of a capillary heater is presented in Yaris et al. [72]. The effect of the wall heat flux and the capillary sizes on the flow stability is studied. Flow instability in a heated capillary tube develops under conditions of high wall heat fluxes, which are the main factor in determining the flow regimes. At high wall heat fluxes the friction and capillary forces, as well as the inlet pressure losses play a dominant role. Under these conditions, a small deviation from equilibrium leads to progressive (exponential) growth of disturbances. The latter is displayed in oscillations of the velocity and temperature of both phases, as well as oscillations of the meniscus position.

An interesting theoretical study, presented by Fogg and Goodson [73], analyses the impact of acoustic waves generated by the rapidly nucleating bubbles. Under some conditions the feedback from the pressure waves inhibits the bubbles growth reducing the effective heat transfer. It is also shown that the pressure depression generated by the propagating pressure pulses can cause other bubbles to grow at lower than expected wall temperatures. However, the size of the experiments and the time-scale involved, make very difficult to obtain accurate measures that allow understanding more in detail these kind of phenomena.

2.10. Instabilities in condensing flows

At least 12 different phenomena have been explained in the previous sections for boiling systems. However, very little research has been done regarding the study of two-phase flow instabilities in condensing flows. As suggested in Delhaye et al. [74], the microscopic and macroscopic particular characteristics of condensing systems are completely different than those triggering the physical mechanisms described for boiling systems.

One of the pioneer studies on instabilities in condensing flow was carried out by Westendorf and Brown [75]. In this work, three different stability regions were reported, as shown in Fig. 6, and two different oscillatory phenomena were described. One corresponding with high frequencies (50–200 Hz) and the other with frequencies between 1 and 10 Hz. The main explanation for the first phenomenon is the occurrence of acoustic resonance, similar to the *thermo-acoustic* instability described in Section 2.8. As shown in this last work, the mechanism triggering the low frequency phenomenon does not fulfil the required characteristics of DWO or PDO. In Soliman and Berenson [76,77] an array of transparent channels is used in order to investigate flow patterns, stability and gravity effects. Several different microscopic phenomena associated with the liquid film behaviour produce pressure and flow oscillations.

2.10.1. DWO mechanism in condensing channels

Very few works studied the occurrence of DWO in condensing systems. Lahey and Podowski [14] presents a brief investigation of a condensing case using frequency-domain analysis. Even though their conclusions suggest that this mechanism does not take place in condensing systems, more research is suggested regarding this specific topic. Similar results were obtained by Ruspini et al. [78]. In this last work it is suggested that due to the characteristic positive slope of the density profile, the feedback effect between propagation times and boundary conditions, which is a destabilising mechanism for boiling systems, makes the system more stable. Moreover, none of these works are focused completely on this phenomenon, hence more research is still needed in order to understand the relation of these mechanisms with the occurrence of instabilities in condensing systems.

2.10.2. Self-sustained oscillations

A low frequency phenomenon (≈1–20 Hz), similar to the one described in Westendorf and Brown [75], was investigated by Bhatt and Wedekind [79]. In the latter study the mechanism triggering the oscillation is explained as a result of the dynamic energy exchange between the vapor compressibility upstream the cooled channel and the inertia of the subcooled liquid. Under these conditions, the system evolves to a limit cycle oscillation. The period of the oscillations is lower than that corresponding to the DWO_{II}. Boyer et al. [80] described the occurrence of a similar phenomenon in a vertical annular channel. The main parameters affecting the oscillations are heat transfer, vapor–liquid density ratio, vapor compressibility, downstream liquid inertia, upstream vapor, upstream and downstream throttling. Even when this phenomenon is associated with a compressible volume upstream from the test section, it is still not clear if it is related with the mechanism triggering PDO in boiling systems. In Bhatt et al. [81] a brief experimental analysis suggests, without being totally conclusive, that this phenomenon is particular of condensing systems. As described in Section 2.1.5, a necessary condition for the occurrence of PDO is the negative slope of the characteristic pressure-drop vs. flow-rate curve. In order to clarify this similitude, the characteristic curve for condensing systems is described in the following section.

2.10.3. Characteristic pressure-drop vs. flow-rate curve for condensing systems

In Fig. 7 the static characteristic pressure-drop vs. flow-rate curve for a downward condensing case is shown. In contrast with the boiling case, in condensing systems the friction pressure-drop curve has not a negative slope region. It can be seen that, in accordance with Fig. 7, the only term that can destabilise the system

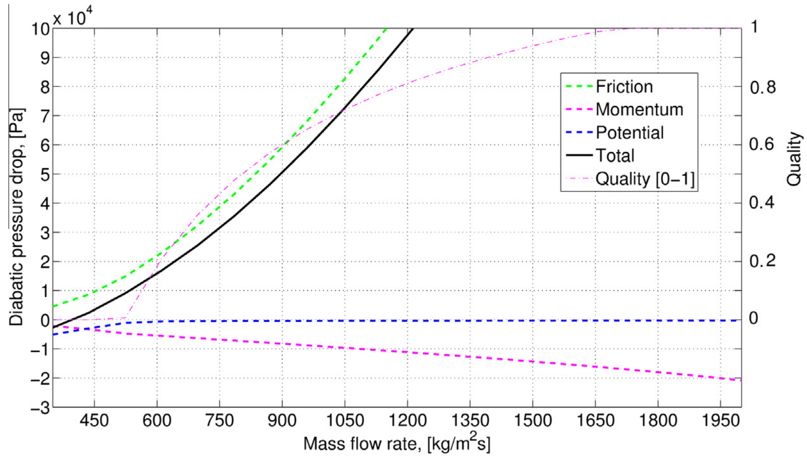


Fig. 7. Decomposition of the different pressure drop components of the pressure-drop vs. flow-rate characteristic curve of a downward flow condensing system.

(negative slope) is the momentum term, which is important only for dimensionless friction numbers, $\Lambda = f_{tp}\frac{L}{D_H}$, much lower than 1 (see [5]). In addition, when condensation takes place in an upward system then the slope of the hydrostatic pressure-drop term will be negative, especially for low flow rates. Therefore, condensing systems are, in principle, also susceptible to experiment instabilities related to the negative region of the pressure drop vs. flow rate characteristic curve (e.g., Ledinegg, flow re-distribution instability, PDO). Delhaye et al. [74] refers to this problem stating that the acceleration pressure drop may be destabilising for condensing flow in heated tubes.

2.10.4. Oscillations in parallel condensing channels

Very few studies analyse the occurrence of macroscopic instabilities in condensing systems. Following the investigations describing *self-sustained oscillations* in single channels, Kobus and Bhatt [82] investigated this phenomenon in a parallel channels system. The same kind of low frequency oscillations associated with the inertia of the subcooled liquid and the compressibility upstream the cooled section are reported. Similarly to the phenomenon described for single channels, the primary physical parameters responsible for this particular type of unstable behaviour include the condenser heat flux, downstream inertia of the subcooled liquid, compressibility in the upstream vapor volume, flow resistance and liquid–vapor density ratio. The last one being the primary physical parameter responsible for the amplitude of the oscillations. An analytical model representing these parameters is also described in the latter, showing good agreement with the experimental data.

2.11. Other types of two-phase transient phenomena

In this section a brief description of other transient issues affecting two-phase flow systems is presented.

2.11.1. Water-hammer phenomena

Modern hydraulic systems operate over a broad range of working regimes. Any sudden change can induce a pressure wave (water-hammer), that in some cases can exceed several times the normal pressure level and cause breakages in pipelines, valves or other components. Yow et al. [83] noted three basic types of severe water hammer occurring at industrial plants that can result in significant damages. They are:

- Rapid valve operation events: when a sudden change occurs in any hydraulic system, a pressure wave is generated and it can produce damages in valves, pipes or other components. Guidaoui et al. [84] present an updated review on the experimental and modelling research on water hammer phenomenon. Most of the phenomena reported in this work correspond to single-phase components.
- Water-slug induced events: when slugs of liquids (accelerated by a high flow of gas) collapse or crash with the pipe walls, then a pressure wave is generated within the gas. Bergant et al. [85] review the water-hammer studies reported in several two-phase flow systems.
- Condensation-induced events: The fast collapse of gas can produce, under some conditions, pressure waves of high amplitudes. Chun and Yu [86] analyse the condensation-induced water hammer phenomenon. They found that condensation-induced water hammer events were responsible of about 34% of the 283 events compiled by Van Duyne et al. [87]. Four different kinds of phenomena are classified in Yow et al. [83]: (1) steam and water counter-flow in a horizontal pipe; (2) subcooled water with condensing steam in a vertical pipe (water cannon); (3) pressurised water entering a vertical, steam-filled pipe; and (4) hot water entering a lower pressure line.

2.11.2. Flow-induced instabilities

These phenomena are one of the major problems in several industrial components. Flow-induced vibration is an important concern for the designers of heat exchangers subjected to high flows of gases or liquids. Two-phase cross-flow occurs in industrial heat exchangers, such as nuclear steam generators, condensers, boilers, etc. Under certain flow regimes and fluid velocities, the fluid forces result in tube vibration and damage due to fretting and fatigue. It is known that four mechanisms are responsible for the excitation of tube arrays in cross-flow Pettigrew et al. [88]. These mechanisms are: (1) turbulence buffeting; (2) vortex shedding; (3) acoustic resonance; and (4) fluid-elastic instability. The latter is proved to be the most damaging in two-phase components, Feenstra [89]. Pettigrew et al. [88] presented a review of all these phenomena occurring in industrial systems. Moreover, a complete review regarding the occurrence of fluid-elastic instabilities can be found in Khushnood et al. [90].

3. Experimental investigations

In this section a description of some of the most important experimental studies describing several two-phase flow instabili-

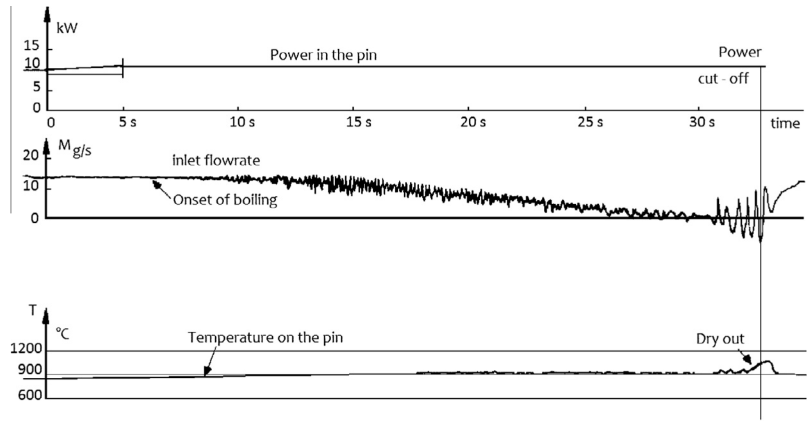


Fig. 8. Flow excursion in a sodium boiling system, Schmitt [95] (Reprinted from Costa [94]).

ties is presented. However, only the phenomena considered in the scope of this work (LED, PDO, DWO) are described in detail.

3.1. Ledinegg or flow excursion

Although there are several experimental works describing the characteristic pressure drop vs. flow rate curve or the Onset of Flow Instability (OFI) Siman-Tov et al. [91]; Stelling et al. [92]; Zhang et al. [93], there are only a few articles analysing experimentally the occurrence of flow excursion phenomenon in two-phase systems. In Fig. 8 an experimental case of flow excursion is shown Costa [94]; Schmitt [95]. This transient evolution occurred in a Liquid Metal Fast Breeder Reactor (LMFBR) using sodium as coolant fluid after the coast-down of the main pump. The total time of the transition is about 30s. In the last part of this flow excursion dryout is produced and consequently the wall temperature increases. Furthermore, what seems to be DWO can be observed. Jiang et al. [96] describe the occurrence of flow excursion transients in a natural circulation loop (HRTL-5). The reported evolution is a slow and long-term process in which both the mass flow rate and the inlet temperature of the heated section decrease while the exit temperature increases. In addition, DWO are reported in the process of the static flow excursion. Yang et al. [97] studied the flow excursion phenomena in the same system described above. In contrast with observations in forced convection systems, in natural convection it is proved that under some conditions a multivalued operation region can exist. This means that for a given pressure-drop, it is possible to find several mass flow rates satisfying the steady-state operational point condition.

More recently, Tao et al. [98] studied experimentally flow excursions in a narrow rectangular channel using a natural convection loop. Before and during the flow excursion oscillations, DWO_{II} are reported. During this transient, the change in the flow pattern regime has an important effect on the evolution of the system. It is proved that the effect of narrow channels plays a significant role promoting flow excursion.

3.1.1. Flow-distribution instability

There are several studies reporting flow distribution problems in two-phase flow systems. As described in the case of Fig. 8, the occurrence of this phenomenon in industrial systems often triggers the dryout and it may provoke burnout. In Margetts [99], flow excursion and flow ill-distribution are reported in a pre-heater used to recover heat from ammonia plants. Akagawa and Sakaguchi [25] presented one of the most complete investigations in the field. In a loop using Freon-113, electrically-heated circular parallel channels (approximately 40 m long, 4 mm internal diameter) are used to study several two-phase flow instabilities. Flow ill-distribution, due to negative slope of the characteristic curve is observed. Additionally, flow excursions between the different channels is also reported. PDO and DWO modes are briefly described. They established a graphical stability criterion for the flow-distribution instability in parallel channels using ΔP vs. G curves. In Ozawa et al. [100] an air/water experimental system is used to study flow distribution and PDO in twin parallel channels. The reported flow distribution and PDO are proved to be of similar characteristics than those observed in boiling channels.

In recent years due to the use of direct steam generation (DSG) for solar heating, some investigations have been carried out in order to understand the flow distribution instability in those systems. In Tshuva et al. [101] the splitting of a two-phase air/water mixture in a system of two parallel channels with common feed and common exit is investigated experimentally. Several parameter maps showing the symmetric and asymmetric flow splitting in the heated channels are described. The results show that at low flow rates and in inclined channels the flow is not symmetric. Similarly, Taitel et al. [102] use four parallel channels in an inclined array with a mixture of air/water to study distribution phenomena. It is found that for low liquid and gas flow rates the two-phase mixture flows predominantly in a single channel, while stagnant liquid fills part of the other three channels. As the flow rates of liquid and gas increase, flow in two, three and eventually in four channels takes place. Minzer et al. [103] presented the experimental results of a boiling system where the flow splits in two parallel channels using water at atmospheric pressure. They observe that, in the zone of multiple stable solutions, all possible solutions are practically obtained and the actual solution depends on the direction leading to the steady state (hysteresis phenomenon). In Baikin et al. [104] similar results are obtained for a four parallel channel boiling system. More recently in Xiong et al. [105], a parallel array of two upward vertical channels using supercritical water is studied. Flow distribution between the channels is reported in connection with other oscillatory phenomena, (DWO_{II}).

3.2. Pressure drop oscillations

Daleas and Bergles [106] report a case of Ledinegg-type instability interacting with an upstream compressible volume inducing oscillations that trigger premature CHF (Critical Heat Flux) in a boiling section. The term *pressure drop oscillation* was given by Stenning [31]. The latter reports DWO_{II} and PDO in a subcooled-boiling horizontal channel using Freon-11 as coolant Stenning and Veziroglu [45]; Stenning et al. [36]. Several steady-state pressure drop vs. flow characteristic curves are shown. Moreover the dynamic evolution of the PDO mode is plotted together with the steady-state characteristic curves. Similar plots to the curves shown in Fig. 4 are presented. The influence of different compressible volumes, upstream of the heated section, on the amplitude of the oscillation is studied. In some of the experimental cases, DWO_{II} are observed in interaction with the PDO mode. Another fundamental investigation about PDO corresponds to Maulbetsch and Griffith [33,34,107]. In these studies PDO and DWO_{II} modes are experimentally investigated. A very controversial conclusion is presented, stating that: "In cases of very long test sections (L/D > 150), there can be sufficient compressibility inherent in the test section itself due to vapor generation to initiate this type of instability". There is sufficient experimental evidence indicating that this conclusion is not well supported, since no other work in the field reported this effect. Actually, there are several experimental cases in which the ratio L/D is higher than 150 where no self-sustained oscillatory phenomena are observed without a compressible volume. A clear example is the investigation presented in Akagawa and Sakaguchi [25], where L/D = 10,000 and the occurrence of PDO modes are not observed. In addition, it should be noted that the characteristics of the DWO phenomena were not known at that time, and these two phenomena could be confused. In Kakac et al. [108,109] a vertical four parallel channels test section is used to investigate PDO and DWO during boiling conditions. Cross-connection between the channels is investigated, indicating that it stabilises the PDO mode. Moreover, the use of cross-connections reduces significantly the period of the oscillations.

Ozawa et al. [21] reported some experimental results regarding the occurrence of PDO mode in a Freon-113 vertical channel. High amplitude DWO_{II} are reported in some parts of the PDO cycle. Another interesting investigation was presented by Ozawa et al. [110], reporting PDO in an air/water system. Oscillations with time periods between 200 and 300 [sec] are observed. During the oscillations, due to the capillarity of the tubes, flow pattern changes between slug and bubbly flow are reported. In addition, high frequency oscillations are also reported when the flow decreases (bubbly flow). In the same manner as for boiling systems, the oscillations occur when the hypothetical equilibrium point is in the negative slope region of the characteristic curve. Years later, Ozawa et al. [100] studied PDO in a parallel array using an air–water mixture. Three different modes were observed: In-phase mode, all the channels oscillate with no phase shift; U-tube mode, the gas flow and the liquid flow oscillate 180° out of phase in the two channels; Multi-mode, the gas flow in each channel oscillates independently (i.e., the oscillation period in each channel differs from the others).

Mentes et al. [111] investigate the effect of different heater surfaces configurations on two-phase flow instabilities. Six different tubes with several heated surfaces are tested in a Freon-11 upflow forced-convection open loop. Changes up to 90% in the heat-transfer coefficients and in the oscillation periods are observed. In addition, changes in the oscillation periods are also reported. For the DWO mode every tube has similar periods, but for the PDO mode there is a great difference among the tubes, although the amount of air in the surge tank remained constant. In the same year, Dogan et al. [112] used an upflow forced convection loop with Freon-11 to study PDO. Experimental steady-state characteristic curves (ΔP vs. G) are obtained. PDO and DWO_{II} are reported both as pure separate modes and also interacting with each other where the stable and unstable regions are distinguished. Similar to the experimental set-up described before, in Yuncu [113]; Yuncu et al. [114] a horizontal boiling channel is used. In all the experimental cases DWO are superimposed to the PDO mode. Several stability maps are reported using the characteristic curves as shown in Fig. 9. In Kakac et al. [47]; Padki et al. [115] PDO are reported in a vertical channel of similar characteristics to the one described before. The main focus of these studies is placed on the temperature variations at the

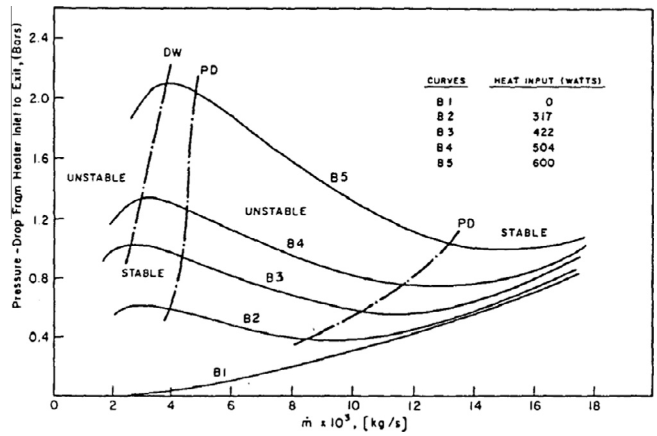


Fig. 9. Characteristic pressure drop vs. flow curves and the stability boundaries of DWO_{II} and PDO modes (Reprinted from Yuncu et al. [114]).

outlet of the heated section. Superimposed DWO on the PDO mode are also observed. The same experimental setup is used by Liu and Kakac [116] in a very interesting investigation. This is the first study analysing the superimposed DWO on the PDO mode. The density-wave mode takes place in the lower mass flow rate region of the characteristic curve (higher qualities). The superimposed DWO are observed for different inlet temperatures and power conditions. Nevertheless, no systematic conclusion is reported on how the DWO mode influences the frequency and amplitude of the PDO mode.

Ding et al. [48] presents a very complete parametric analysis. The effects of mass flux rate and inlet temperature on the oscillation period and amplitude, for both PDO and DWO modes, are investigated. Under the DWO mode *thermal oscillations* are observed. It is also shown that the DWO mode can take place in the negative slope region of the characteristic curve, in contrast to the vertical cases where this mode is reported in the positive slope region, as indicated in Fig. 9. In addition, the position of the two-phase/over-heated vapor boundary is investigated in relation with the occurrence of the *thermal oscillation* phenomenon. As reported in Wedekind [117], under some conditions the evolution of this point can be highly chaotic.

Xiao et al. [118] reported the occurrence of DWO_I, DWO_{II} and PDO using two vertical parallel channels and water as coolant. In this study the DWO_I mode is called 2^{nd} DWO. In some cases, the PDO are reported to occur without surge tank due to the parallel array condition. In addition, flow reversal is observed in each of the channels and superimposed DWO occurs during the PDO mode, but though this is one of the most interesting experiments, due to its conditions, no further information about the PDO mode is reported. In Reinecke and Mewes [119] pressure-drop investigations are reported in a downward vertical tube, analysing PDO in monolithic reactors. The main focus of this study is the modelization of the system as it will be described in the next sections.

Another interesting study was presented in Guo et al. [120], where PDO are studied in a water forced convection loop with a helical heated section at intermediate pressure (30 bar). In this investigation the compressible gas volume positions, non-uniform heat flux distributions and various helix-axis inclinations are studied. For a given set of parameters, the existence of a critical compressible volume is experimentally determined. Moreover, it is also observed that moving the surge tank upstream (farther from the test section) increases notably the stability of the system. When the surge tank is placed right before the test section, the non-uniform heat flux distribution has no significant effect on the stability of the system. On the other hand, when the surge tank is farther from the test section the non-uniform heat flux distribution influences the stability limits. Finally, the helix-axis inclination has not significant influence in the occurrence of PDO. Guo et al. [121] use the same experimental system to study the heat transfer properties of the system under PDO. As a result of the PDO, the transient local heat transfer coefficient oscillates with a reverse phase characteristics (respect to the flow rate) and it shows an asymmetrical and non-uniform feature.

In Komakli et al. [122] the influence of mass flow rate and inlet temperature on the stability of PDO and DWO phenomena are analysed. Using the same system, Karsli et al. [123] studied the effect of heat transfer enhancement in the stability of different instabilities modes: PDO, DWO and ThO (Thermal Oscillations). The heat transfer is modified by using five tubes with different characteristics and different pitch. The unstable region for PDO is larger for tubes with enhanced surfaces than for the bare tube. Periods and amplitudes of pressure-drop type oscillations and density-wave type oscillations change depending on the heater tube configurations. The same system and experimental results are presented in Yilmaz et al. [124].

Kakac and Cao [125] studied *pressure drop* and thermal oscillations in vertical and horizontal channels. Even though this investigation is related to the modelling of those instability modes, several experimental data are presented. DWO are observed in interaction with PDO and ThO modes.

More recently, Ruspini [126] studied specifically the influence of DWO on the occurrence of PDO phenomenon in a horizontal boiler using R134a as a coolant. In most of the described cases, PDO are triggered by the occurrence of DWO_{II}. Experimental stability maps as a function of N_{Pch} and N_{Sub} are presented for both, PDO and DWO. In addition, the internal and external characteristic pressure drop vs. flow curves are presented and the classical assumptions used to model PDO are critically discussed. It is proved that even though the oscillation periods of the different modes are different, they are coupled through energy exchange.

3.3. Density-wave instabilities

Density-wave instabilities are the most studied phenomena in the literature. As presented in Section 2.2 there are three main types of *density-wave* instabilities according to the inducing mechanism. Historically, only the phenomenon classified as DWO_{II}, induced by friction terms, has been normally considered as *density-wave* oscillations. Even when the distinction between these phenomena was introduced by Fukuda and Kobori [7], it took several years until this classification was adopted by the researchers. In this section, several experimental investigations describing the different *density-wave* modes are described.

As mentioned in Kakac and Bon [19] several articles reported oscillations in subcooled single and parallel channel systems during the 1950s Semenovkel [127]; Wallis and Heasley [128]. Nevertheless, it is not until the middle 1960s that this kind of phenomena started to be systematically investigated. Jeglic and Yang [28] studied the onset of flow oscillations in a boiling single vertical channel. A transparent test section is used in order to study visually the flow patterns during the unstable phenomena. Flow excursions with associated burning of the system and superimposed DWO_{II} are reported. Two different kinds of test section are used: an electrically heated test section (Inconel); and a porous wall transparent test section. In the latter, the injection of air or steam is used to simulate the oscillatory phenomenon of diabatic systems in an adiabatic condition. When steam is injected, the system behaves in the same manner as in the diabatic case (metallic test section). On the contrary when air is injected, no oscillatory phenomena are reported. Stenning and Veziroglu [129] used an air/water system to study the occurrence of DWO_{II} phenomenon in a controlled manner. It is observed that the oscillations also take place in adiabatic systems (air/water). Stability maps of the density ratio vs. normalised pressure drop are presented.

Stenning et al. [36] used a forced convection single boiling channel with Freon-11 and water as working fluids. Three different kinds of instabilities are described, they are called type I, II, III, corresponding respectively with PDO, DWO_{II} and ThO instabilities. DWO_{II} are associated with the dryout condition at the outlet of the test section. In addition, the interaction of PDO and DWO_{II} modes is seen in most of the cases. In a similar way it is proved that the ThO mode is triggered by the occurrence of the higher frequency phenomena (DWO_{II}), as explained in Section 2.5. Static characteristic curves are obtained and the PDO evolution, with superimposed DWO, are shown on these curves. It is observed that the increase in the inlet throttling stabilises the system. On the other hand, the high stabilising effect of the liquid–vapor density ratio is observed. Decreases in the system pressure (higher liquid–vapor density ratio) are proved to destabilise the system. Furthermore, a substantial decrease of the boiling heat transfer coefficient during the oscillations is reported. Even though some stability maps of mass flow-rate vs. subcooled temperature are shown, no significant conclusion about the stability limits prediction is presented. Most of the results of this investigation are the extension of the studies presented in Stenning and Veziroglu [45,32].

Dijkman et al. [130] investigated these phenomena in a loop using water under natural and forced convection. In accordance to the described oscillations and the characteristics of the system, it is possible to conclude that the phenomenon reported is DWO_{II}. It is proved that the forced convection mode is more stable than the natural convection mode. The study is focused on the experimental description of the transfer functions in order to characterise the dynamics of the system (power → inlet mass flow rate; power → void fraction). In a similar manner, Dorsh [131] used a forced convection loop with Freon-113 to evaluate the frequency response functions (impedance maps) to forced oscillations in order to evaluate the system dynamic of a boiler. Moreover, Mathisen [132] presents a study in a natural circulating parallel-channel using water as working fluid. A very complete steady-state characterisation of the power vs. flow-rate curve is presented. Burnout of some of the channels is reported in association with the onset of flow oscillations. The effects of pressure, subcooling and exit throttling are analysed for a single channel. In reference to the two-parallel channels analysis, it is observed a 180° shift (out-phase) between the channels flow when DWO_{II} occurs. The parallel system configuration results more unstable than the single channel configuration.

One of the most discussed studies regarding *density-wave* phenomena is presented by Yadigaroglu and Bergles [37]. They use a boiling, single channel, upward system with Freon-13 to study stability regions. High-order modes (DWO_{III}) are reported in interaction with the normal mode (DWO_{II}). The stability limits are plotted as a function of the enthalpy parameter vs. a dimensionless subcooling, as show in Fig. 10. In this figure the limits for the higher frequency modes corresponding to the DWO_{III} are shown.

Collins and Gacesa [35] performed an experimental program to investigate parallel-channel instabilities in a full-scale simulated nuclear reactor channel operating in vertical, high-pressure, upward conditions and using water as coolant. In this investigation two 19-rod electrically heated bundles are connected in parallel with an unheated by-pass between a common inlet and an outlet headers. Two different kinds of phenomena are reported. A high frequency random oscillation, associated probably with the mechanism explained for TAO (thermo-acoustic oscillations) (28 Hz) and DWO with high quality conditions (DWO_{II}). In the latter mode,

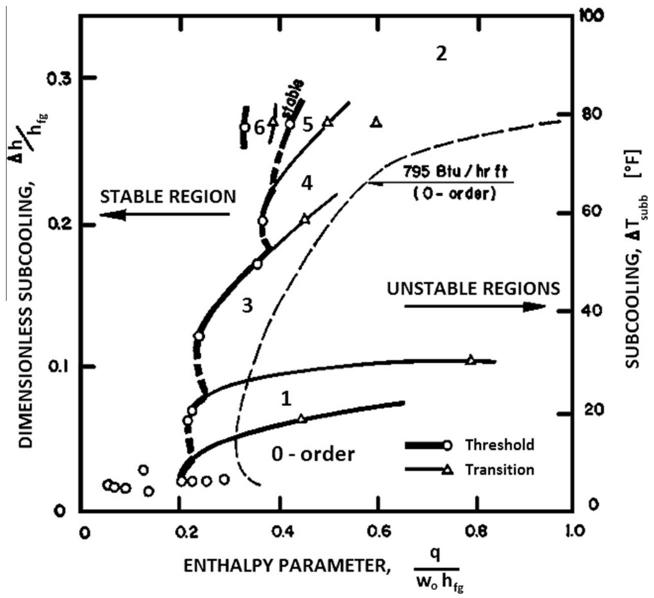


Fig. 10. Stability map for different *density wave* oscillations modes (Reprinted from Yadigaroglu and Bergles [133]).

a low frequency modulation, or what the authors identify as beating, is reported. The frequency of this beating is not constant, indicating that it is a consequence of two oscillations of similar frequencies more than an independent phenomenon. Moreover when the power is increased the amplitude of the oscillations grows and the beating phenomenon becomes less significant. Regarding the occurrence of oscillations in parallel channels, Veziroglu and Lee [134] studied two cross connected parallel channels. It is shown that the cross-connection makes the system more stable. In addition, without the cross-connection the oscillation has a shift of 180 degrees in the inlet flow, whereas when the cross-connection is used the oscillations between the two channels are in-phase.

In Matsui [135,136] a vertical upward closed loop is used under forced and natural convection. One of the particularities of this study is the use of n-pentane as a coolant. This is one of the first investigations reporting DWO_I (low quality). Moreover, even though this kind of phenomena is normally associated with natural convection systems, the oscillatory phenomenon is observed for both forced and natural convection. When forced convection is used a reduction of the unstable region is observed. In addition, a photographic study of the flow pattern during the oscillations is presented. In Krishnan and Friedly [61] the stability of a heated channel using nitrogen is investigated. Under the experiment conditions thermo-acoustic oscillations (TAO) are found and DWO modes are proved to be stable for the whole parameter region. Friedly [62] investigated DWO in a similar experimental system, reporting DWO in interaction with TAO. In this case the nitrogen was subcooled at a fixed temperature and the total pressure drop was dominated by the pressure drops at the inlet an outlet restrictions.

Saha [137] presents an experimental investigation of DWO_{II} phenomenon in a forced convection loop using Freon-113. One of the advantages of using Freon coolants is that heater walls can stand film-boiling conditions. Constant pressure-drop conditions were imposed to the heated section by using a parallel by-pass. Some of the plots show back-flow due to this parallel configuration. Oscillations of pressure and flow are reported, however no information on the temperature evolution is presented. One of the features of this investigation is to report the stability limits using the N_{Pch} vs. N_{Sub} stability maps Zuber and Findlay [138]. Moreover, the effects of inlet–outlet restrictions and system pressure are analysed. As explained before, it is found that an increase in the inlet restriction stabilises the system while an increase in the outlet restriction destabilises it. In addition, the system is observed to be completely stable to the high-order mode (DWO_{III}). The results presented in this experimental investigation are the extension of the studies published in Saha et al. [139]; Saha and Zuber [140]. One of the most interesting investigations regarding the occurrence of DWO is made by Fukuda and Kobori [141]. They use an upward double channel to study DWO_I and DWO_{II} phenomena in forced and natural circulation. A model of the mechanisms involved in the occurrence of these two phenomena is proposed. A cross-sectional valve is used to mix the flows at the outlet of each channel before the chimneys. When the valve is open, the system behaves in a more stable manner, showing that cross-connections at the outlet stabilise the system.

Ünal et al. [142] studied DWO_{II} in an industrial upward steam-generator heated by sodium flowing downwards inside an array of 139 tubes. The temperature in the cross section of the superheated steam region oscillates irregularly due to non-equilibrium effects between phases. The observed period of oscillation is between one and two times the transit time. Ünal [29,143,144] measured DWO_{II} in forced and natural convection in single, parallel and a helicoidal water channels heated by a counter-current stream of sodium. It is found that the steam quality at the outlet of the tube at the inception of the DWO depends mainly on the system pressure, whereas the influence of other parameters is secondary. Interestingly, in long one-through steam generator tubes ($L/D > 4100$) the stability margin of DWO becomes independent of the inlet throttling, in agreement with Maulbetsch and Griffith [33].

Another very interesting investigation was carried out by Daney et al. [145]. In this work, DWO_{II} are studied in a long test section ($L/D = 46000$) using supercritical helium as working fluid to simulate superconducting power-transmission lines. DWO_{II} with a time period of several minutes (twice the transient time) are observed, together with enthalpy waves propagating along the system. It is found that the vapor/liquid density ratio greatly influences the stability of the system. Multiple frequencies (DWO_{III}) with a dominant frequency (DWO_{II}) are reported by Roy et al. [146] in an annular geometry with low-pressure Freon-113. The energy associated with the secondary frequencies is about one-third of the total energy. DWO_{III} could have been induced by the momentum terms (see Section 2.2.3) due to the large hydraulic diameter. Yang et al. [147] reported a phenomenon identified as a DWO in a vertical U-tube evaporator using Freon-12 as working fluid. The experiments show that flow oscillations in the vertical U-tube evaporator may cause serious heat transfer deterioration leading to large temperature excursions at the tube wall.

Aritomi et al. [51] investigated transient thermo-hydraulics phenomena during start-up in a natural circulation boiling water reactors (BWR). Geysering, natural boiling oscillation (NBO) and DWO_{II} are reported. DWO_{II} are observed at high heat flux, but the main focus is taken for the GES and NBO phenomena, whose mechanisms are discussed. In Delmastro and Clausse [148] oscillations in a natural convection loop using water as coolant are presented. The chaotic nature of the experimental phase-space trajectories of the DWO_{II} is analysed. Liu et al. [46] analysed the characteristics of transition boiling and thermal oscillations (ThO) in Freon-22 upflow forced-convection in a single channel, which are triggered by DWO. The interplay of heat storage and transfer between the tube wall and the fluid causes oscillations of the boiling boundaries and the wall temperature. The relevance of wall heat capacity and conductivity is mentioned. Wang et al.

[149] studied the influence of the pressure, inlet subcooling, flow rate and exit throttling on DWO_{II} in a high-pressure forced-convection single channel. All the conclusions agree with the results discussed in previous studies. Karsli et al. [123] observed that heat-transfer enhancement increases the amplitude and frequency of DWO_{II}.

In recent years, the study of natural convection systems received a lot of attention. Kim and Lee [150] analyse the different interacting modes induced in a natural circulation loop with an expansion tank. Geysering, DWO_I, Natural boiling oscillation, DWO_{II} and PDO are reported. However, since several phenomena occur simultaneously it is not clear how they interact with each other. Several experimental stability maps (heat flux vs. inlet subcooling) are shown and the stability regions for different phenomena are identified. It is observed that PDO stabilise if friction is increased in the tank line. Kruijf et al. [151] presented the results of a natural convection system. Experimental data in the whole operational range is gathered in a N_{Pch} vs. N_{Sub} stability map. Surprisingly, for low subcooling values, the stability of the facility increases with N_{Pch}. Kok et al. [152] built a loop based on fluid-to-fluid scaling technique to simulate the dynamics of the Dodewaard natural circulation BWR. In such a design the transit time was adjusted to match that from the reactor, resulting in a complex geometry loop. Marcel et al. (2008a) demonstrated that in stability studies, however, a time scaling rule must be preserved when using that technique. Furthermore, they show the time scaling rule has a single relation with the geometry scaling rule. Zboray et al. [153] investigated DWO_{II} in a natural circulation loop focusing in non linear dynamics. They operated the loop in the vicinity of the linear stability boundary and report the flow undergoes the so-called Feigenbaum scenario, the period doubling route to chaos, as one penetrates into the unstable operating region. In a scaled loop, Marcel et al. [154] investigated the thermal–hydraulic stability of the natural circulation ESBWR. They predict a stable behaviour of the system with an associated low resonance frequency when representing the nominal reactor conditions. They relate this behaviour with a static-head dominated phenomenon. In contrast, when applying an artificial void reactivity feedback, the resonance frequency increases showing good agreement with density-waves travelling through the core section. Despite the differences between the two modes, the authors report a smooth transition regarding the resonance frequency when varying the void reactivity coefficient from zero to nominal value [155]. Similarly, Manera and van der Hagen [156] studied instabilities in a natural convection experiment simulating the start-up conditions in a natural circulation BWR equipped with a chimney. Intermittent and sinusoidal oscillations, supposedly flashing-induced by DWO_I, are reported at high and low inlet subcooling temperatures respectively. They observed that increasing the system pressure has a stabilising effect, reducing both the extension of the unstable region and the magnitude of the flow oscillations amplitude. The shape of the stability limits are similar to those observed in Furuya et al. [157], suggesting that it is a typical curve for flashing-induced DWO phenomenon. These results are described with more detail in Furuya [44].

In most of these experimental investigations the reported oscillations, DWO_I, show a strong correlation between the time period and the travelling time of the enthalpy perturbations in the liquid region of the heated tube. Marcel et al. [158] presented a frequency decomposition of these modes, but it is still not possible to stablish for which parameter region each of the modes will be dominant. Marcel et al. [159,160] presented a very complete study on natural convection instabilities in single and parallel channels, with special focus on the study of *geysering* and *flashing* phenomena. In the single channel case, intermittent and sinusoidal oscillations are shown. Both phenomena are identified as *flashing* instability. A dynamical analysis of the two-phase front during oscillations suggests that condensation plays a minor role in the sinusoidal oscillations case. This result agrees with the axial temperature profile measured in the chimney region at the onset of the vapor front. The stability maps show agreement with previous results. Very interesting phenomena are observed in the case of two parallel channels equipped with parallel chimneys. Four different behaviours are reported in Marcel [155]:

- Stable flow circulation at low heat flux, corresponding to very low vapor quality values.
- Periodic oscillations at low-to-medium heat flux. The primary flow is roughly in-phase with the partial flow in both channels. The main instability mechanism in this case is FSH. Since the oscillations period is several times the boiling delay time, it could be concluded that the geysering mechanism plays a secondary role. The two channels behave independently except for the synchronization during the flashing events.
- Periodical oscillations at medium heat flux. They are attributed to multi-fractal deterministic chaos, as shown in Demaziere et al. [161]. The wavelet decomposition of the primary flow signal exhibited self-similarity properties. Bifurcations have been observed in the experiments which suggests that period-doubling is the route to chaos followed by the system.
- Out-of-phase periodical oscillations at high heat flux conditions. The primary flow exhibits a period which is half the period of the partial flows in the different channels. The coupling between them creates reversed flow, causing hot spots in the heated regions. This effect creates large gradients in the axial temperature profile which induce condensation. For this reason, the period of these oscillations is overestimated by the classical DWO theory and underestimated by predictions based on geysering mechanisms, suggesting that flashing and geysering phenomena coexist.

Yun et al. [162] studied the influence of pressure, non-uniform heating and asymmetric inlet throttling in twin parallel channels. Out-of-phase and in-phase DWO_{II} in parallel channels are reported. The parallel system is in general more unstable than the single channel case. Non-uniform heating shows a destabilising effect. The latter has a negative impact on the design of industrial components where non-uniform heating conditions are usually employed. Liang et al. [163,164] reported PDO, ThO and DWO_{II} instabilities in a straight horizontal tube using Freon-22 showing several static characteristic curves for different conditions. It is observed that DWO_{II} mode has the shortest period and the lowest amplitude. In this case it should be noted that the time acquisition is comparable to the oscillation period, thus the phenomenon cannot be described accurately. The ThO occurs with the longest periods and the highest amplitude among the three modes. Ruspini [126] reported experimental DWO_{II} in a horizontal boiler using R134a. In this work, the influence of compressible volumes (nitrogen) at the boiler inlet are studied. It is found that the presence of compressible gases strongly decreases the stability of the DWO_{II} modes.

3.4. Instabilities in narrow channels

A very complete review of two-phase flow instabilities in narrow channels can be found in Tadrist [17]. In this section a brief description of experimental evidence of two-phase flow instabilities in narrow channels is presented. Kennedy et al. [66] study the onset of nucleate boiling (ONB) and the onset of flow instability (OFI) both experimental and numerically. The values predicted by Saha and Zuber [165] empirical correlation overpredicts the heat flux leading to onset of flow instability. A more recent work studying this kind of phenomena, is presented in Qi et al. [166], where both ONB and OFI are described for a nitrogen evaporator. During the unstable modes (low frequency and high amplitude) the phase difference between pressure drop and mass flow is 180°, indicating that the system was working in a negative slope of the heater's characteristic curve, as explained in Section 2.1.5 for the PDO phenomenon.

Kandlikar [67] and Hetsroni et al. [70] studied the heat transfer in multichannel evaporators. In both works, the effects of the oscillations in the heat transfer and pressure drop are significant. In consequence, none of the available models seems to describe these variables accurately. Brutin et al. [69] describes vapor recoil caused by intermittent dry out. This phenomenon, described in several works, is very characteristic of narrow-channel system. These oscillations are due to the competition of the inertia or gravity effects and the vapor recoil pressure linked to the imposed heat flux on the wall. Bergles and Kandlikar [167] reviewed the existing studies on critical heat flux in micro-channels, concluding that most of the available CHF data at that time was taken under unstable conditions. In most cases, the critical conditions are the result of PDO (due to compressible volume), Ledinegg instability or flow distribution instability. Consequently, the unstable reported CHF values were larger than what would be expected for a stable case. When there is a significant compressible volume upstream of the heated section (PDO), an oscillating flow may lead to CHF. Qu and Mudawar [68] stated that the compressibility could be caused by an entrained air bubble, a flexible hose, or a large volume of degassed liquid. However, in many of these unstable cases the compressibility could also be due to the recoil of vapor into the inlet plenum, as described in several experiments. Huh et al. [168] had observed oscillations of long period (200 s) and high amplitude in a single micro-channel system. The authors described the flow-pattern transition (Elongated slug/semi-annular) as the main cause of the oscillations. However, the observed large period and phase difference suggest that this oscillation is caused by the interaction with the external loop (PDO) more than by the bubble collapse at the outlet, as described. In addition, flow reversal is also present during the oscillations, as reported in previous studies.

One of the most complete experimental studies is presented in Kandlikar et al. [169]. Two main stabilization techniques, artificial nucleation sites and pressure drop elements, are used to avoid the unstable conditions in a parallel micro-channel boiler. Artificial nucleation sites (laser drilled cavities) are introduced in the heated wall in order to improve the nucleation of vapor. It is shown that the introduction of artificial nucleation sites alone increase the instabilities, while in combination with pressure drop elements helps to reduce the instabilities. On the other hand, the introduction of pressure drop elements at the inlet of the channels appears to be the more efficient method to reduce the occurrence of flow reversal and the oscillations. Bogojevic et al. [170] studied these phenomena in a silicon heat sink with 40 parallel rectangular channels. Measure of temperature in different points of the channels is implemented. Two different modes are described: low amplitude high frequency (LAHF) and high amplitude low frequency (HALF) oscillations. High speed camera imaging shows that the bubble growth time and the period between two successive refills of the micro-channels are in the same order of the LAHF. On the other hand, HALF oscillations seem to be caused by the interaction with the external system. Yuan et al. [171] study OFI and DWO_{II} in two long parallel-channels ($L/D_H > 150$). Over the OFI point the mass flow rate can suffer a high decrease for increments of the applied heat. Density wave oscillations (DWO_{II}) are observed and described for several different experimental configurations. Stability maps (N_{Pch}, N_{Sub}) are constructed and the stabilising effect of the pressure increase are observed.

3.5. Summary of experimental studies

In Table 1 a summary of several experimental investigations reporting two-phase flow instabilities is shown.

4. Numerical and analytical investigations

Several works in the literature describe the modelling of two-phase flow systems. One of the first works summarising different analytical and empirical models was performed by Wallis [178]. Several years later, Ishii and Hibiki [179] presented a rigorous mathematical formulation for the models describing multi-phase flow systems. In any case, today many issues concerning two-phase flow still remain empirically based, being rarely possible to make accurate calculations based solely on first principles. Instead, it is much more common the use of correlations synthesised from experimental data. The assessment of pressure drop and heat transfer coefficients is a particularly good example of the empirical basis of these calculations. Good reviews of boiling/condensing models and correlations are presented in Stephan [180], Whalley [181], Hetsroni [182].

4.1. Models, formulations and numerical schemes

In general, the description of two-phase flow phenomena is based on conservation principles. Several forms of the conservation equations have been obtained [138,183,74]. Regarding investigations on two-phase flow instabilities, one-dimensional models are the most popular choice. In the literature it is possible to find mainly four models:

- *Two-fluid model, TFM*: This is the most general formulation for two-phase flow modelling. Six equations, three for each phase need to be solved and several constitutive laws (friction, heat transfer and interfacial) at the boundary and at the interface are required Kakac and Bon [19]. Particularly important are the constitutive relations for interfacial and wall heat transfer, which are very dependent on the particular characteristics of each situation. The main concern in applying TFM for instabilities is that most of the correlations are obtained under steady-state conditions. Examples of TFM implementations for instability analysis can be found in Dykhuizen et al. [184,185].
- *Drift-flux model, DFM*: The *drift-flux model* introduced by Zuber and Findlay [138] is a 1D approximation of the two-fluid model that introduces a time-independent correlation between the void fraction and the relative velocity between phases [178]. It allows representing the velocity difference between the different phases (slip) and the radial void distribution. There are several versions of DFM, mainly depending on the assumption for the void distribution parameter [138,186].
- *Slip-flow model, SFM*: In this kind of model phases are considered to be segregated in two different streams. It is useful to represent flow regimes such as annular where the two streams assumption is close to the real case [187].
- *Homogeneous model, HM*: This is the simplest and most popular model to represent transient phenomena in two-phase flow systems. In this model the two-phase flow is treated as a single-phase compressible fluid. The velocity of the phases is considered equal and in most cases a thermo-dynamic equilibrium condition between the phases is assumed. In this case the model is called Homogeneous Equilibrium Model (HEM).

The conservation equations for the different models can be found elsewhere in the literature mentioned above. Several techniques are used in order to obtain a solution to this system of equations.

Table 1
Experimental studies analysing two-phase flow instabilities in boiling systems.

Author	Phenomena	Type	Fluid	Conf.	Ch.	Comments
Wallis and Heasley [128]	DWO_I, DWO_{II}	nat	Pentane	upw	2	Three parallel channel oscillation modes are identified
Daleas and Bergles [106]	PDO	forc	Water	hor	1	CHF induced by oscillations
Stenning and Veziroglu [45]	ChP, DWO_{II}, PDO, ThO	forc	Freon-11	hor	1	Propose a model for PDO. This exp. is used in Stenning [31], Stenning and Veziroglu [32], Stenning et al. [36]
Jeglic and Yang [28]	LED, DWO_{II}	forc	Air/water	upw	1	Transparent sections, porous wall (air injection)
Cornelius [57]	TAO, DWO_I, GES	Nat/forc	Freon-114	hor	1	Supercritical conditions
Maulbetsch and Griffith [33]	PDO, DWO_{II}	forc	Water	hor	1	Influence of the compressible volume
Stenning and Veziroglu [129]	DWO_{II}	forc	Air/water	down	1	DWO in an adiabatic system
Dijkman et al. [130]	DWO_{II}	nat/forc	Water	upw	1	Evaluation of transfer functions
Mathisen [132]	DWO_{II}	nat	Water	upw	2	Very complete parameter analysis
Dorsh [131]	DWO_{II}	forc	Freon-113	upw	1	Frequency response of the system
Yadigaroglu and Bergles [37]	DWO_{II}, DWO_{III}	forc	Freon-13	upw	1	High-order modes
Collins and Gacesa [35]	DWO_{II}, DWO_I	forc	Water	upw	2	Bundles with 19 rod heaters
Akagawa and Sakaguchi [25]	ChP, FDI, DWO_{II}	forc	Freon-113	hor	3	flow distribution mechanisms. $L = 40$ m (L/D = 10,000)
Matsui [135]	DWO_I	forc/nat	n-Pentane	upw	1	Forced convection increase stability
Saha and Zuber [165]	DWO_{II}	forc	Freon-11	upw	1	Stability maps. Parameter analysis (K_{in}, K_{out}, P_{in})
Krishnan and Friedly [61]	TAO, DWO_{II}	forc	Nitrogen	hor	1	Stable in the DWO sense
Kakac et al. [109]	DWO_{II}, PDO	forc	Freon-113	upw	4	Cross connection between channels
Fukuda and Kobori [141]	DWO_I, DWO_{II}	forc/nat	Water	vertical	2	DWO_I mechanism model
Ozawa et al. [110]	ChP, PDO	forc	Air/water	hor	1	Capillary tubes, flow pattern changes
Ozawa et al. [21]	ChP, DWO_{II}, PDO	forc	Freon-113	upw	1	Interacting DWO_{II} and PDO
Daney et al. [145]	DWO_{II}	forc	Helium	helical	1	$L = 185$ m helical test section (L/D = 46,000)
Ünal [29]	DWO_{II}	forc/nat	Water	upw	–	Several test sections (helical, parallel, single). Heated with sodium
Dogan et al. [112]	ChP, DWO_{II}, PDO	forc	Freon-11	upw	1	Interacting DWO_{II} and PDO
Mentes et al. [111]	DWO_{II}, PDO	forc	Freon-11	upw	1	Effect of heat transfer augmentation
Mishima et al. [172]	CHF, PDO, DWO_{II}, CHF	forc	Water	upw	1	Relation between burnout and instabilities
Yang et al. [147]	DWO_I or GES	forc	Freon-22	upw	1	U-tube test section
Roy et al. [146]	DWO_{II}, DWO_{III}	forc	Freon-113	upw	1	Annular test section and high-order frequencies
Ozawa et al. [100]	ChP, FDI, PDO	forc	Air/water	hor	2	Three modes: In-phase, U-tube mode; multichannel mode
Yuncu [113]	ChP, PDO, DWO_{II}	forc	Freon-11	hor	1	Use of characteristic curves as stability maps
Padki et al. [115]	PDO, ThO	forc	Freon-11	upw	1	Influence of thermal effects
Aritomi et al. [51]	GES, DWO_I, DWO_{II}, NBO	nat	Water	upw	2	Study of start-up conditions, focused on BWR
Xiao et al. [118]	DWO_I, DWO_{II}, PDO	forc	Water	upw	2	High pressure (30–210 [bar])
Aritomi et al. [52]	GES	nat	Water	upw	2	Discussion of Geysering phenomena
Jovic et al. [22]	FDI, PDO	forc	Air/water	upw	3	PDO in an adiabatic system
Liu et al. [46]	ThO, DWO_{II}	forc	Freon-12	upw	1	Wall capacity, axial conduction
Delmastro and Clausse [148]	DWO_I	nat	Water	upw	1	Phase trajectories and chaos analysis
Wang et al. [149]	DWO_{II}	forc	Water	upw	1	Parameters analysis (T_{in}, P_{in}, G_{in})
Kyung and Lee [173]	DWO_I, DWO_{II}	nat	Freon-13	upw	1	Stability maps
Kok et al. [152]	DWO_{II}	nat	Freon-12	upw	1	Nominal conditions
Ding et al. [48]	PDO	forc	Freon-11	hor	1	Parameter analysis (T_{in}, G_{in})
Jiang et al. [174]	GES, FSH, DWO_I	nat	Water	upw	2	Start up analysis
Tshuva et al. [101]	FDI	forc	Air/water	inclined	2	Flow distribution is studied
Kim and Lee [150]	DWO_I, DWO_{III}, GES, PDO	nat	Water	upw	1	Several instability interacting modes
Guo et al. [120]	PDO	forc	Water	helical	1	Parameter analysis, critical volume
Zboray et al. [153]	DWO_{II}	nat	Freon-12	upw	1	Non-linear behaviour
Komakli et al. [122]	DWO_{II}, PDO, ThO	forc	Freon-11	hor	1	Parameter analysis (T_{in}, G_{in})
Manera and van der Hagen [156]	FSH, DWO_I	nat	Water	upw	1	Start-up conditions
Taitel et al. [102]	FDI	forc	Air/water	inclined	4	Flow distribution is studied
Minzer et al. [103]	ChP, FDI	forc	Water	inclined	2	Flow splitting and the static characteristics are studied
Kruijf et al. [151]	DWO_{II}	nat	Freon-12	upw	1	Atypical stability limit (N_{Pch},N_{Sub})
Baars and Delgado [175]	DWO_I, DWO_{III}	nat	Water	upw	1	Interaction of the DWO_I and DWO_{III}
Marcel [155]	GES, FLS, DWO_I	nat	Water	upw	4	Two chimneys and bypass channels are included, Marcel et al. [158,160]
Kakac and Bon [19]	ChP, PDO, DWO_{II}, THO	forc	Freon-11	upw/hor	1	DWO interact with PDO and ThO modes
Marcel et al. [154]	DWO_I, DWO_{II}	nat	Freon-134	upw	1	Influence of neutronic feedback
Yun et al. [162]	DWO_{II}	forc	Water	upw	2	Stability maps (N_{Pch},N_{Sub})
Jain et al. [176]	DWO_I, DWO_{II}	nat	Water	upw	4	Several chimney sections
Deng et al. [177]	DWO_{II}, PDO	forc	Water	upw	2	Rifled channels
Liang et al. [164]	ChP, DWO_{II}, PDO	forc	Freon-22	upw	1	Not significant conclusion
Xiong et al. [105]	FDI, DWO_{II}	forc	Water	upw	2	Super critical conditions
Tao et al. [98]	LED, DWO	nat	Water	upw	1	Narrow rectangular channel
Ruspini [126]	PDO, DWO_{II}, DWO_{III}	forc	R134a	hor	1	Coupling between PDO-DWO

ChP: characteristic pressure drop vs. flow rate curve; LED: Ledinegg or flow excursion; FDI: flow distribution instability; PDO: pressure drop oscillations; DWO: density-wave oscillations; ThO: thermal oscillations; TAO: thermo-acoustic oscillations; GES: geysering; FSH: flashing induced instability; NBO: natural boiling oscillations.

- *Frequency-domain formulation, FDM*: Normally, the Laplace transform of the equations is taken in order to transform from the time-domain to the frequency-domain. The spatial dependencies are eliminated by taking a lumped model (integral method) but it can also be solved by discretizing in space or applying the method of characteristics [188]. Some examples of the frequency-domain formulation can be found in [5,140,189–191,14].

- *Time-domain formulation, TDF*: The equations are discretized in time using different numerical techniques such as finite difference methods, finite volumes methods, etc. The spatial dependence is normally treated using two different techniques:
- *Lumped formulation*: A lumped formulation of the conservation equations is obtained by the *integral method*. The integral method is used for the purpose of reducing the dimension of the problem. It consists on integrating the governing equations over the domain of interest to substitute the continuous dependence of parameters by an average dependence [192,193].
- *Distributed formulation*: It consists in discretizing the spatial dependence and formulate an algebraic problem based on the values of the variables at the nodes. Two techniques are used to select the discretization:
  – *FNS, fixed nodes scheme*: The discretization nodes are distributed in a fixed spatial position and the different terms of the model are evaluated according to the nodal values. Several numerical techniques such FDM, FVM, FEM can be used [192,194,195].
  – *MNS, moving nodes scheme*: In this case the discretization is defined according to an assumed spatial distribution in some variable (enthalpy) and the model is reformulated according to this new discretization [196–198,194].

In general, FDF is aimed to the assessment of the most dangerous eingenvalue of the characteristic equation in order to determinate the stability margin. This is performed by previously linearizing the flow equations around the steady state. In such case, however, non-linear effects such as limit cycles are lost. Nevertheless, albeit quite cumbersome, FDF can still be applied to determine the amplitude of the limit cycles by means of Hopf bifurcation techniques [38]. Other non-linear techniques, such as harmonic linearization, are still not yet fully explored to study two-phase flow instabilities. In any case, TDF is the most common way to analyse non-linear effects like cycles and chaos.

In the following sections, a review of several numerical and analytical investigations regarding two-phase flow instabilities is presented. Some studies have summarised particular aspects of the two-phase flow instabilities [19,18,199].

4.2. Ledinegg or flow excursion

Based on the condition of negative slope of the characteristic pressure drop vs. mass flow rate, there are several studies proposing simple models and correlations to calculate the Onset of Fluid Instability (OFI) based on steady-state calculations [200,92,201–204,93].

Achard et al. [189] presented a comprehensive linear stability study based in a frequency-domain lumped parameter model. In this investigation, the analytical results predict excursive instability (i.e., Ledinegg) for the zero-frequency limit. A similar analysis is developed in Guido et al. [205], where an analytical expression for the stability limit of the Ledinegg phenomena is obtained based in a lumped parameter linear model. This stability limit is function of the N_{Pch} and N_{Sub} numbers and the concentrated inlet/outlet friction factors. Padki et al. [206] presented a linearised stability analysis of *Ledinegg* and PDO. A stability criterion based on bifurcation analysis is derived in terms of the steady-state external and internal characteristic curves. It is proved that the Ledinegg instability is caused by a saddle-node bifurcation while the PDO are caused by super-critical Hopf bifurcations.

More recently, several investigations reported numerical examples of the dynamic evolution during the flow excursion. For example in Ambrosini et al. [192] a lumped parameter model is used to simulate a boiling channel and the Ledinegg stability limit is predicted in a N_{Pch} vs. N_{Sub} non-dimensional map. Using a similar analysis, the existence of a negative slope region in supercritical conditions is studied numerically in Ambrosini [207]; Gomez et al. [208]. Schlichting et al. [209] presented a few transient simulations showing flow excursions and DWO phenomena. Ruspini et al. [24,210] describes the use of a high-order hp-adaptive method in the resolution of transient thermo-hydraulic phenomena. The evolution of a single boiler for Ledinegg unstable cases is analysed. In these simulations it is possible to see that for an unstable point the system can evolve to both lower and higher flow rates. The dynamic changes of the characteristic pressure drop vs. flow rate curve due to delays in the propagation of the enthalpy information are presented.

4.2.1. Flow-distribution instability

Akagawa and Sakaguchi [25] presented one of the first analysis of the flow distribution instability, both experimental and analytically. A geometrical criterion based on the shape of the steady-state characteristic curves is presented. More recently, Natan et al. [211] analysed a two parallel boiling channels system in connection with the use of Direct Steam Generation (DSG) for solar heating. A flow pattern based model is used to analyse the flow distribution and steady-state characteristic curves. It is found that the flow splitting between the two parallel channels is not symmetric even for symmetric heating. For asymmetric heating conditions, most of the liquid tends to flow in the pipe which absorbs less heat. Minzer et al. [212] presented a simple transient model to simulate the behaviour of a parallel boiling system. Similarly to the flow excursion in a single channel, the simulations show the trajectories of the system evolving from the unstable to the stable operation points. In addition, whenever several stable solutions are possible, the final state solution depends on the inlet flow rate history (hysteresis phenomenon). In Taitel et al. [213] a control system using the total flow and the inlet valves is proposed in order to control the flow distribution instability. Baikin et al. [104] presented the experimental and numerical analysis of four parallel boiling channels. In the case where only some of the channels are heated, it is found that most of the flow tends to take place in the unheated channels. Taitel and Barnea [214] presented a flow pattern based model to study the transient evolution of the flow-distribution phenomenon. The transient responses to finite disturbances in flow and heating power are analysed. The simulations show that depending on the amplitude of the perturbations, in some cases the transient trajectories can cause the excursion to other final states. Finally in Zhang et al. [215], a homogeneous model is used to study the stability and controllability of parallel boiling channels. As a main conclusion it is proved that the most stable systems are those where the characteristics of each channel are different. In addition when the channels are identical, the total flow does not change as a result of the flow-distribution variation in the individual channels. Thus in general, for parallel arrays it is recommended the use of uneven channel conditions.

4.3. Pressure drop oscillations

Several analytical studies were presented during the 1960s regarding the occurrence of oscillations in boiling systems [216,217]. Stenning and Veziroglu [45] propose a model including the pressure drops in the valves, inertia in the pipelines and a compressible ideal gas model for the compressible volume. This first model is extended in Stenning et al. [36]; Stenning and Veziroglu [129] to take into account the thermal capacity of the pipe and the heat exchange with the fluid. In these last works, a perturbation linear analysis is applied in order to obtain the system stability boundaries. In addition, a non-linear analysis of the limit cycles is performed by solving numerically the ODE system. The necessary parameters are measured or estimated from experimental data. With the resulting linearised model, the predicted oscillation periods are 300% longer than the experimental ones, even when the predicted analytical stability limits are in accordance with the experimental data. In the case of the non-linear model, the predicted periods are between 40% and 100% longer than those obtained experimentally. Maulbetsch and Griffith [34] present a linear stability analysis of the PDO phenomena. The assumptions of this model are similar to the one described previously, but the effects of heat transfer and thermal capacity are neglected. An analytical formula for the frequency of the oscillations is obtained. The stability limits agree with the experimental ones but the periods are not compared. Ozawa et al. [21] studied the PDO phenomenon experimentally and analytically. A lumped parameter model and a linearization technique, similar to the ones described before, are presented. The effects of the wall thermal capacity and the inlet valves are neglected. Moreover, the channel pressure drop is approximated by a cubic polynomial. The results show that even though the stability limits are predicted accordingly to the experimental values, the differences of the theoretical and experimental periods are close to 100%. In addition, in most of the previous investigations, DWO are superimposed to the PDO in the experimental data used to compare with the theoretical cases.

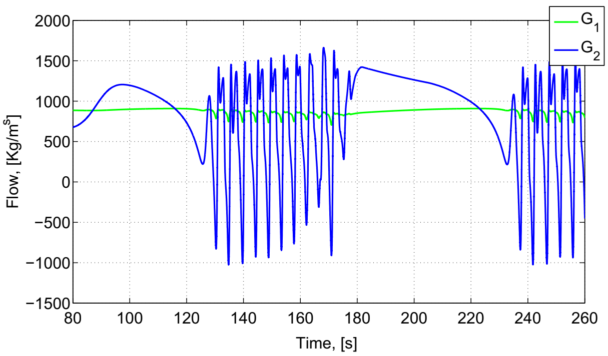
In Akyuzlu [218] Akyuzlu et al. [219] a finite difference scheme is used to solve the non-linear system representing a single vertical channel. A homogeneous equilibrium model is implemented neglecting the wall thermal storage. This theoretical analysis is conservative in predicting the stability boundaries for PDO. The amplitude of the oscillations is well predicted but the periods are underestimated. It should be noted that no DWO phenomena are observed in the experimental data used for validation. This fact should be remarked, since in most of the previous works the results obtained using a quasi-steady state model for the heater section (no DWO) are compared with experimental data where DWO are superimposed to the PDO phenomenon. Gürgenci et al. [220] present a simplified non-linear analysis. The effects of wall heat storage, the fluid properties variations and the inertia terms are neglected. The non-linear system is solved by a FDM. It should be remarked that in this case a vertical channel system is described so the gravitational terms are included in the model. The amplitude of the predicted limit cycles is in agreement with the experimental data, but the oscillation periods are 100% longer than the experimental values. The HEM model presented by Dogan et al. [112] shows that heat-transfer variations are relevant in generating and sustaining the PDO. In Yuncu et al. [114] a frequency-domain analysis based on a HEM is performed in order to obtain the stability limits for PDO. The stability predictions agree within the 50% with the experimental values.

In Kakac et al. [47]; Padki et al. [115] a steady-state drift-flux model is used to represent a vertical-boiling channel. The effects of wall thermal capacity are taken into account and a FDM is used in order to solve the non-linear system, finding relatively good agreement between the experimental and theoretical results. It is found that, the period and amplitudes of the oscillations increase with decreasing flow rate. Padki et al. [206] was the first using the bifurcation theory based on a lumped parameter integral model showing that PDO is caused by a Hopf bifurcation as the heat input is increased. The necessary conditions for the occurrence of PDO and Ledinegg phenomena based on the slope of the characteristic curve are obtained, see Section 2.1.5. Liu et al. [221] compared dynamic simulations with experimental data obtained in Liu and Kakac [116]. A bifurcation analysis based on a lumped parameter model is presented. Several limit cycles are analysed concluding that, for increasing mass flow rates, PDO limit-cycles are generated after a supercritical Hopf bifurcation, which converge again to an asymptotically stable equilibrium point after a reverse supercritical Hopf bifurcation takes place.

Reinecke and Mewes [119] presented an analytical and experimental investigation of PDO in a vertical tube using an air/water mixture. A simple mathematical model is presented, using the experimental characteristic curve and an ideal gas model for the compressible volume. The agreement of the numerical results and the experimental data is good, both in frequency and amplitude. Cao et al. [222] presented an experimental and an analytical investigation. A drift-flux model is proposed to describe the steady-state heated section, neglecting heater wall effects. Oscillation amplitudes are overestimated, but the periods are reasonably well predicted. In Cao et al. [223] the previous model is extended to subcooled boiling, which improves the pressure drop calculation and the assessment of the stability margins. In Srinivas and Pushpavanam [224] a HEM is used to study the stability limits and dynamic behaviour of PDO. Bifurcation diagrams are used to determine the stability regions for Ledinegg and PDO. Moreover, some examples of dynamic simulations using the method developed in Narayanan et al. [225] are shown. Oscillations with really sharp transitions, much faster than the fluid particle transit time are reported. However, no discussion about the steady-state assumption for the heated channel under those conditions is presented.

More recently, Mawasha and Gross [226] analysed PDO in a horizontal boiling channel. An empirical third order polynomial correlation is used in order to represent the characteristic curve [113]. The periods of the numerical simulations agree with the experimental data, but the amplitude is over-predicted. The heater thermal capacity does not produce any significant effect in the oscillations. Kakac and Cao [125] study this phenomenon in vertical and horizontal systems using a drift-flux model for the heater, reporting good agreement with the experimental data. A similar analysis is presented in Kakac et al. [227]. Zhang et al. [228] presented the numerical analysis of PDO in parallel channels, focusing in the design of a control system to avoid this kind of phenomena in electronic cooling systems. Two control strategies are proposed, control through the inlet valve and control using the supply pump. Here, contrary to the findings of other researchers, the effect of the wall capacity influences the oscillations. In Grzybowski and Mosdorf [229], PDO in parallel and single channels are analysed. The thermal and hydrodynamic interaction between the heated channels is considered using a very simple model. Synchronous and asynchronous oscillations in the neighbouring channels are observed. The general evolution of the system is strongly dependent on the shape of the characteristic curve and in the thermal interaction of the channels. Moreover, the existence of chaotic regions due to the nature of these interactions is demonstrated.

One of the most original studies, since the pioneer article of Stenning and Veziroglu [45], is the one presented by Schlichting [230] where a HEM is used to simulate a boiling channel. An ideal gas compressible volume is modeled upstream the heated channel. The features of this new full dynamic model allow to simulate PDO, DWO and Ledinegg phenomena. The interaction between DWO and PDO is briefly analysed. Nevertheless, the simulated conditions differ from the normal experimental conditions usually found in the literature, therefore no comparison with experimental data is reported. A summary of these results is presented in Schlichting et al. [209]. Similarly, Ruspini et al. [231] compare the results of a dynamic model for a heated channel with those obtained using a classical steady-state model. While the steady-state predicts periodic oscillations for any size of compressible volume, the dynamic model predicts a transition between stable and unstable behaviour depending on the system parameters. It is also shown that in certain cases the results obtained with the steady-state model do not fulfil the assumptions made to obtain this kind of



(a)

Fig. 11. Numerical simulation of high-amplitude PDO with superimposed DWO_{II}. G1 and G2 correspond respectively to the mass flow rate before and after the surge tank (Reprinted from Ruspini [126]).

simplified models. In consequence, the usage of these results to describe real systems should be carefully studied. In addition, the effects of a compressible volume in the system are studied. The existence of a critical volume was proved through several simulations. The stability effects of the external fluid inertia are also analysed, confirming that the variation of the length between the surge tank and the heated section has a strong influence on the stability of the system, as observed experimentally. Ruspini et al. [126] applied an hp-adaptive numerical scheme to solve a dynamic homogeneous model of a heated pipe. Both phenomena, DWO and PDO, are simulated and the interaction of these two phenomena is analysed. The implemented adaptive scheme allows them to save computational time by changing the time step and space approximation order according to the complexity of the involved phenomena at each time step. In Fig. 11 the interacting PDO-DWO oscillations are shown, by plotting the mass flow rate up-stream and down-stream from the surge tank. In horizontal channels the high-amplitude PDO are triggered by DWO_{II} as was observed in experiments. The numerical results are compared to experimental data. A good agreement of the stability limits is obtained for both modes.

4.4. Density-wave instabilities

It took some years until the different phenomena involved in DWO were identified and studied systematically. Wallis and Heasley [128] was one of the first articles analysing oscillations in two-phase flow systems. Stenning et al. [36] implemented a lumped parameter model of a heated section with inlet and outlet throttling, predicting oscillations in the order of 1.5 to 2.0 times the residence time of a fluid particle in the heated section. The stability boundaries of the system are obtained using a frequency-domain analysis. Bouré and Mihaila [3] proposed the density effect mechanism, involving time delays, to explain the oscillatory behaviour of boiling channels. Zuber [4] presents a distributed formulation expressed in terms of the mixture center of mass, introducing the slip velocity between the phases. Ishii and Zuber [5] extended this formulation and propose a set of dimensionless numbers in order to set a similitude criterion between different two-phase flow systems. The subcooling (N_{Sub}), phase change (N_{Pch}), drift (N_D), density (N_ρ), Froude (Fr) and Reynolds (Re) dimensionless numbers were proposed to analyse the phenomena taking place in boiling systems. Following this theoretical investigation, Ishii [6] used a frequency-domain analysis to obtain the system characteristic equation, assuming no slip between the phases. The stability limits for several cases are plotted in N_{Pch} vs. N_{Sub} maps. In such a work it is observed that the stability of a boiling system increases when increasing the subcooling level, system pressure, slip velocity, inlet restriction; and decreases with the heat flux, outlet restriction (very strongly). These last investigations introduced the theoretical basis for the understanding of the DWO_{II} mechanism. A simple correlation to predict the DWO_{II} stability limit is proposed. In Saha and Zuber[140] this formulation is extended with a thermal non-equilibrium model. For low subcooling this model fits better the experimental data. However, in the high subcooling region the equilibrium model gives more accurate results.

An interesting study was presented in Yadigaroglu and Bergles [37,133], where the authors attempt to explain analytically the high-order *density-wave* modes (DWO_{III}) by using transfer functions of the system main variables. Takitani [232] presented a simplified lumped parameter model with moving boundaries. The stability limits obtained using this model agree with the experimental data but the predicted oscillation periods have differences up to 150%. Lahey and Moody [187] made a complete analysis of the two-phase flow modelling in Boiling Water Reactors, including the study of Ledinegg and DWO using frequency-domain methods. This instability analysis is an extension of the analytical results presented in previous investigations Yadigaroglu and Lahey [233]. Based in a frequency-domain analysis of a HEM, Fukuda and Kobori [7] introduced the concept of the *density-wave* oscillations induced by gravity (DWO_I). Five different kinds of *density-wave* instability modes are described: due to gravity in the heated section and in the chimney DWO_I; due to friction in the heated section and in the chimney DWO_{II}; and due to acceleration in the heated section DWO_{III}. Belblidia and Weaver [234] performed a linear stability analysis that confirms previous results. Achard et al. [189] use a HEM lumped parameter model in order to analyse the linear stability of a boiling channel. The effect of the gravity and friction in a boiling channel are analysed. "Stability islands" are detected for low friction numbers, which are related with the occurrence of high-order oscillations (DWO_{III}) as reported experimentally, as shown in Fig. 12. In Achard et al. [38] a similar investigation is made by performing a non-linear analysis through the use of Hopf-bifurcation techniques, valid near the marginal-stability boundaries. It is shown that the non-linear terms can change significantly the stability limits for both normal and high order modes. This investigation also describes cases where a finite-amplitude forced perturbation can cause a divergent instability

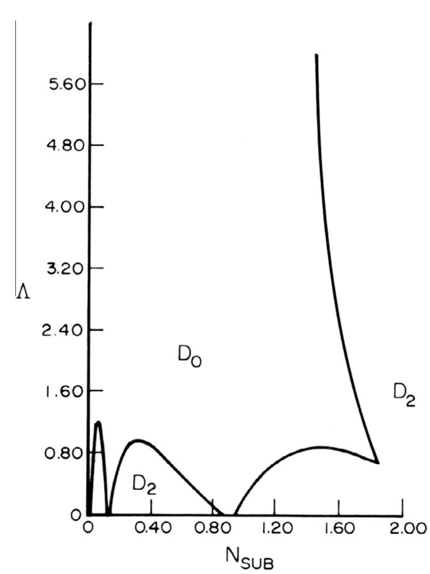


Fig. 12. Friction vs. Subcooling dimensionless numbers stability map (Reprinted from Achard et al. [189]). Stability islands are reported corresponding with the high-order modes (DWO_{III}).

on the stable region of the linear-stability boundary (sub-critical Hopf bifurcations).

Another interesting study was presented in Atkinson and Friedly [190], where the influence of the thermal wall capacity of the heater is analysed. It is shown that this effect does not change significantly the stability limits but it is very sensitive in the non-linear evolution of large amplitude oscillations. It is showed that this effect is sufficient to guarantee bounded oscillations, as the ones observed experimentally. Di Marco et al. [235] found corresponding stability islands in a single boiling channel using a lumped parameter model.

In Nakanishi and Kaji [236] a D-partition method is used to make a linear analysis based in a homogeneous flow model. A stability map based on the inlet and outlet resistances is used to analyse the stability of the system. The stability limits are proved to be in accordance with experimental data. It is also proved that in the case of superheated exit conditions gravity has no effect on the stability threshold. Dykhuizen et al. [184,185] described the application of a *two-fluid* model to make a linear stability analysis of the DWO_{II} phenomenon. The predicted limits are in agreement with the experimental data for high subcooling numbers, however, for low subcooling this boundary is predicted conservatively. A parameter analysis shows that the effect of the interfacial drag, the mass exchange between the phases and the void distribution have no significant influence in the stability thresholds. Furutera [237] study the validity of the homogeneous model in the description of the stability limits. The results of several pressure, subcooling and heat capacity models are contrasted with experimental data. It is proved that, in general terms, the best approximation is made with no subcooling model and heat capacity of the wall when that mechanism is physically relevant (massive tubes).

Lahey and Podowski [14] made a very complete description of the use of frequency-domain tools (such as the Nyquist plots) in the study of these phenomena in BWR. A very extensive summary with the results of previous studies and the analysis of single and parallel channel systems is presented. Rizwan and Dorning [186] presented linear and non-linear techniques to study the stability limits of a boiling channel. A drift-flux model including the void distribution parameter C_0, see Zuber and Findlay [138]; Wallis [178], is implemented. This factor seems to be important for thermal equilibrium analysis since it leads to limits that agree considerably better with the experimental data. In subsequent studies by Rizwan and Dorning [238,239], the effect of a periodic perturbation imposed to the pressure drop boundary condition is studied. It is shown that the system can exhibit sub-harmonic, quasi-periodic or chaotic evolution depending on the amplitude and the frequency of the periodic forcing. Following this kind of analysis, Clausse and Lahey [196] used a HEM to model a boiling channel coupled with an adiabatic chimney, taking into account liquid-density variations with temperature. It is shown that autonomous (i.e., not forced) periodic limit cycles and aperiodic chaotic response are induced in this kind of systems. In this last work, it is introduced the use of a Moving Node Scheme (MNS) for the numerical discretization. Delmastro et al. [240] analysed the effect of gravity in the N_{Pch} vs. N_{Sub} stability plane. A destabilising effect of the gravitational term for higher subcoolings and a stabilising effect at lower subcoolings is reported. A simple natural convection loop is used to compare experimental and analytical results finding a good agreement.

Rizwan [193] presented a critical view of the classical mechanisms used to explain the DWO_{II} phenomenon. Using numerical simulations and experimental data, it is concluded that the density waves travelling in the pipe do not play a significant role in the generation of the oscillations. The two fundamental mechanisms related with the occurrence of DWO_{II} are the delayed change of the pressure drop, according to the inlet velocity, and the feedback process by which the inlet velocity is modified according to the pressure drop changes (i.e., outlet throttling). Unfortunately the mechanisms triggering DWO_I and DWO_{III} phenomena are not considered in this investigation. In Rizwan [241] the same investigation is extended to a distributed heat source. The numerical results show that the channel becomes less stable by the introduction of a different axial heat flux profile if it increases the two-phase region length. When a single humped distribution is used then the channel becomes less stable, respect to the uniform distribution, for low inlet subcooling and more stable for high inlet subcooling. Chang and Lahey [242] analysed the occurrence of instabilities focused on the safety of BWRs. It is found that chaos may occur in a boiling channel coupled with an adiabatic chimney, in agreement with Clausse and Lahey[196]. Moreover, in some cases the heated wall dynamics has proved to have a significant destabilising effect.

Podowski and Rosa [243] studied the effects of various modeling concepts and numerical approaches on the transient response and stability of boiling channels. It is analysed the impact of the numerical discretization on the convergence and accuracy of computations. Four different models are investigated: (a) Homogeneous equilibrium model (HEM), (b) Thermodynamic equilibrium model with plastic slip (SEM), (c) profile-fit model of subcooled boiling with slip (SPFM), (d) mechanistic model of subcooled boiling with slip (SMM). In addition, the effect of distributed and average parameters is investigated. Fig. 13 shows the differences of the Marginal Stability Boundary (MSB) for different models. As can be seen, the homogeneous model predicts conservatively the stability boundaries respect to the models considering slip and subcooled boiling. In Narayanan et al. [225] the effects of heat distribution and the response to forced perturbations are studied. The interaction of the natural frequency of the DWO and a fixed forcing frequency of the imposed pressure drop gives rise to various phenomena: relaxation oscillations, sub-harmonic oscillations, quasi-periodic and chaotic solutions. In Garea [244]; Garea et al.

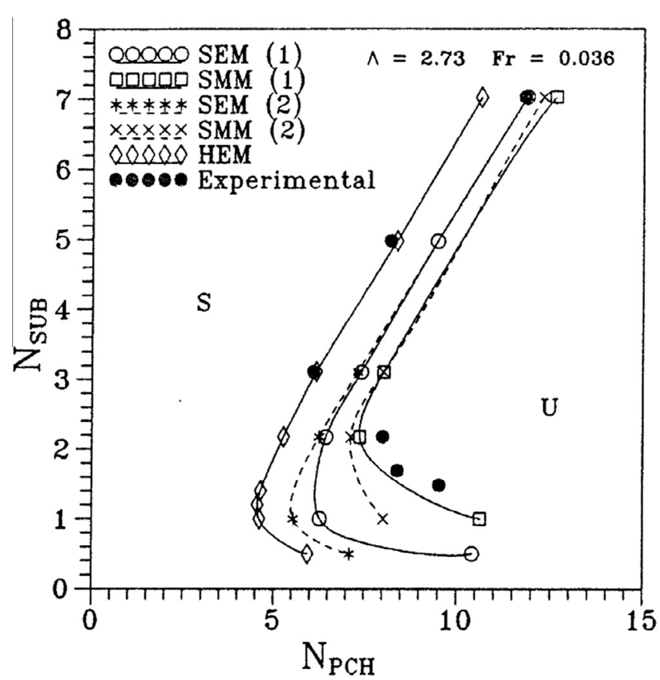


Fig. 13. The effects of different models on the marginal stability boundary for DWO_{II} (Reprinted from Podowski and Rosa [243]). SEM thermodynamic equilibrium model with slip; SMM mechanistic model of subcooling boiling with slip; HEM Homogeneous equilibrium model, no slip; (1) distributed parameters; (2) average steady-state parameters.

[197] the application of a general MNS to the calculation of DWO stability boundaries is made. Several numerical aspects of this scheme implementation are discussed, such as the need of using an even number of nodes to adequately represent the dynamics of the subcooled region.

Ambrosini et al. [192] used the homogeneous equilibrium balance equations and presented a comparison between lumped and distributed parameter models. The prediction of the marginal stability boundaries is quite similar using both of them. The main mechanism triggering DWO_{II} are discussed with relation to the criticisms introduced by Rizwan [193]. The results indicate that for high inlet subcoolings the mechanism proposed by Rizwan is more adequate than the classical mechanism. Under these conditions: the period of oscillations is considerably longer than twice the fluid transit time; the outlet density does not oscillate in phase with the outlet pressure drop and the density-wave phenomenon is mostly governed by flow perturbations rather than by actual density wave propagation. On the other hand, for low inlet subcooling conditions it is found that the classical description of the main mechanisms is more accurate. Under these conditions: the oscillations period is closer to twice the fluid transit time; the outlet density oscillations are correlated with the outlet pressure drop oscillations; density-wave propagation can be observed along the channel. Delmastro et al. [245] derived a simple mathematical model based purely on delay equations obtained from a homogeneous model. Using a linear perturbation method good agreement with a distributed parameter model is found. The delay model is extended to analyse non-linear effects in Juanico et al. [246]. Sub-critical as well as super-critical Hopf bifurcations are found, and a dimensionless parameter is proposed to map the risk of the instabilities.

Lee and Kim [247] described numerically a natural convection loop. The stability boundaries of LED, DWO_I and DWO_{II} are analysed numerically. The influence of an expansion tank upstream from the heated section is investigated. In all the cases the compressible volume destabilises the system. Nayak et al. [248] describe the application of a homogeneous model for the simulation of a BWR natural convection reactor. Both DWO_I and DWO_{II} modes are predicted. The frequency of DWO_{II} instability is higher than that corresponding to DWO_I. The effect of neutronic feedback is investigated. These effects are also investigated by Prasad and Pandey [249]. In the latter investigation, the boiling system undergo into chaotic oscillations (neutronic-DWO_{II}) when a strong void reactivity feedback is applied (neutron flux – void fraction). For the DWO_I, subcritical and supercritical Hopf bifurcations are found. A review of several modelling investigations in single- and two-phase flow natural convection is presented in Goswami and Paruya[199]. A lumped parameter analytical model based on a HEM formulation is presented in Marcel et al. [158] for investigating flashing-induced DWO_I. The authors report an explicit relation for describing the stability boundary which shows a reasonable agreement with their experimental results. In order to simulate the geysering phenomenon in a steam-water natural circulation loop, Paruya and Bhattacharya [250] derived a moving nodal model (lumped parameter model).

Very recently, Paruya et al. [194] compared the performance of FNS and MNS. The analysis suggests that MNS is more efficient and has a better convergence than FNS. Numerical simulations show the appearance of instability islands for high Froude numbers in short channels. Moreover, the strong effect of the subcooling in the period of the oscillations, as described in Rizwan [193]; Ambrosini et al. [192], is reported. In addition, the occurrence and characteristics of DWO under thermodynamic supercritical conditions is reported in Ambrosini [207]; Ambrosini and Sharabi [251]; Gomez et al. [208].

Ruspini et al. [78] study numerically DWO_{II} and LED phenomena for boiling and condensing systems. A comparison with previous DWO stability criteria was presented. In general terms, only the Ishii's simplified criterion for DWO_{II} predicts accurately the stability limits. Subcooled, saturated and superheated inlet conditions are studied, observing instabilities in the first two regions. Ruspini [195] study the effect of compressible volumes and inertia, before and after the heated section, on the stability limit for DWO_{II}. It was found that the inlet inertia (longer inlet pipes) increases the stability of the system. On the contrary, for the increase of outlet inertia (longer outlet pipes) the stability of the system is not just decreased but also high-order oscillations, DWO_{III}, are induced. In Fig. 14 the stability limits for the different cases are shown. The frequency of these high-order oscillations was found to be between 2.5 and 10 times the frequency of the normal mode, according to the (N_{Pch}, N_{Sub}) region. Wavelet decomposition is used in order to analyse the evolution of different oscillatory modes. In addition, it was found that when a compressible volume is placed upstream of the heated section the system becomes highly unstable, for both Ledinegg and DWO_{II}. In contrast, when the compressible volume is fixed downstream of the heated section the system becomes more stable in a DWO_{II} sense. The results of these investigations are extended in Ruspini [126].

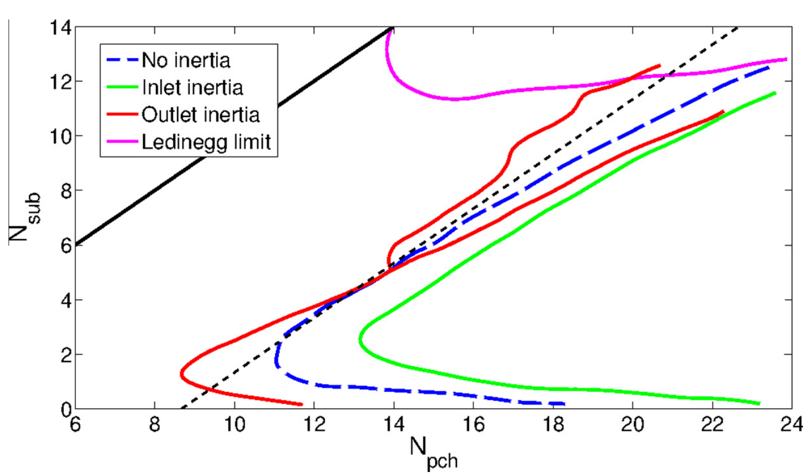


Fig. 14. Comparison of the stability limit for the three numerical experiments. No external inertia (blue line), inlet inertia (green line) and outlet inertia (red line). In the case of outlet inertia higher-modes (DWO_{III}) are observed. The higher-mode stability limit is also plotted in red line. The dotted line indicates the limit corresponding to Ishii's criterion (Reprinted from Ruspini [195]). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Applying the drift-flux with flashing vapor generation [252] investigated the stability of a self-pressurized natural-circulation low-thermodynamic-quality nuclear reactor. Since the operational range of such system is a very narrow strip within the N_{Pch} vs. N_{Sub} plane, these authors propose a novel plane that is more adequate to visualise the results. It was found that the less stable mode is due to flashing induced DWO_I, and that the neutronic feedback and pressure stabilise the system.

4.4.1. DWO in parallel channels

Gerliga and Dulevskiy [39] presented one of the first analytical investigations regarding the occurrence of thermo-hydraulic oscillations in parallel channels. In this work the characteristic equation for a parallel system is derived. Fukuda and Hasegawa [40] derived the governing equations for a general array of parallel boiling channels with different characteristics. Aritomi et al. [253] study DWO in a forced convection upflow boiling system with parallel channels. A drift-flux model is implemented and a linear stability analysis is performed using a transfer function method. The experimental and analytical results for a twin-parallel channel system are compared obtaining a good agreement. This investigation is extended in Aritomi et al. [254], where the DWO phenomenon is studied in more than two channels. In the case of more than three channels, it is observed a similar behaviour than for twin channels, regardless of whether there is an odd or even number of channels. In this case the flow instability first occurs in the most unstable pair of channels.

A very extensive investigation is made by Taleyarkhan et al. [191], using a model that accounts for subcooled boiling, arbitrary heat flux distribution, distributed and local hydraulic losses, heated wall dynamics and slip flow in ventilated parallel channels. This study is focused in the description of thermo-hydraulic phenomena in BWRs. This analysis suggests that radial variations of power, subcooling and ventilation between parallel channels can have a substantial impact on the stability margins. Comparison with experimental data confirms the basic predicted trends and a good agreement with the stability limits is observed.

Guido et al. [255,205] presented an analytical stability analysis of parallel boiling channels. Explicit expressions for the stability limits of Ledinegg and DWO_{II} are obtained. In addition, the oscillation periods for twin parallel channels are calculated. The reported modes correspond with in-phase and out-of-phase oscillations. In the case of a non-identical channels system, the normal modes are not longer in-phase or out-of-phase, but the phase-shift depends on the individual conditions. In addition, for intermediate and large inlet subcooling lengths, when different power distribution between the channels is used the system becomes more unstable. Clausse et al. [256] extended this analysis using a perturbation method to analyse the feedback between the boiling channels and the external system. For different channels, the in-phase and out-of-phase modes interact with each other and consequently more complex modes, involving coupling between the channels and the loop, are induced. The results of this study explain the differences of the modes reported in experimental investigations. Moreover, it is proved that the phase-shift is very sensitive to small differences between channels.

Lee and Pan [257] studied the behaviour of a system with 1–5 channels using a MNS. It is proved that the multiple channel system becomes more unstable with an increase of the channel number. In all simulations the most heated channel exhibits the largest oscillation, and is out-of-phase with the other channels. When a forced perturbation is imposed, periodic, quasi-periodic and chaotic oscillations may appear. In Hiraya et al. [258] a lumped-parameter model is used to study two parallel channels in a natural convection regime. In-phase (loop instability) and out-of-phase (channel-to-channel) oscillations are found. The effects of various parameters in the stability limits are analysed. The resistance coefficients in the single-phase region, K_{in} (total flow) and K_i (each channel) are stabilising factors. In contrast, the resistance coefficients in the two-phase flow region K_{out} (total flow) and K_e (each flow) are destabilising factors, as described in other investigations. Prasad et al. [259] simulate a twin-parallel in a natural circulation system using a lumped parameter and a commercial code (RELAP5/MOD3.4). The lumped parameter model predicts similar trends to the observed in the RELAP5 simulations. DWO_I and DWO_{II} modes are investigated. The effects of gravitational and frictional pressure drops and geometrical parameters on these oscillation modes are investigated. Both channels oscillate out-of-phase in the DWO_I region due to dominant gravitational pressure drop at low powers. On the other hand, for the DWO_{II} region, the channels oscillate in-phase and out-of-phase depending on the dominance of two-phase frictional pressure drop and the downcomer inertia. The downcomer inertia is varied by changing the dimensions of the boiling system. Thus, geometrical parameters influence the DWO_{II} mode but not the DWO_I.

Genglei et al. [260] study oscillations in 1–2–4–9 parallel channels using the commercial code RELAP5. A comparison with experimental data is made in order to validate the results. It is found that in some cases the non-equilibrium model overestimates the stable region. In contrast, HEM predicts conservative limits in all the cases. DWO, Ledinegg instability and flow distribution instability are investigated. The stability limits for the DWO_I and DWO_{II} modes are analysed. Both modes stabilise as the system pressure increases. Similarly, Colombo et al. [261] use RELAP5 to investigate a parallel twin-channel system. In this investigation it is also found that the non-equilibrium model (RELAP5) is not conservative for the prediction of the stability boundaries. A sensitivity analysis shows that an increase in the inlet resistances and in the system pressure stabilise the system. In turn, nonuniform heating makes the system more unstable with the increase of nonuniform degree, as shown experimentally.

5. Discussion

An updated comprehensive assessment of the main mechanisms triggering two-phase flow instabilities has been presented. In particular, a detailed presentation of the main experimental and analytical results concerning the Ledinegg instability, flow distribution instability, density-wave oscillations and pressure drop oscillations has been made. Based on the results and trends presented in this review, the following set of recommendations for possible future research lines is offered:

Experimental research needed.

- As described in Section 2.10, the knowledge on two-phase flow instabilities in condensing systems is still very limited. In total not more than five articles can be found in the open literature that analyse the mechanisms triggering unstable phenomena. Therefore, the investigation of flow instabilities in condensing systems is recommended.
- The interaction between PDO and DWO still requires more detailed study. In particular, as seen in Schlichting [230], horizontal boiling channels are more vulnerable to the interaction between these two modes. This interaction could be the cause of the discrepancies seen in the amplitudes and frequencies observed in many experimental investigations like Yuncu et al. [114], Komakli et al. [122] and Ding et al. [48].
- Another interesting issue is the influence of compressible volumes on PDO and DWO. Very few works analyse the effects of compressible volumes downstream the heated section on

two-phase flow instability phenomena, especially for PDO and DWO modes. In particular, the PDO phenomenon in systems with small compressible volumes close to the test section inlet and the influence of compressible volumes in the stability limits of the DWO modes are good candidates for future research.

- Experimental analysis of DWO in short test sections (small friction numbers Λ) would help to understand more about the influence of the momentum terms on DWO phenomena. Moreover, the use of this kind of test section would be interesting to study in which cases PDO can be triggered solely by the compressibility of the two-phase mixture.
- Finally, the interaction mechanisms between DWO and Thermo-Acoustic Oscillations and microscopic instabilities still requires a better experimental description in order to understand the involved phenomena.

Analytical research needed.

- More analytical investigations should be conducted in order to understand the different mechanisms related with instabilities in condensing systems.
- As described in Section 4.3, most of the theoretical studies analysing PDO assume a *quasi-steady* state model for the heated channels. However none of these investigations study the limitations of this assumption in the representation of physical systems. Moreover, none of these studies are able to describe the interaction between PDO and DWO modes, present in most experimental results.
- More analytical investigations are needed in order to clarify the basic mechanisms and parameters influence associated with the occurrence of high-order density-wave oscillations (DWO_{III}).
- There is enough evidence that chaotic phenomena can be expected in two-phase flow oscillations. Further investigation of these features is then needed, applying modern system dynamics techniques.
- Finally, in parallel channels, the analysis of non-linear effects, such as supercritical and subcritical bifurcations and chaotic oscillations, would be an interesting research issue.

6. Conclusions

An updated review of the main mechanisms triggering and sustaining two-phase flow instabilities was introduced. The main phenomena were described in order to give the reader the necessary tools to distinguish among them. The main experimental and analytical investigations regarding the occurrence of the phenomena studied in this work were analysed. Several aspects of the current state-of-the-art in the two-phase flow instabilities field were critically discussed. Finally, some recommendations are included to encourage researchers in the area to further investigate new aspects of these interesting phenomena.

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