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On Density Wave Instability Phenomena – Modelling and Experimental Investigation

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1. Introduction

Density Wave Oscillations (DWOs) are dealt with in this work as the most representative instabilities frequently encountered in the boiling systems. This *dynamic type* instability mode – resulting from multiple feedback effects between the flow rate, the vapour generation rate and the pressure drops in the boiling channel – constitutes an issue of special interest for the design of industrial systems and equipments involving vapour generation (Yadigaroglu, 1981). In the nuclear area, instability phenomena can be triggered both in Boiling Water Reactor (BWR) fuel channels (where they are moreover coupled through neutronic feedbacks with the neutron field), and in steam generators, which experience boiling phenomena inside parallel tubes. The latter is typical configuration of all the *once-through* steam generators, considered in this work with respect to integral Small-medium Modular Reactors (SMRs)[1] applications.

Extensive attention is required because parallel channel instability is very difficult to be immediately detected when occurs in steam power systems, being the total mass flow of the system stable while the instability is locally triggered among some of the parallel channels. Thermally induced oscillations of the flow rate and system pressure are undesirable, as they can cause mechanical vibrations, problems of system control, and in extreme cases induce heat transfer surface burn-out. Large amplitude fluctuations in the heater wall temperature (so named *thermal oscillations*) usually occur under DWO conditions. Continual cycling of the wall temperature can lead to thermal fatigue problems which may cause tube failure.

It is clear from these examples that the flow instabilities must be avoided in the design and operation of the various industrial systems. The safe operating regime of a two-phase heat exchanger can be determined by instability threshold values of system parameters such as flow rate, pressure, inlet temperature and exit quality. To the aim, both basic experiments and numerical analyses are necessary.

This work is dedicated to the study (from theoretical, numerical and experimental point of view) of density wave phenomena, aimed at instability threshold prediction, DWO characterization and linear stability analysis as well.

[1] The *integral layout* – shared by the SMR designs – provides that all the primary system components are hosted inside the reactor vessel. This permits to reduce by design risks and effects of several postulated accidents, as well as to introduce improved technological solutions for the single plant components (e.g., the helically coiled steam generators fitting with the increased compactness of the system).

First, modelling effort based on the development of an analytical dynamic model – via integration of the 1D governing equations – is described. The simplest Homogeneous Equilibrium Model (HEM), in which phasic slip and subcooled boiling are neglected, has been considered. Non-linear features of the modelling equations have permitted to represent the complex interactions between the variables triggering the instability. Several sensitivity studies have been carried out, on the operating conditions, on system geometrical features, and on the empirical coefficients used to better model two-phase flow structure. Theoretical predictions from analytical model are then verified via qualified numerical simulation tools. Both the thermal-hydraulic dedicated code RELAP5 and the multi-physics code COMSOL have been applied.

Final objective of the developed modelling on density wave instabilities has been to prepare (pre-test analyses) and interpret (post-test analyses) an experimental campaign carried out at SIET labs (Piacenza, Italy), where parallel channel instability phenomena have been directly investigated with a test section reproducing in full scale two helical tubes of the IRIS (International Reactor Innovative and Secure) steam generator (Papini et al., 2011). Due to the complexity of the helical geometry, the basic experimental investigation provided is of utmost importance for the diffusion of such helically coiled steam generators.

The chapter is structured as follows. Physical insight into the distinctive features leading to DWO mechanism is provided in Section 2. Modelling and experimental investigations on instability phenomena available from the open literature are described in Section 3. Section 4 and 5 present the analytical modelling developed in this work for DWO theoretical predictions, whereas numerical modelling (using RELAP5 and COMSOL codes) is briefly discussed in Section 6. Modelling efforts start necessarily from the simplifying and sound case of straight vertical tube geometry, which is referenced for validating the whole modelling tools. Description of the experimental campaign for DWO characterization in helical coil tubes is shortly presented in Section 7. The peculiar influence of the helical shape on the instability occurrence is examined in Section 8. Suited modifications of the models are introduced in order to simulate the experimental results.

2. Density Wave Oscillations (DWOs)

The classical interpretation of density wave oscillations, proposed e.g. by Yadigaroglu & Bergles (1972) and recently confirmed by the noteworthy review of Kakaç & Bon (2008), ascribes the origin of the instability to waves of *heavier* and *lighter* fluids, and respective delays through the channel.

The difference in density between the fluid entering the heated channel (subcooled liquid) and the fluid exiting (low density two-phase mixture) triggers delays in the transient distribution of pressure drops along the tube, which may induce self-sustained oscillations. A constant pressure drop (or better, the same, not necessarily constant with time, pressure drop for the multiple parallel channels) is the proper boundary condition that can excite those dynamic feedbacks which are at the source of the instability mechanism. A remark is now mandatory. The mentioned boundary condition can be provided by connecting two or more parallel channels with common upper and lower headers (for this reason, *density wave instabilities* are commonly referred to as *parallel channel instabilities*). When dealing with DWO investigation in a single boiling channel, the experimental apparatus must be designed such to effectively maintain a constant pressure variation along the tube. In case of modelling, it is enough to impose the boundary condition $\Delta P = P_{in} - P_{out} = const$; in case of experimental investigation, a system configuration with a large bypass tube parallel-connected to the heated channel must be used to properly reproduce the phenomenon. The suited boundary condition is preserved only for a sufficiently large ratio between bypass area and heated channel area (Collins & Gacesa, 1969).

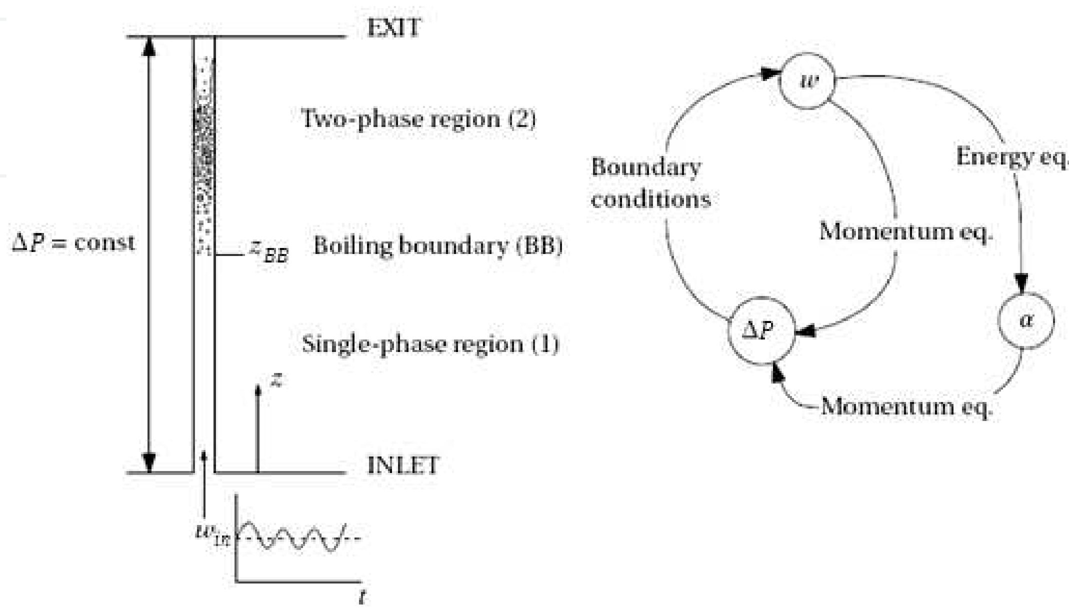

Fig. 1. Density wave instability mechanism in a single boiling channel, and respective feedbacks between main physical quantities. (Reproduced from (Yadigaroglu, 1981))

Going more into details, the physical mechanism leading to the appearance of DWOs is now briefly described (Yadigaroglu & Bergles, 1972). A single heated channel, as depicted in Fig. 1, is considered for simplicity. The instantaneous position of the boiling boundary, that is the point where the bulk of the fluid reaches saturation, divides the channel into a single-phase region and a two-phase region. A sudden outlet pressure drop perturbation, e.g. resulting from a local microscopic increase in void fraction, can be assumed to trigger the instability by propagating a corresponding low pressure pulse to the channel inlet, which in turn causes an increase in inlet flow. Considered as a consequence an oscillatory inlet flow entering the channel (Lahey Jr. & Moody, 1977), a propagating enthalpy perturbation is created in the single-phase region. The boiling boundary will respond by oscillating according to the amplitude and the phase of the enthalpy perturbation. Changes in the flow and in the length of the single-phase region will combine to create an oscillatory single-phase pressure drop perturbation (say $\Delta P_{1\phi}$). The enthalpy perturbation will appear in the two-phase region as quality and void fraction perturbations and will travel with the flow along the channel. The combined effects of flow and void fraction perturbations and the variation of the two-phase length will create a two-phase pressure drop perturbation (say $\Delta P_{2\phi}$). Since the total pressure drop across the boiling channel is imposed:

$$\delta\Delta P_{tot} = \delta\Delta P_{1\phi} + \delta\Delta P_{2\phi} = 0 \quad (1)$$

the two-phase pressure drop perturbation will create a feedback perturbation of the opposite sign in the single-phase region. That is (Rizwan-Uddin, 1994), in order to keep the *constant-pressure-drop boundary condition*, the increase of exit pressure drop (following the positive perturbation in inlet velocity that transforms into a wave of *higher density)* will result indeed into an instantaneous drop in the inlet flow. The process is now reversed as the density wave, resulting from the lower inlet velocity, travels to the channel exit: the pressure drop at channel exit decreases as the wave of *lower density* reaches the top, resulting in an increase in the inlet flow rate, which starts the cycle over again. With correct timing, the flow oscillation can become self-sustained, matched by an oscillation of pressure and by the single-phase and two-phase pressure drop terms oscillating in counter-phase.

In accordance with this description, as a complete oscillating cycle consists in the passage of two perturbations through the channel (*higher density* wave and *lower density* wave), the period of oscillations T should be of the order of twice the mixture transit time τ in the heated section:

$$T = 2\tau \tag{2}$$

In recent years, Rizwan-Uddin (1994) proposed indeed different descriptions based on more complex relations between the system parameters. His explanation is based on the different speeds of propagation of velocity perturbations between the single-phase region (speed of sound) and the two-phase region (so named *kinematic velocity*). This behaviour is dominant at high inlet subcooling, such that the phenomenon seems to be more likely related to mixture velocity variations rather than to mixture density variations. In this case, the period of oscillations is larger than twice the mixture transit time.

2.1 Stability maps

The operating point of a boiling channel is determined by several parameters, which also affect the channel stability. Once the fluid properties, channel geometry and system operating pressure have been defined, major role is played by the mass flow rate Γ, the total thermal power supplied Q and the inlet subcooling Δh_{in} (in enthalpy units). Stable and unstable operating regions can be defined in the three dimensional space (Γ, Q, Δh_{in}), whereas mapping of these regions in two dimensions is referred to as the stability map of the system. No universal map exists. Moreover, the usage of dimensionless stability maps is strongly recommended to cluster the information on the dynamic characteristics of the system.

The most used dimensionless stability map is due to Ishii & Zuber (1970), who introduced the *phase change number* N_{pch} and the *subcooling number* N_{sub}. The phase change number scales the characteristic frequency of phase change Ω to the inverse of a single-phase transit time in the system, instead the subcooling number measures the inlet subcooling:

$$N_{pch} = \frac{\Omega}{\frac{w_{in}}{H}} = \frac{\frac{Q}{AH}\frac{v_{fg}}{h_{fg}}}{\frac{w_{in}}{H}} = \frac{Q}{\Gamma h_{fg}}\frac{v_{fg}}{v_f} \tag{3}$$

$$N_{sub} = \frac{\Delta h_{in}}{h_{fg}}\frac{v_{fg}}{v_f} \tag{4}$$

Fig. 2 depicts a typical stability map for a boiling channel system on the stability plane N_{pch}–N_{sub}. The usual stability boundary shape shows the classical *L shape* inclination, valid in general as the system pressure is reasonably low and the inlet loss coefficient is not too large (Zhang et al., 2009). The stability boundary at high inlet subcooling is a line of constant equilibrium quality. It is easy to demonstrate (by suitably rearranging Eqs.(3), (4)) that the constant exit quality lines are obtained as:

$$N_{sub} = N_{pch} - x_{ex}\frac{v_{fg}}{v_f} \tag{5}$$

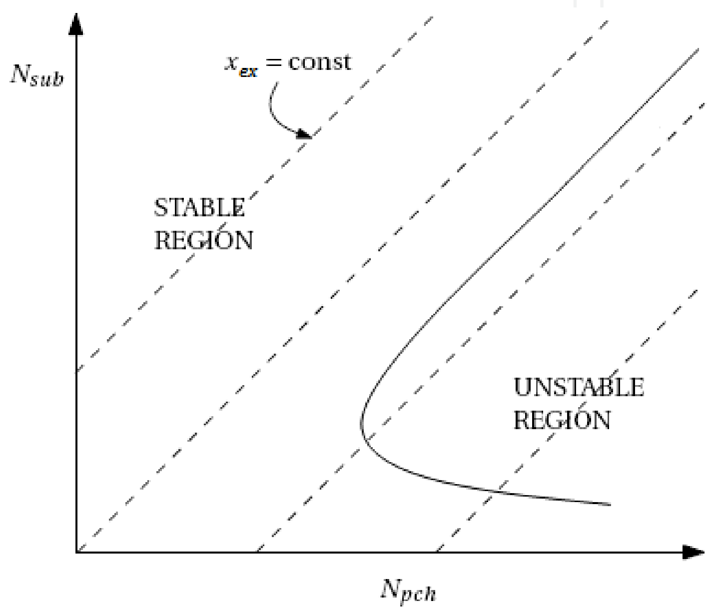

Fig. 2. Typical stability map in the N_{pch}–N_{sub} stability plane exhibiting L shape

2.2 Parametric effects

In the following parametric discussion, the influence of a change in a certain parameter is said to be stabilizing if it tends to take the operating point from the unstable region (on the right of the boundary) to the stable region (on the left of the boundary) (Yadigaroglu, 1981).

2.2.1 Effects of thermal power, flow rate and exit quality

A stable system can be brought into the unstable operating region by increases in the supplied thermal power or decreases in the flow rate. Both effects increase the exit quality, which turns out to be a key parameter for system stability.
The destabilizing effect of increasing the ratio Q/Γ is universally accepted.

2.2.2 Effects of inlet subcooling

The influence of inlet subcooling on the system stability is multi-valued. In the high inlet subcooling region the stability is strengthened by increasing the subcooling, whereas in the low inlet subcooling region the stability is strengthened by decreasing the subcooling. That is, the inlet subcooling is stabilizing at high subcoolings and destabilizing at low subcoolings, resulting therefore in the so named *L shape* of the stability boundary (see Fig. 2).

Intuitively this effect may be explained by the fact that, as the inlet subcooling is increased or decreased, the two-phase channel tends towards stable single-phase liquid and vapour operation respectively, hence out of the unstable two-phase operating mode (Yadigaroglu, 1981).

2.2.3 Effects of pressure level

An increase in the operating pressure is found to be stabilizing, although one must be careful in stating which system parameters are kept constant while the pressure level is increased. At constant values of the dimensionless subcooling and exit quality, the pressure effect is made apparent by the specific volume ratio v_{fg}/v_f (approximately equal to the density ratio ρ_f/ρ_g). This corrective term, accounting for pressure variations within the Ishii's dimensionless parameters, is such that the stability boundaries calculated at slightly different pressure levels are almost overlapped in the N_{pch}–N_{sub} plane.

2.2.4 Effects of inlet and exit throttling

The effect of inlet throttling (single-phase region pressure drops) is always strongly stabilizing and is used to assure the stability of otherwise unstable channels.

On the contrary, the effect of flow resistances near the exit of the channel (two-phase region pressure drops) is strongly destabilizing. For example, stable channels can become unstable if an orifice is added at the exit, or if a riser section is provided.

3. Review of density wave instability studies

3.1 Theoretical researches on density wave oscillations

Two general approaches are possible for theoretical stability analyses on a boiling channel:

i. frequency domain, linearized models;
ii. time domain, linear and non-linear models.

In *frequency domain* (Lahey Jr. & Moody, 1977), governing equations and necessary constitutive laws are linearized about an operating point and then Laplace-transformed. The transfer functions obtained in this manner are used to evaluate the system stability by means of classic control-theory techniques. This method is inexpensive with respect to computer time, relatively straightforward to implement, and is free of the numerical stability problems of finite-difference methods.

The models built in *time domain* permit either 0D analyses (Muñoz-Cobo et al., 2002; Schlichting et al., 2010), based on the analytical integration of conservation equations in the competing regions, or more complex but accurate 1D analyses (Ambrosini et al., 2000; Guo Yun et al., 2008; Zhang et al., 2009), by applying numerical solution techniques (finite differences, finite volumes or finite elements). In these models the steady-state is perturbed with small stepwise changes of some operating parameter simulating an actual transient, such as power increase in a real system. The stability threshold is reached when undamped or diverging oscillations are induced. Non-linear features of the governing equations permit to grasp the feedbacks and the mutual interactions between variables triggering a self-sustained density wave oscillation. Time-domain techniques are indeed rather time consuming when used for stability analyses, since a large number of cases must be run to

produce a stability map, and each run is itself time consuming because of the limits on the allowable time step.
Lots of lumped-parameter and distributed-parameter stability models, both linear and non-linear, have been published since the ’60-’70s. Most important literature reviews on the subject – among which are worthy of mention the works of Bouré et al. (1973), Yadigaroglu (1981) and Kakaç & Bon (2008) – collect the large amount of theoretical researches. It is just noticed that the study on density wave instabilities in parallel twin or multi-channel systems represents still nowadays a topical research area. For instance, Muñoz-Cobo et al. (2002) applied a non-linear 0D model to the study of out-of-phase oscillations between parallel subchannels of BWR cores. In the framework of the future development of nuclear power plants in China, Guo Yun et al. (2008) and Zhang et al. (2009) investigated DWO instability in parallel multi-channel systems by using control volume integrating method. Schlichting et al. (2010) analysed the interaction of PDOs (*Pressure Drop Oscillations*) and DWOs for a typical NASA type phase change system for space exploration applications.

3.2 Numerical code simulations on density wave oscillations

On the other hands, qualified numerical simulation tools can be successfully applied to the study of boiling channel instabilities, as accurate quantitative predictions can be provided by using simple and straightforward nodalizations.
In this frame, the best-estimate system code RELAP5 – based on a *six-equations* non-homogeneous non-equilibrium model for the two-phase system[2] – was designed for the analysis of all transients and postulated accidents in LWR nuclear reactors, including Loss Of Coolant Accidents (LOCAs) as well as all different types of operational transients (US NRC, 2001). In the recent years, several numerical studies published on DWOs featured the RELAP5 code as the main analysis tool. Amongst them, Ambrosini & Ferreri (2006) performed a detailed analysis about thermal-hydraulic instabilities in a boiling channel using the RELAP5/MOD3.2 code. In order to respect the imposed *constant-pressure-drop boundary condition*, which is the proper boundary condition to excite the dynamic feedbacks that are at the source of the instability mechanism, a single channel layout with impressed pressures, kept constant by two inlet and outlet plena, was investigated. The Authors demonstrated the capability of the RELAP5 system code to detect the onset of DWO instability.
The multi-purpose COMSOL Multiphysics® numerical code (COMSOL, Inc., 2008) can be applied to study the stability characteristics of boiling systems too. Widespread utilization of COMSOL code relies on the possibility to solve different numerical problems by implementing directly the systems of equations in PDE (*Partial Differential Equation*) form. PDEs are then solved numerically by means of finite element techniques. It is just mentioned that this approach is globally different from previous one discussed (i.e., the RELAP5 code), which indeed considers finite volume discretizations of the governing equations, and of course from the simple analytical treatments described in Section 3.1. In this respect, linear and non-linear stability analyses by means of the COMSOL code have been provided by

[2] The RELAP5 hydrodynamic model is a one-dimensional, transient, *two-fluid model* for flow of two-phase steam-water mixture. Simplification of assuming the same interfacial pressure for the two phases, with equal phasic pressures as well, is considered.

Schlichting et al. (2007), who developed a 1D drift-flux model applied to instability studies on a boiling loop for space applications.

3.3 Experimental investigations on density wave oscillations

The majority of the experimental works on the subject – collected in several literature reviews (Kakaç & Bon, 2008; Yadigaroglu, 1981) – deals with straight tubes and few meters long test sections. Moreover, all the aspects associated with DWO instability have been systematically analysed in a limited number of works. Systematic study of density wave instability means to produce well-controlled experimental data on the onset and the frequency of this type of oscillation, at various system conditions (and with various operating fluids).

Amongst them, are worthy of mention the pioneering experimental works of Saha et al. (1976) – using a uniformly heated single boiling channel with bypass – and of Masini et al. (1968), working with two vertical parallel tubes. To the best of our knowledge, scarce number of experiments was conducted studying full-scale long test sections (with steam generator tubes application), and no data are available on the helically coiled tube geometry (final objective of the present work). Indeed, numerous experimental campaigns were conducted in the past using refrigerant fluids (such as R-11, R-113 ...), due to the low critical pressure, low boiling point, and low latent heat of vaporization. That is, for instance, the case of the utmost work of Saha et al. (1976), where R-113 was used as operating fluid.

In the recent years, some Chinese researches (Guo Yun et al., 2010) experimentally studied the flow instability behaviour of a twin-channel system, using water as working fluid. Indeed, a small test section with limited pressure level (maximum pressure investigated is 30 bar) was considered; systematic execution of a precise test matrix, as well as discussions about the oscillation period, are lacking.

4. Analytical lumped parameter model: fundamentals and development

The analytical model provided to theoretically study DWO instabilities is based on the work of Muñoz-Cobo et al. (2002). Proper modifications have been considered to fit the modelling approach with steam generator tubes with imposed thermal power (representative of typical experimental facility conditions).

The developed model is based on a *lumped parameter approach* (0D) for the two zones characterizing a single boiling channel, which are single-phase region and two-phase region, divided by the boiling boundary. Modelling approach is schematically illustrated in Fig. 3.

Differential conservation equations of mass and energy are considered for each region, whereas momentum equation is integrated along the whole channel. Wall dynamics is accounted for in the two distinct regions, following lumped wall temperature dynamics by means of the respective heat transfer balances. The model can apply to *single boiling channel* and *two parallel channels* configuration, suited both for instability investigation according to the specification of the respective boundary conditions:

i. constant ΔP across the tube for *single channel*;
ii. same $\Delta P(t)$ across the two channels (with constant total mass flow) for *parallel channels* (Muñoz-Cobo et al., 2002).

The main assumptions considered in the provided modelling are: *(a)* one-dimensional flow (straight tube geometry); *(b)* homogeneous two-phase flow model; *(c)* thermodynamic equilibrium between the two phases; *(d)* uniform heating along the channel (linear increase of quality with tube abscissa *z*); *(e)* system of constant pressure (pressure term is neglected within the energy equation); *(f)* constant fluid properties at given system inlet pressure; *(g)* subcooled boiling is neglected.

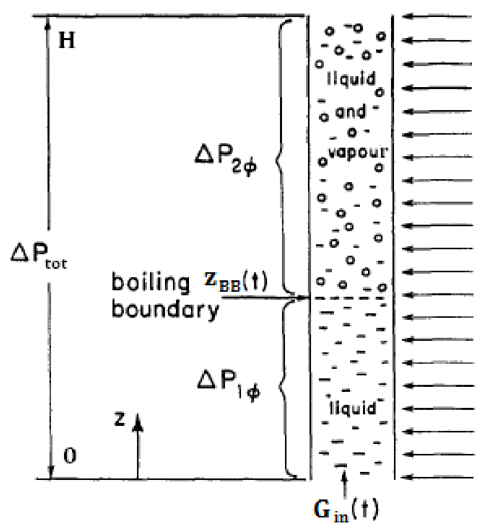

Fig. 3. Schematic diagram of a heated channel with single-phase ($0 < z < z_{BB}$) and two-phase ($z_{BB} < z < H$) regions. Externally impressed pressure drop is ΔP_{tot}. (Adapted from (Rizwan-Uddin, 1994))

4.1 Mathematical modelling

Modelling equations are derived by the continuity of mass and energy for a single-phase fluid and a two-phase fluid, respectively.
Single-phase flow equations read:

$$\frac{\partial \rho}{\partial t} + \frac{\partial G}{\partial z} = 0 \tag{6}$$

$$\frac{\partial (\rho h)}{\partial t} + \frac{\partial (Gh)}{\partial z} = Q''' \tag{7}$$

Two-phase mixture is dealt with according to homogeneous flow model. By defining the homogeneous density ρ_H and the reaction frequency Ω (Lahey Jr. & Moody, 1977) as follows:

$$\rho_H = \rho_f \left(1 - \overline{\alpha}\right) + \rho_g \overline{\alpha} = \frac{1}{v_f + \overline{x} v_{fg}} \tag{8}$$

$$\Omega(t) = \frac{Q(t) v_{fg}}{A H h_{fg}} \tag{9}$$

one gets:

$$\frac{\partial \rho_H}{\partial t} + \frac{\partial G}{\partial z} = 0 \tag{10}$$

$$\frac{\partial j}{\partial z} = \Omega(t) \tag{11}$$

Momentum equation is accounted for by integrating the pressure balance along the channel:

$$\int_0^H \frac{\partial G(z,t)}{\partial t} dz = \Delta P(t) - \Delta P_{acc} - \Delta P_{grav} - \Delta P_{frict} \tag{12}$$

As concerns the wall dynamics modelling, a lumped two-region approach is adopted. Heated wall dynamics is evaluated separately for single-phase and two-phase regions, following the dynamics of the respective wall temperatures according to a heat transfer balance:

$$\frac{dQ^{1\phi}}{dt} = M_h^{1\phi} c_h \frac{dT_h^{1\phi}}{dt} = Q^{1\phi} - (hS)^{1\phi}\left(T_h^{1\phi} - T_{fl}^{1\phi}\right) \tag{13}$$

$$\frac{dQ^{2\phi}}{dt} = M_h^{2\phi} c_h \frac{dT_h^{2\phi}}{dt} = Q^{2\phi} - (hS)^{2\phi}\left(T_h^{2\phi} - T_{fl}^{2\phi}\right) \tag{14}$$

4.2 Model development

Modelling equations are dealt with according to the usual principles of lumped parameter models (Papini, 2011), i.e. via integration of the governing PDEs (*Partial Differential Equations*) into ODEs (*Ordinary Differential Equations*) by applying the Leibniz rule. The hydraulic and thermal behaviour of a single heated channel is fully described by a set of 5 non-linear differential equations, in the form of:

$$\frac{d\eta_i}{dt} = f_i(\eta) \qquad i = 1, 2, \ldots, 5 \tag{15}$$

where the state variables are:

$$\begin{array}{lll} \eta_1 = z_{BB} & \eta_2 = x_{ex} & \eta_3 = G_{in} \\ \eta_4 = T_h^{1\phi} & \eta_5 = T_h^{2\phi} & \end{array} \tag{16}$$

In case of *single boiling channel modelling*, boundary condition of constant pressure drop between channel inlet and outlet must be simply introduced by specifying the imposed ΔP of interest within the momentum balance equation (derived following Eq. (12), consult (Papini, 2011)).

In case of *two parallel channels modelling*, mass and energy conservation equations are solved for each of the two channels, while parallel channel boundary condition is dealt imposing within the momentum conservation equation: *(i)* the same pressure drop dependence with time – $\Delta P(t)$ – across the two channels; *(ii)* a constant total flow rate.

First, steady-state conditions of the analysed system are calculated by solving the whole set of equations with time derivative terms set to zero. Steady-state solutions are then used as initial conditions for the integrations of the equations, obtaining the time evolution of each computed state variable. Input variable perturbations (considered thermal power and channel inlet and exit loss coefficients according to the model purposes) can be introduced both in terms of step variations and ramp variations.
The described dynamic model has been solved through the use of the MATLAB software SIMULINK® (The Math Works, Inc., 2005).

4.3 Linear stability analysis

Modelling equations can be linearized to investigate the neutral stability boundary of the nodal model.
The linearization about an unperturbed steady-state initial condition is carried out by assuming for each state variable:

$$\eta(t) = \eta^0 + \delta\eta \cdot e^{\lambda t} \tag{17}$$

To simplify the calculations, modelling equations are linearized with respect to the three state variables representing the hydraulic behaviour of a boiling channel, i.e. the boiling boundary $z_{BB}(t)$, the exit quality $x_{ex}(t)$, and the inlet mass flux $G_{in}(t)$. That is, linear stability analysis is presented by neglecting the dynamics of the heated wall ($Q(t) = const$).
The initial ODEs – obtained after integration of the original governing PDEs – are (Papini, 2011):
Mass-Energy conservation equation in the single-phase region:

$$\frac{dz_{BB}}{dt} = b_1 \tag{18}$$

Mass-Energy conservation equation in the two-phase region:

$$\frac{dx_{ex}}{dt} = b_4 = b_2 + b_3 \frac{dz_{BB}}{dt} \tag{19}$$

Momentum conservation equation (along the whole channel):

$$\frac{dG_{in}}{dt} = b_5 \tag{20}$$

By applying Eq. (17) to the selected three state variables, as:

$$z_{BB}(t) = z_{BB}^0 + \delta z_{BB} \cdot e^{\lambda t} \tag{21}$$

$$x_{ex}(t) = x_{ex}^0 + \delta x_{ex} \cdot e^{\lambda t} \tag{22}$$

$$G_{in}(t) = G_{in}^0 + \delta G_{in} \cdot e^{\lambda t} \tag{23}$$

the resulting linear system can be written in the form of:

$$\delta z_{BB} E_{11} + \delta x_{ex} E_{12} + \delta G_{in} E_{13} = 0 \tag{24}$$

$$\delta z_{BB} E_{21} + \delta x_{ex} E_{22} + \delta G_{in} E_{23} = 0 \qquad (25)$$

$$\delta z_{BB} E_{31} + \delta x_{ex} E_{32} + \delta G_{in} E_{33} = 0 \qquad (26)$$

The calculation of the system eigenvalues is based on solving:

$$\begin{vmatrix} E_{11} & E_{12} & E_{13} \\ E_{21} & E_{22} & E_{23} \\ E_{31} & E_{32} & E_{33} \end{vmatrix} = 0 \qquad (27)$$

which yields a cubic characteristic equation, where λ are the eigenvalues of the system:

$$\lambda^3 + a\lambda^2 + b\lambda + c = 0 \qquad (28)$$

5. Analytical lumped parameter model: results and discussion

Single boiling channel configuration is referenced for the discussion of the results obtained by the developed model on DWOs. For the sake of simplicity, and availability of similar works in the open literature for validation purposes (Ambrosini et al., 2000; Ambrosini & Ferreri, 2006; Muñoz-Cobo et al., 2002), typical dimensions and operating conditions of classical BWR core subchannels are considered.
Table 1 lists the geometrical and operational values taken into account in the following analyses.

Heated channel	
Diameter [m]	0.0124
Length [m]	3.658
Operating parameters	
Pressure [bar]	70
Inlet temperature [°C]	151.3 – 282.3
k_{in}	23
k_{ex}	5

Table 1. Dimensions and operating conditions selected for the analyses

5.1 System transient response

To excite the unstable modes of density wave oscillations, input thermal power is increased starting from stable stationary conditions, step-by-step, up to the instability occurrence. Instability threshold crossing is characterized by passing through damping out oscillations (Fig. 4-(a)), limit cycle oscillations (Fig. 4-(b)), and divergent oscillations (Fig. 4-(c))). This process is rather universal across the boundary. From stable state to divergent oscillation state, a narrow transition zone of some kW has been found in this study.
The analysed system is non-linear and pretty complex. Trajectories on the phase space defined by boiling boundary z_{BB} vs. inlet mass flux G_{in} are reported in Fig. 4 too. The operating point on the stability boundary (Fig. 4-(b)) is the cut-off point between stable (Fig. 4-(a)) and unstable (Fig. 4-(c)) states. This point can be looked as a bifurcation point. The

limit oscillation is a quasi-periodic motion; the period of the depicted oscillation is rather small (less than 1 s), due to the low subcooling conditions considered at inlet.

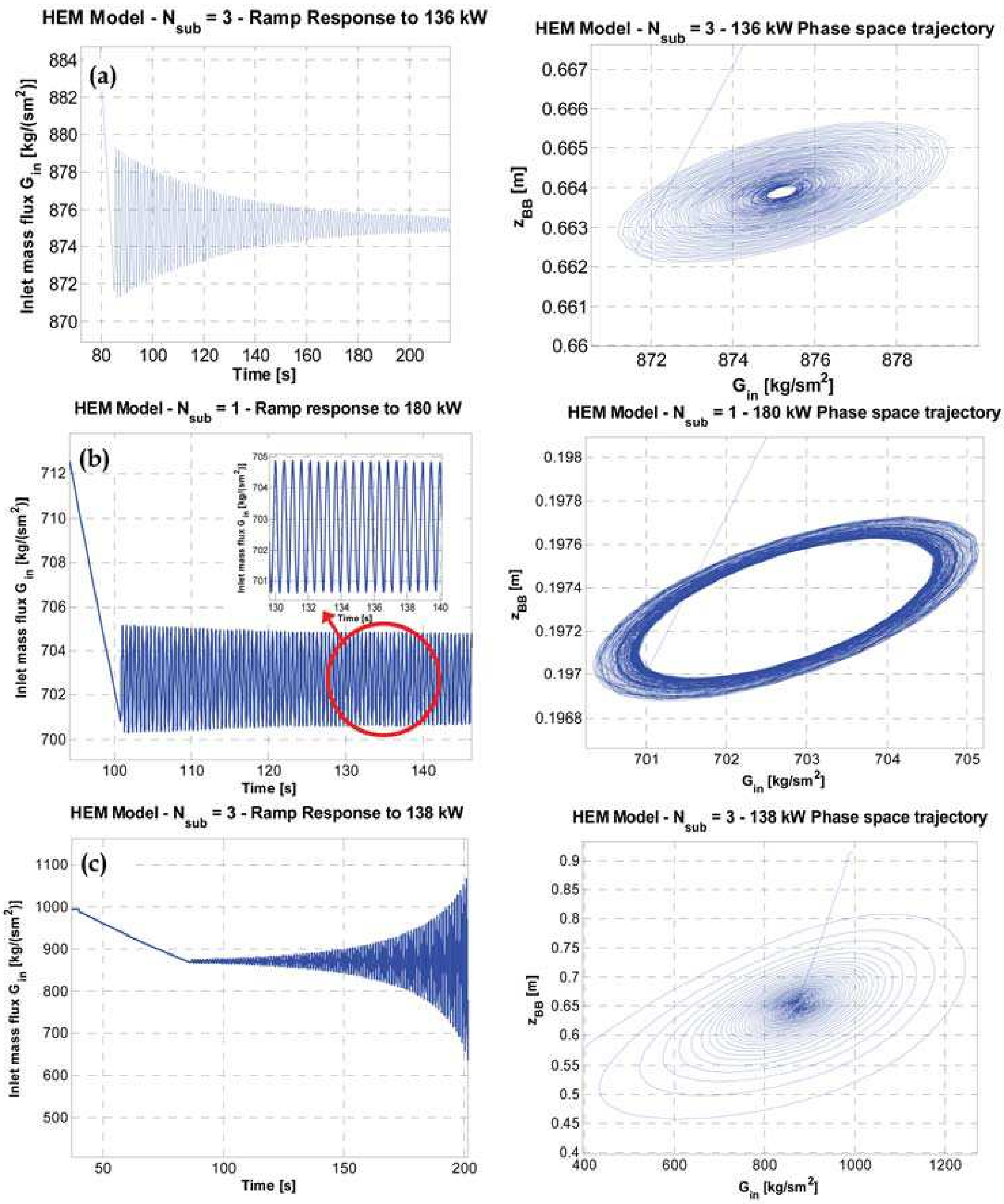

Fig. 4. Inlet mass flux oscillation curves and corresponding trajectories in the phase space (a) Stable state – (b) Neutral stability boundary – (c) Unstable state

With reference to the eigenvalue computation, by solving Eq. (28), at least one of the eigenvalues is real, and the other two can be either real or complex conjugate. For the complex conjugate eigenvalues, the operating conditions that generate the stability boundary are those in which the complex conjugate eigenvalues are purely imaginary (i.e., the real part is zero). Crossing the instability threshold is characterized by passing to positive real part of the complex conjugate eigenvalues, which is at the basis of the diverging response of the model under unstable conditions.

5.2 Description of a self-sustained DWO

The simple two-node lumped parameter model developed in this work is capable to catch the basic phenomena of density wave oscillations. Numerical simulations have been used to gain insight into the physical mechanisms behind DWOs, as discussed in this section.
The analysis has shown good agreement with some findings due to Rizwan-Uddin (1994). Fully developed DWO conditions are considered. By analysing an inlet velocity variation and its propagation throughout the channel, particular features of the transient pressure drop distributions are depicted.
The starting point is taken as a variation (increase) in the inlet velocity. The boiling boundary responds to this perturbation with a certain delay (Fig. 5), due to the propagation of an enthalpy wave in the single-phase region. The propagation of this perturbation in the two-phase zone (via quality and void fraction perturbations) causes further lags in terms of two-phase average velocity and exit velocity (Fig. 6).

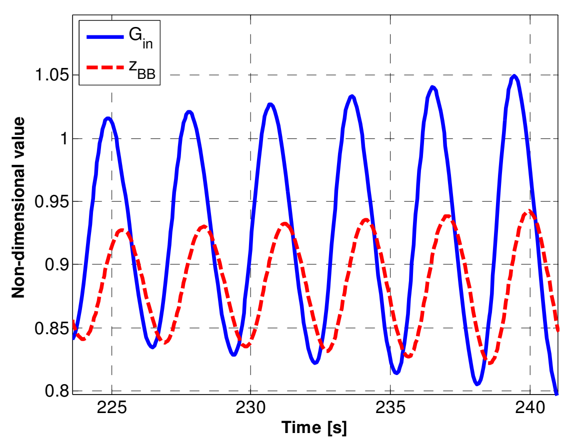

Fig. 5. Dimensionless inlet mass flux and boiling boundary. N_{sub} = 8; Q = 133 kW

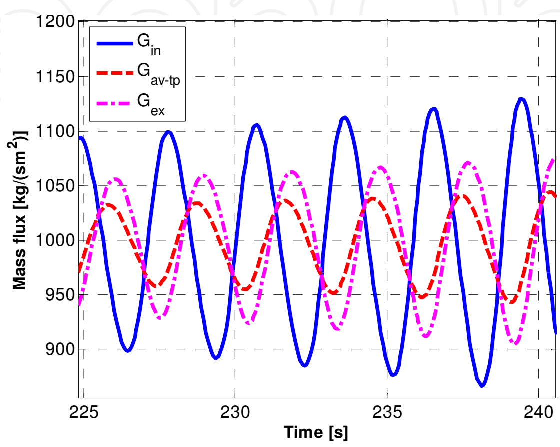

Fig. 6. Mass flux delayed variations along the channel. N_{sub} = 8; Q = 133 kW

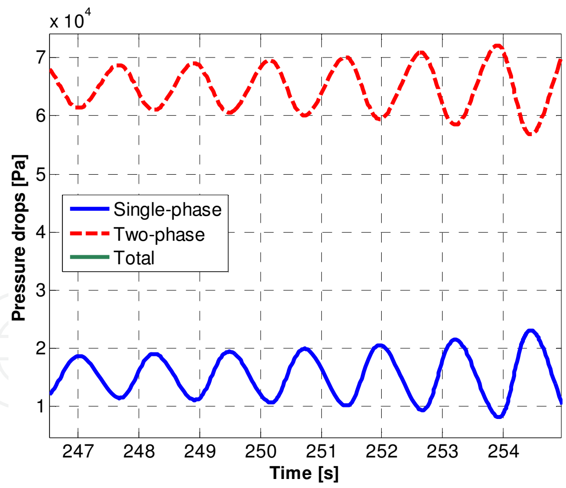

Fig. 7. Oscillating pressure drop distribution. N_{sub} = 2; Q = 103 kW

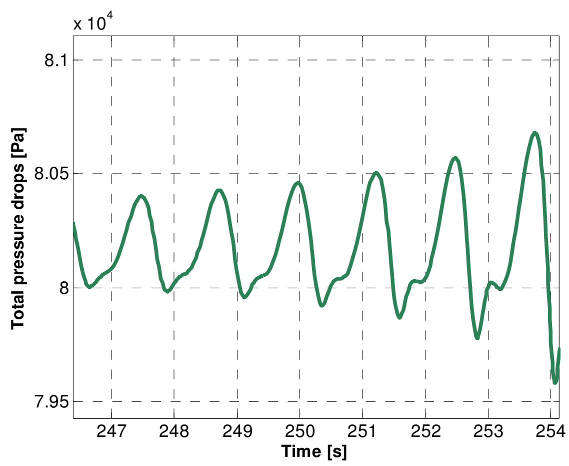

Fig. 8. “Shark-fin” oscillation of total pressure drops. N_{sub} = 2; Q = 103 kW

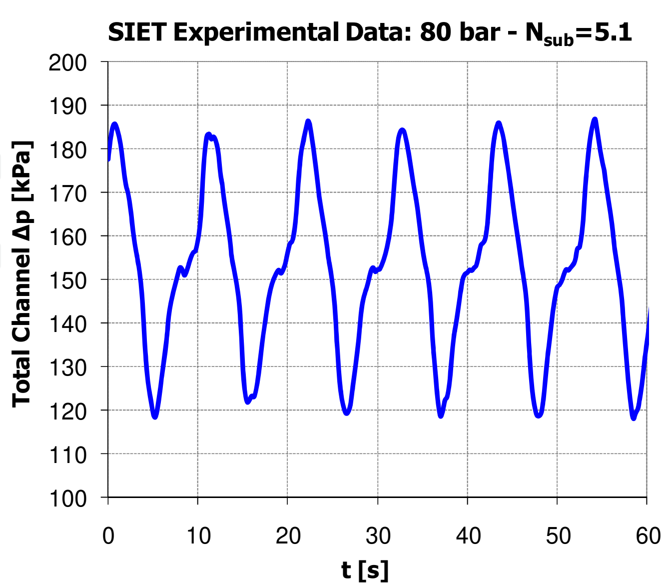

Fig. 9. Experimental recording of total pressure drop oscillation showing “shark-fin” shape (SIET labs)

All these delayed effects combine in single-phase pressure drop term and two-phase pressure drop term acquiring 180° out-of-phase fluctuations (Fig. 7). What is interesting to notice, indeed, is that the 180° phase shift between single-phase and two-phase pressure drops is not perfect (Rizwan-Uddin, 1994). Due to the delayed propagation of initial inlet velocity variation, single-phase term increase is faster than two-phase term rising. The superimposition of the two oscillations – in some operating conditions – is such to create a total pressure drop along the channel oscillating as a non-sinusoidal wave. The peculiar trend obtained is shown in Fig. 8; relating oscillation shape has been named "shark-fin" shape. Such behaviour has found corroboration in the experimental evidence collected with the facility at SIET labs (Papini et al., 2011). In Fig. 9 an experimental recording of channel total pressure drops is depicted. The experimental pressure drop oscillation shows a fair qualitative agreement with the phenomenon of "shark-fin" shape described theoretically.

5.3 Sensitivity analyses and stability maps

In order to provide accurate quantitative predictions of the instability thresholds, and of their dependence with the inlet subcooling to draw a stability map (as the one commonly drawn in the N_{pch}–N_{sub} stability plane (Ishii & Zuber, 1970), see e.g. Fig. 2), it is first necessary to identify most critical modelling parameters that have deeper effects on the results.

Several sensitivity studies have been carried out on the empirical coefficients used to model two-phase flow structure. In particular, specific empirical correlations have been accounted for within momentum balance equation to represent two-phase frictional pressure drops (by testing several correlations for the two-phase friction factor multiplier Φ_{lo}^2 [3]).

In this respect, a comparison of the considered friction models is provided in Table 2: Homogeneous Equilibrium pressure drop Model (HEM), Lockhart-Martinelli multiplier, Jones expression of Martinelli-Nelson method and Friedel correlation are selected (Todreas & Kazimi, 1993), respectively, for the analysis. It is worth noticing that the main contribution to channel total pressure drops is given by the two-phase terms, both frictional and in particular concentrated losses at channel exit (nearly 40-50%). Fractional distribution of the pressure drops along the channel plays an important role in determining the stability of the system. Concentration of pressure drops near the channel exit is such to render the system prone to instability: hence, DWOs triggered at low qualities may be expected with the analysed system.

The effects of two-phase frictions on the instability threshold are evident from the stability maps shown in Fig. 10. The higher are the two-phase friction characteristics of the system (that is, with Lockhart-Martinelli and Jones models), the most unstable results the channel (being the instability induced at lower thermodynamic quality values). Moreover, RELAP5 calculations about DWO occurrence in the same system are reported as well (see Section 6). In these conditions, Friedel correlation for two-phase multiplier is the preferred one.

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[3] When *"lo"* subscript is added to the friction multiplier, *liquid-only* approach is considered. That is, the liquid phase is assumed to flow alone with total flow rate.
Conversely, when *"l"* subscript is applied, *only-liquid* approach is considered. That is, the liquid phase is assumed to flow alone at its actual flow rate.

	HEM		Lockhart-Martinelli		Jones		Friedel	
Term	*ΔP [kPa]*	*% of total*	*ΔP [kPa]*	*% of total*	*ΔP [kPa]*	*% of total*	*ΔP [kPa]*	*% of total*
ΔP_{grav}	12.82	17.31%	12.82	7.96%	12.82	10.96%	12.82	14.62%
ΔP_{acc}	10.24	13.84%	10.24	6.36%	10.24	8.76%	10.24	11.68%
ΔP_{in}	15.35	20.74%	15.35	9.54%	15.35	13.12%	15.35	17.51%
$\Delta P_{frict,1\phi}$	0.96	1.29%	0.96	0.59%	0.96	0.82%	0.96	1.09%
$\Delta P_{frict,2\phi}$	10.61	14.33%	39.84	24.75%	23.54	20.12%	14.97	17.07%
ΔP_{ex}	24.06	32.50%	81.73	50.79%	54.07	46.22%	33.36	38.04%
ΔP_{tot}	74.03	100%	160.94	100%	116.97	100%	87.69	100%

Table 2. Fractional contributions to total channel pressure drop (at steady-state conditions). Test case: Γ = 0.12 kg/s; T_{in} = 239.2 °C; Q = 100 kW (x_{ex} = 0.40)

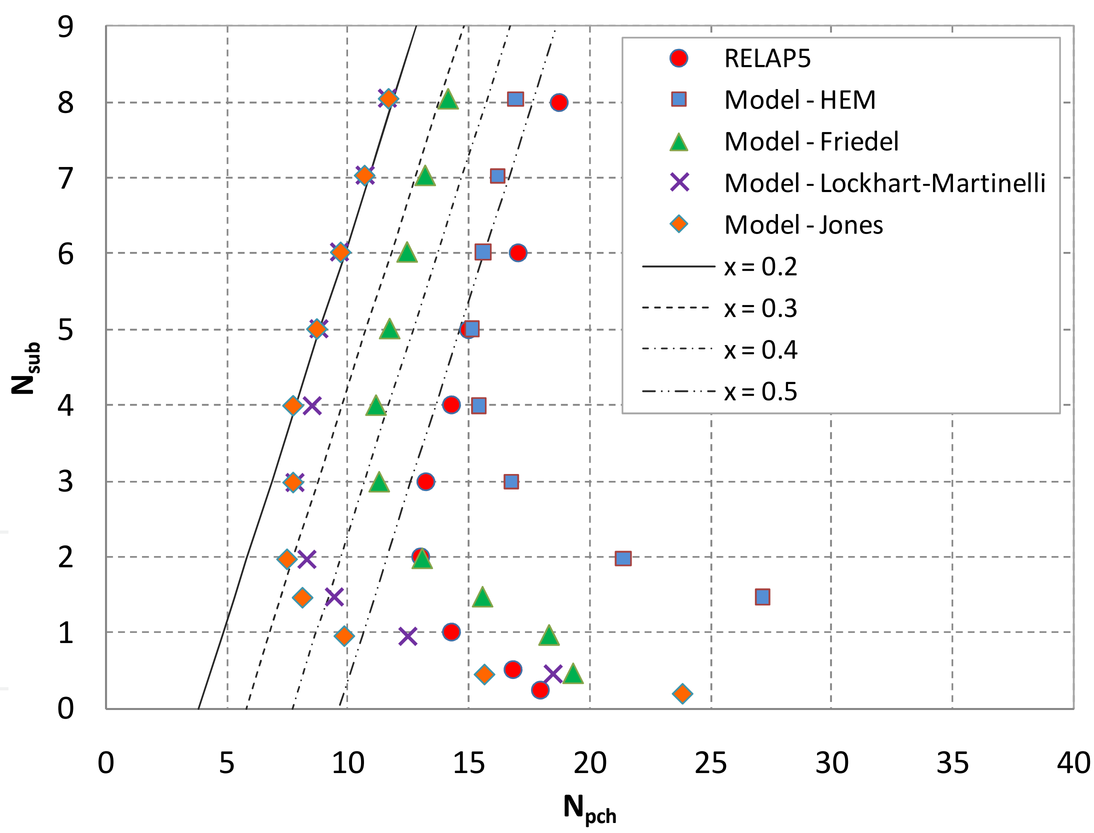

Fig. 10. Stability maps in the N_{pch}–N_{sub} stability plane, drawn with different models for two-phase friction factor multiplier

The influence of the two-phase friction multiplier on the system stability (via the channel pressure drop distribution) is made apparent also in terms of eigenvalues computation. Fig. 11 reports the results of the linear stability analysis corresponding to the four cases depicted in Table 2.

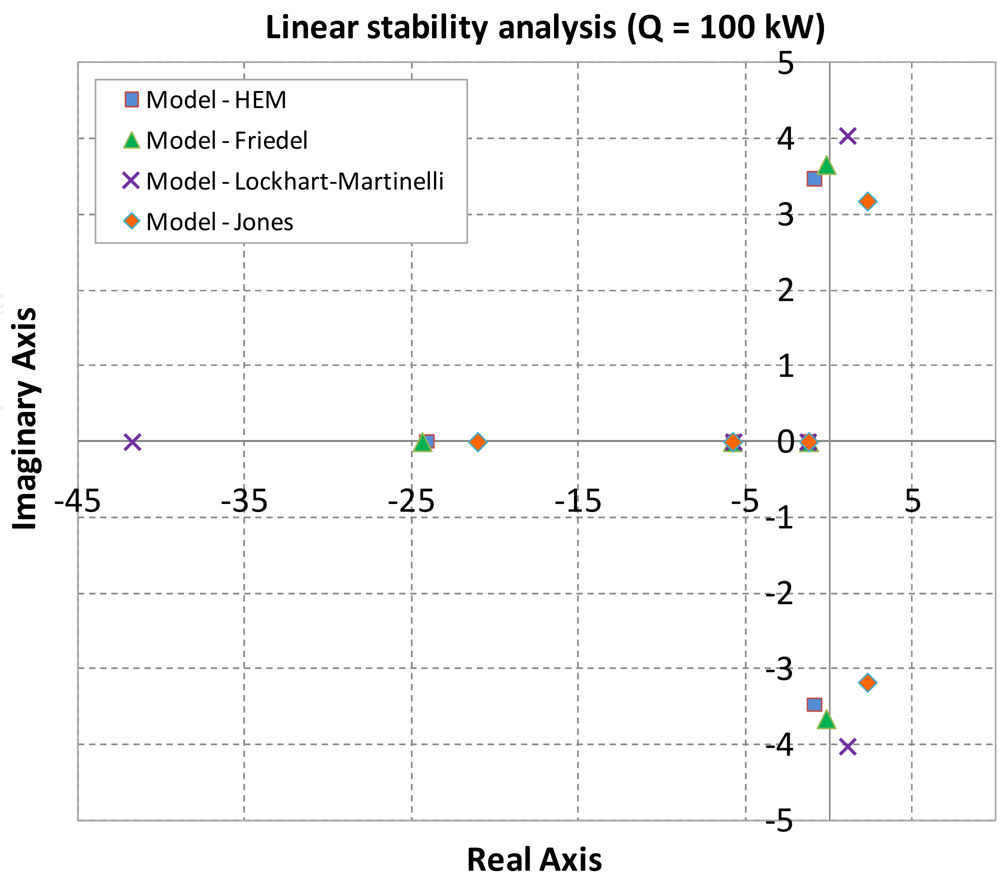

Fig. 11. Sensitivity on two-phase friction factor multiplier in terms of system eigenvalues. Test case: Γ = 0.12 kg/s; T_{in} = 239.2 °C; Q = 100 kW (x_{ex} = 0.40)

6. Numerical modelling

Theoretical predictions from analytical model have been then verified via qualified numerical simulation tools. Both, the thermal-hydraulic dedicated code RELAP5 and the multi-physics code COMSOL have been successfully applied to predict DWO inception and calculate the stability map of the single boiling channel system (vertical tube geometry) referenced in Section 4 and 5. The final benchmark – considering also the noteworthy work of Ambrosini et al. (2000) – is shown in Fig. 12.

As concerns the RELAP5 modelling, rather than simulating a fictitious configuration with single channel working with imposed ΔP, kept constant throughout the simulation (as provided by Ambrosini & Ferreri (2006)), the attempt to reproduce realistic experimental apparatus for DWO investigation has been pursued. For instance, the analyses on a single boiling channel have been carried out by considering a large bypass tube connected in parallel to the heated channel. As discussed in Section 2, the bypass solution is in fact the typical layout experimentally adopted to impose the constant-pressure-drop condition on a single boiling channel[4]. Instability inception is established from transient analysis, by increasing the power generation till fully developed flow oscillations occur.

[4] As a matter of fact, in the experimental apparatus the mass flow rate is forced by an external feedwater pump, instead of being freely driven according to the supplied power level.

As concerns the COMSOL modelling, a thermal-hydraulic 1D simulator valid for water-steam mixtures has been first developed, via implementation in the code of the governing PDEs for single-phase and two-phase regions, respectively. Linear stability analysis has been then computed to obtain the results reported in Fig. 12, where both, homogeneous model for two-phase flow structure (as assumed by the analytical model) and appropriate drift-flux model accounting for slip effects as well are considered. As the proper prediction of the instability threshold depends highly on the effective frictional characteristics of the reproduced channel (see Section 5.3), the possibility of implementing most various kinds of two-phase flow models (drift-flux kind, with different correlations for the void fraction) renders the developed COMSOL model suitable to apply for most different heated channel systems.

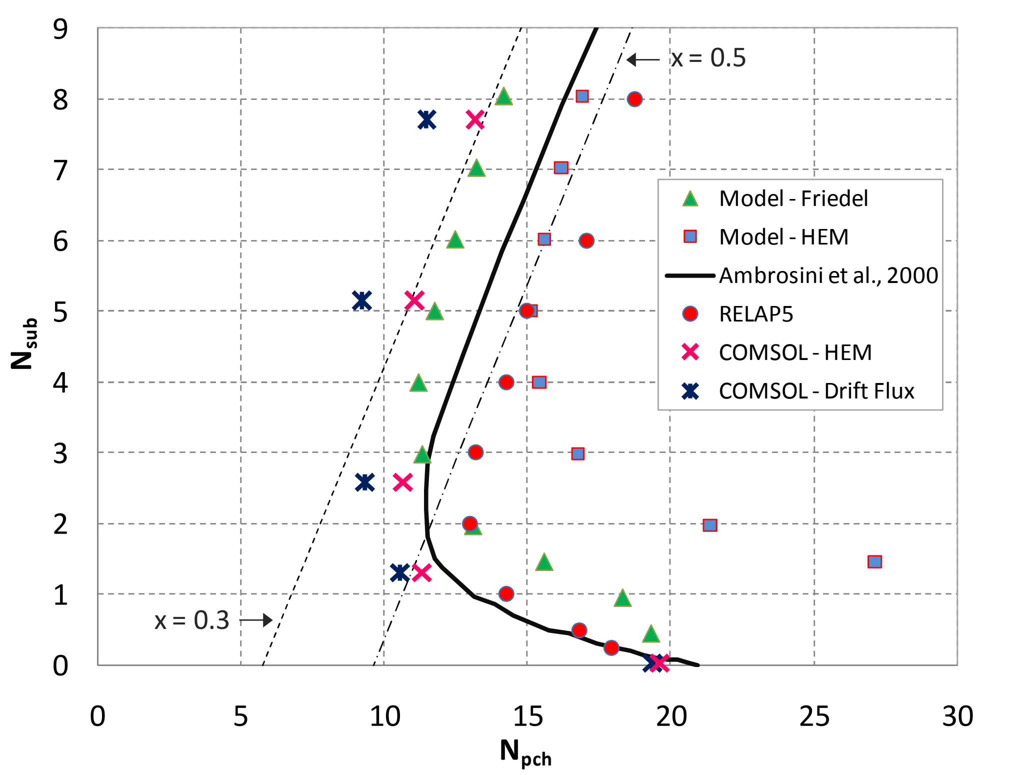

Fig. 12. Validation benchmark between analytical model and numerical models with RELAP5 and COMSOL codes

7. Experimental campaign with helical coil tube geometry

In order to experimentally study DWOs in helically coiled tubes, a full-scale open-loop test facility simulating the thermal-hydraulic behaviour of a helically coiled steam generator for applications within SMRs was built and operated at SIET labs (Piacenza, Italy) (Papini et al., 2011). Provided with steam generator full elevation and suited for prototypical thermal-hydraulic conditions, the facility comprises two helical tubes (1 m coil diameter, 32 m length, 8 m height), connected via lower and upper headers. Conceptual sketch is depicted in Fig. 13, whereas global and detailed views are shown in Fig. 14.
The test section is fed by a three-cylindrical pump with a maximum head of about 200 bar; the flow rate is controlled by a throttling valve positioned downwards the feed water pump

and after a bypass line. System pressure control is accomplished by acting on a throttling valve placed at the end of the steam generator. An electrically heated helically coiled pre-heater is located before the test section, and allows creating the desired inlet temperature. To excite flow unstable conditions starting from stable operating conditions, supplied electrical power was gradually increased (by small steps, 2-5 kW) up to the appearance of permanent and regular flow oscillations.
Nearly 100 flow instability threshold conditions have been identified, in a test matrix of pressures (80 bar, 40 bar, 20 bar), mass fluxes (600 kg/m²s, 400 kg/m²s, 200 kg/m²s) and inlet subcooling (from -30% up to saturation). Effects of the operating pressure, flow rate and inlet subcooling on the instability threshold power have been investigated, pointing out the differences with respect to classical DWO theory, valid for straight tubes.

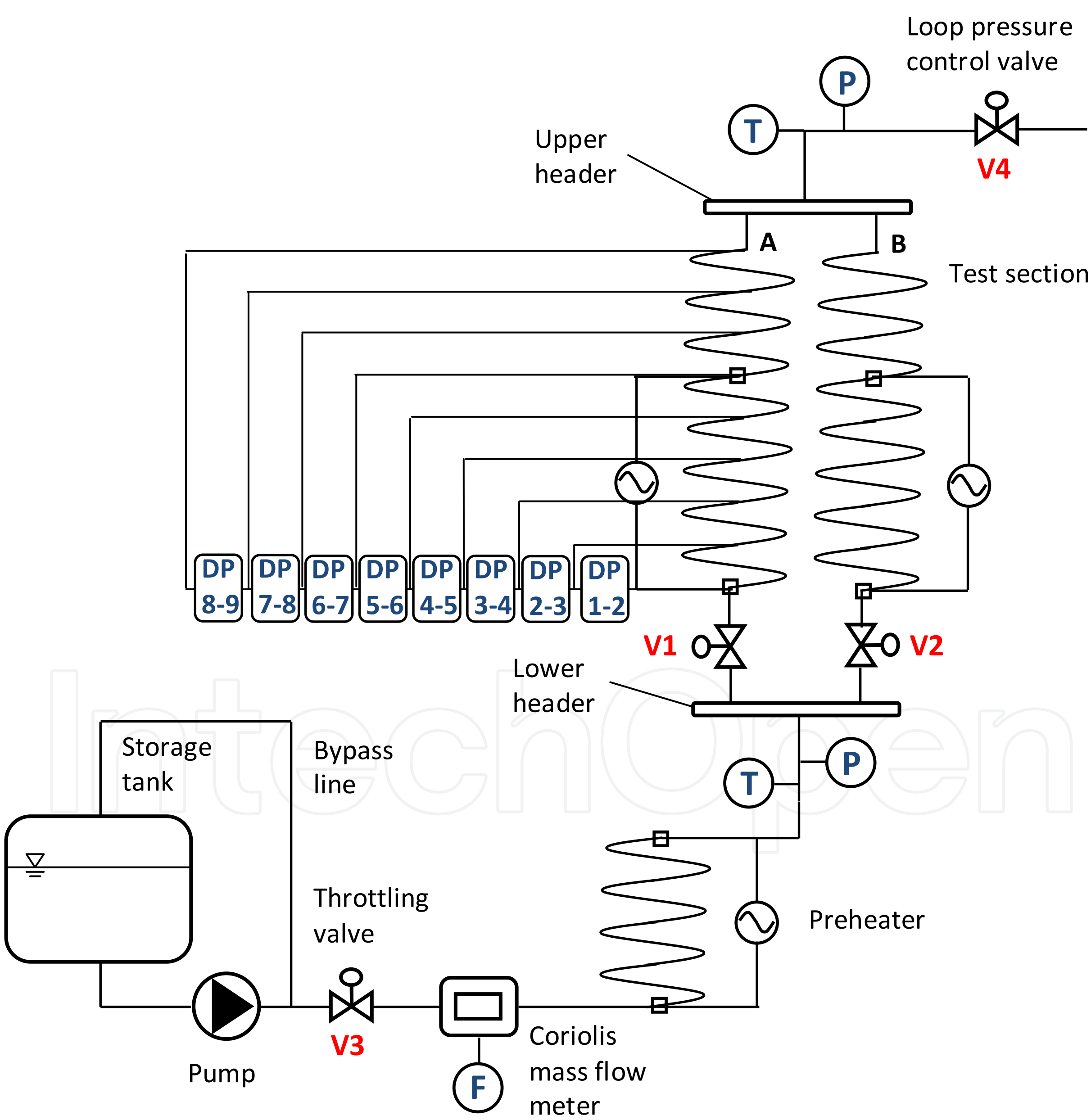

Fig. 13. Sketch of the experimental facility installed at SIET labs. (Papini et al., 2011)

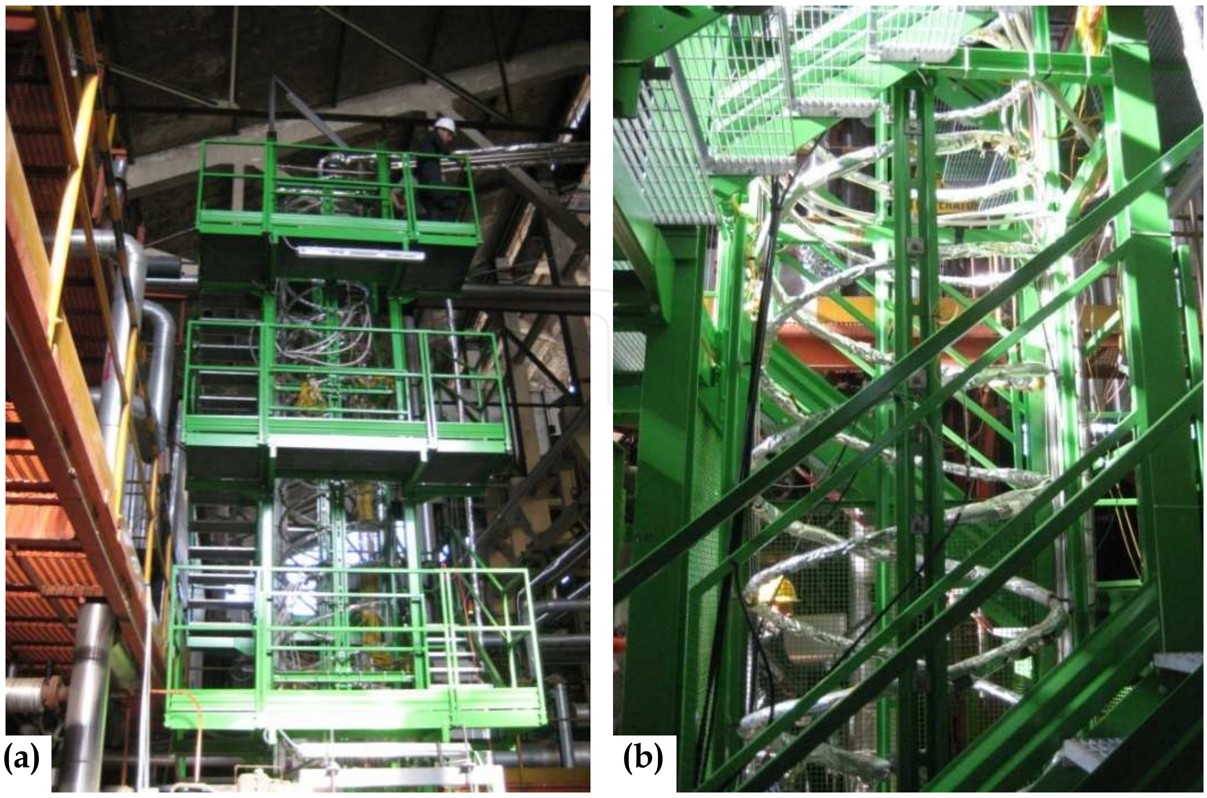

Fig. 14. Global view (a) and detailed picture (b) of the helical coil test facility (SIET labs)

7.1 Experimental characterization of a self-sustained DWO

DWO onset can be detected by monitoring the flow rate, which starts to oscillate when power threshold is reached. Calibrated orifices installed at the inlet of both parallel tubes permitted to measure the flow rate through the recording of the pressure drops established across them. Oscillation amplitude grows progressively as the instability is incepted. Throughout our analyses the system was considered completely unstable (corresponding to instability threshold crossing) when flow rate oscillation amplitude reached the 100% of its steady-state value. Obviously, the flow rate in the two channels oscillates in counter-phase, as shown in Fig. 15-(a). The “square wave” shape of the curves is due to the reaching of instruments full scale.

The distinctive features of DWOs within two parallel channels can be described as follows.

System pressure oscillates with a frequency that is double if compared with the frequency of flow rate oscillations (Fig. 15-(b)).

Counter-phase oscillation of single-phase and two-phase pressure drops can be noticed within each channel. Pressure drops between pressure taps placed on different regions of Channel A, in case of self-sustained instability, are compared in Fig. 15-(c). Pressure drops in the single-phase region (DP 2-3) oscillate in counter-phase with respect to two-phase pressure drops (DP 6-7 and DP 8-9). The phase shift is not abrupt, but it appears gradually along the channel. As a matter of fact, the pressure term DP 4-5 (low-quality two-phase region) shows only a limited phase shift with respect to single-phase zone (DP 2-3).

Moreover, large amplitude fluctuations in channel wall temperatures, so named *thermal oscillations* (Kakaç & Bon, 2008), always occur (Fig. 15-(d)), associated with fully developed density wave oscillations that trigger intermittent film boiling conditions.

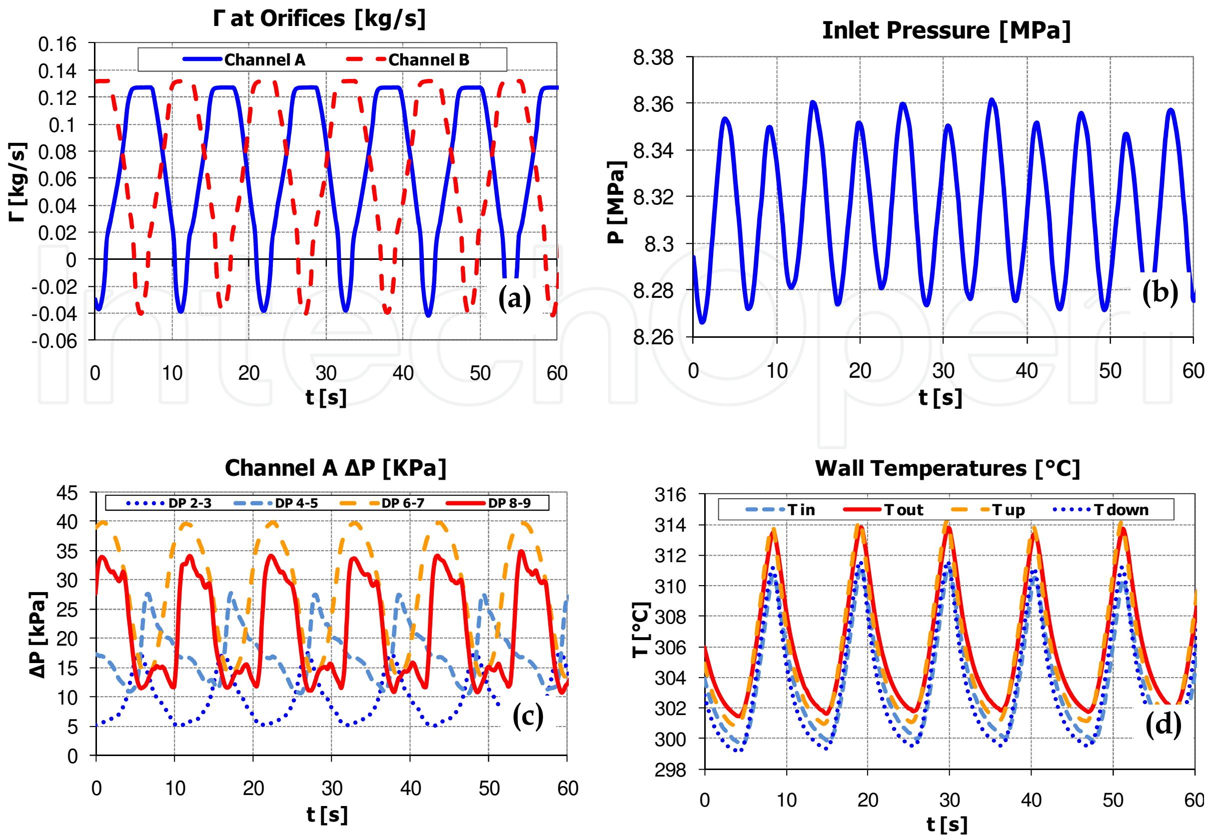

Fig. 15. Flow rate oscillations (a), system pressure oscillations (b), pressure drops oscillations (c) and wall temperature oscillations (d) during fully developed instabilities.
Data collected with: P = 83 bar; T_{in} = 199 °C; G = 597 kg/m²s; Q = 99.3 kW

7.2 Experimental results

The experimental campaign provided a thorough threshold database useful for model validation. Collected threshold data have been clustered in the N_{pch}–N_{sub} stability plane.
Peculiar influence of the helical coil geometry (ascribable to the centrifugal field induced by tube bending) has been main object of investigation. For the sake of brevity, just the experimental results at P = 40 bar are hereby presented. Instability threshold data for the three values of mass flux (G = 600 kg/m²s, 400 kg/m²s and 200 kg/m²s) are depicted in Fig. 16, whereas limit power dependence with the inlet subcooling is shown in Fig. 17.
The effects on instability of the thermal power and mass flow rate do not show differences in the helical geometry when compared to the straight tube case (refer to the parametric discussion of Section 2.2). In short, an increase in thermal power or a decrease in channel mass flow rate are found to trigger the onset of DWOs; both effects increase the exit quality, which turns out to be a key parameter for boiling channel instability.
Instead, it is interesting to focus the attention on the effects of the inlet subcooling. With respect to the *L shape* of the stability boundary, generally exhibited by vertical straight tubes, the present datasets with helical geometry show indeed two different behaviours: *(a)* "conventional" at medium-high subcoolings, with iso-quality stability boundary and slight stabilization in the range N_{sub} = 3 ÷ 6 (close to *L shape*); *(b)* "non-conventional" at low subcoolings, with marked destabilizing effects as the inlet temperature increases and approaches the saturation value.

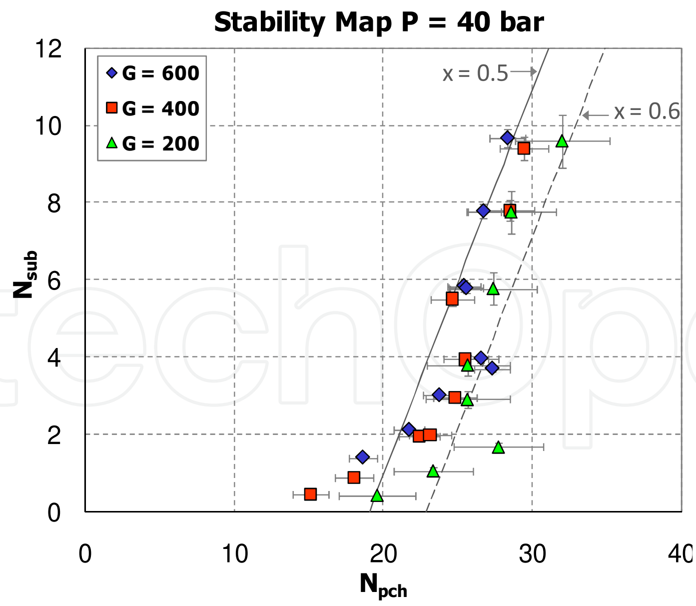

Fig. 16. Stability map obtained at P = 40 bar and different mass fluxes (G = 600 kg/m²s, 400 kg/m²s, 200 kg/m²s)

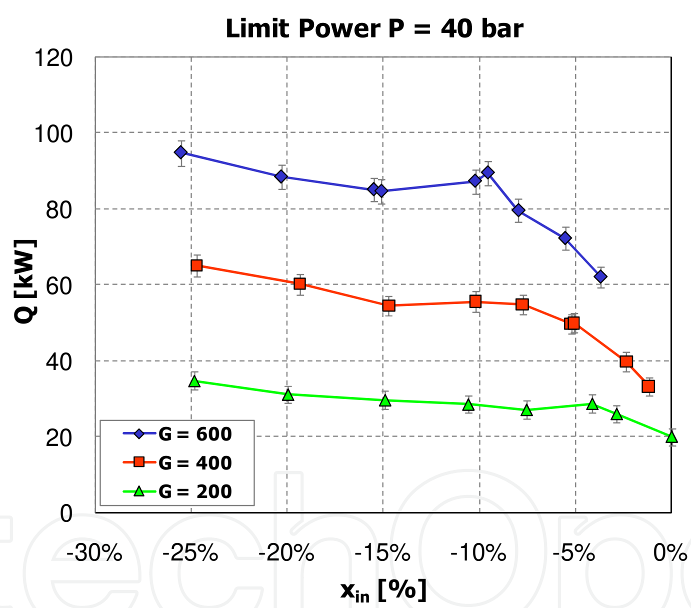

Fig. 17. Limit power for instability inception at P = 40 bar as function of inlet subcooling and for different mass fluxes

8. Comparison between models and experimental results

To reproduce and interpret the highlighted phenomena related to the investigated helical coil geometry, both the analytical lumped parameter model and the RELAP5 code have been applied. Proper modifications to simulate the experimental facility configuration (Table 3) include introduction of a riser section downstream the heated section and approximation of the helical shape by assuming a straight channel long as the helical tube and with the same inclination of the helix.

Heated channel	
Diameter [m]	0.01253
Heated length [m]	24
Riser length [m]	8
Helix inclination angle [deg]	14.48°
Operating parameters	
Pressure [bar]	20 – 40 – 80
Mass flux (per channel) [kg/m²s]	200 – 400 – 600
Inlet subcooling [%]	-30 ÷ 0
k_{in}	45
k_{ex}	0

Table 3. Dimensions and operating conditions of the experimental facility

8.1 Analytical modelling of the experimental facility

Best results have been obtained via the analytical model, on the basis of a modified form of the widespread and sound Lockhart-Martinelli two-phase friction multiplier, previously tuned on the frictional characteristics of the system (Colorado et al., 2011). The modified Lockhart-Martinelli multiplier (*only-liquid* kind) used for the calculations reads:

$$\Phi_l^2 = 1 + \frac{3.2789}{X_{tt}} + \frac{0.3700}{X_{tt}^{2.0822}} \tag{29}$$

To comply with the form of the modelling equations, passing from *"only-liquid"* to *"liquid-only"* mode is required. The following relation (Todreas & Kazimi, 1993) is considered:

$$\Phi_{lo}^2 = \Phi_l^2 \left(1 - x\right)^{1.75} \tag{30}$$

Though the developed analytical model seems to underestimate the instability threshold conditions (that is, the predicted instabilities occur at lower qualities), rather satisfactory results turn out at low flow rate values (G = 200 kg/m²s). In these conditions, fair agreement is found with the peculiar instability behaviour of helical coil geometry, characterized by a marked destabilization near the saturation when inlet temperature is increased (i.e., inlet subcooling is reduced). Fig. 18-(a) shows how the peculiar stability boundary shape, experimentally obtained for the present helical-coiled system, is well predicted. Finally, the comparison between model and experimental findings is considerably better at high pressure (P = 80 bar; Fig. 18-(b)), where the homogenous two-phase flow model – at the basis of the modelling equations – is more accurate.

8.2 RELAP5 modelling of the experimental facility

Marked overestimations of the instability onset come out when applying the RELAP5 code to the helical coil tube facility simulation (see Fig. 18), mainly due to the lack in the code of specific thermo-fluid-dynamics models (two-phase pressure drops above all) suited for the complex geometry investigated.

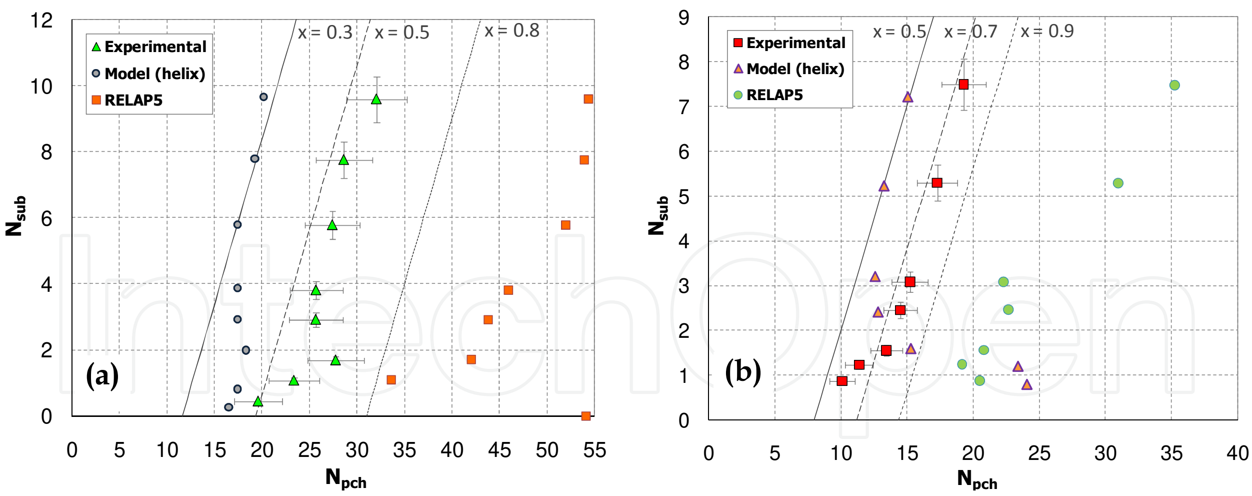

Fig. 18. Comparison between experimental, theoretical and RELAP5 results.
(a) P = 40 bar; G = 200 kg/m²s – (b) P = 80 bar; G = 400 kg/m²s

9. Conclusions

Density wave instability phenomena have been presented in this work, featured as topic of interest in the nuclear area, both to the design of BWR fuel channels and the development of the steam generators with peculiar reference to new generation SMRs.

Parametric discussions about the effects of thermal power, flow rate, inlet subcooling, system pressure, and inlet/exit throttling on the stability of a boiling channel have been stated. Theoretical studies based on analytical and numerical modelling have been presented, aimed at gaining insight into the distinctive features of DWOs as well as predicting instability onset conditions.

An analytical lumped parameter model has been developed. Non-linear features of the modelling equations have permitted to represent the complex interactions between the variables triggering the instability. Proper simulation of two-phase frictional pressure drops – prior to proper representation of the pressure drop distribution within the channel – has been depicted as the most critical concern for accurate prediction of the instability threshold. Dealing with the simple and known-from-literature case of vertical tube geometry, theoretical predictions from analytical model have been validated with numerical results obtained via the RELAP5 and COMSOL codes, which have proved to successfully predict the DWO onset.

The study of the instability phenomena with respect to the helical coil geometry, envisaged for the steam generators of several SMRs, led to a thorough experimental activity by testing two helically coiled parallel tubes. The experimental campaign has shown the peculiar influence of the helical geometry on instability thresholds, evident mostly in a pretty different parametric effect of the inlet subcooling.

The analytical model has been satisfactorily applied to the simulation of the experimental results. Correct representation of the stationary pressure drop distribution (partially accomplished thanks to the experimental tuning of a sound friction correlation) has been identified as fundamental before providing any accurate instability calculations. In this respect, the RELAP5 code cannot be regarded for the time being as a proven tool to study DWO phenomena in helically coiled tubes.

10. Acknowledgments

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11. Nomenclature

A tube cross-sectional area [m^2]
c specific heat [J/kg°C]
G mass flux [kg/m^{2}s]
H tube length (heated zone) [m]
h specific enthalpy [J/kg]
heat transfer coefficient, Eqs.(8),(9) [W/m^2°C]
j volumetric flux ($(x/\rho_g + (1-x)/\rho_f) \cdot G_{2\phi}$) [m/s]
k concentrated loss coefficient [-]
M tube mass [kg]
N_{pch} phase change number ($Q/(\Gamma h_{fg}) \cdot v_{fg}/v_f$) [-]
N_{sub} subcooling number ($\Delta h_{in}/h_{fg} \cdot v_{fg}/v_f$) [-]
P pressure [bar]
Q thermal power [W]
Q''' thermal power per unit of volume [W/m^3]
S heat transfer surface [m^2]
T temperature [°C]
period of oscillations, Eq.(2) [s]
t time [s]
v specific volume [m^3/kg]
w liquid velocity [m/s]
X_{tt} Lockhart-Martinelli parameter ($((1-x)/x)^{0.9} \cdot (\rho_g/\rho_f)^{0.5} \cdot (\mu_f/\mu_g)^{0.1}$) [-]
x thermodynamic quality [-]
z tube abscissa [m]
α void fraction [-]
ΔP pressure drops [Pa]
Γ mass flow rate [kg/s]
η state variable
λ system eigenvalue
μ dynamic viscosity [Pa s]
ρ density [kg/m^3]
τ heated section transit time [s]
$\Phi^2_{l/lo}$ two-phase friction multiplier ($\Delta P_{tp}/\Delta P_{l/lo}$) [-]
Ω reaction frequency ($Q/(AH) \cdot v_{fg}/h_{fg}$) [1/s]

Subscripts

acc accelerative
av average
BB boiling boundary
ex exit
f saturated liquid
fl fluid bulk
frict frictional
g saturated vapour
grav gravitational
H homogeneous model
h heated wall
in inlet
l only-liquid
lo liquid-only
tot total
tp two-phase
1ϕ single-phase region
2ϕ two-phase region

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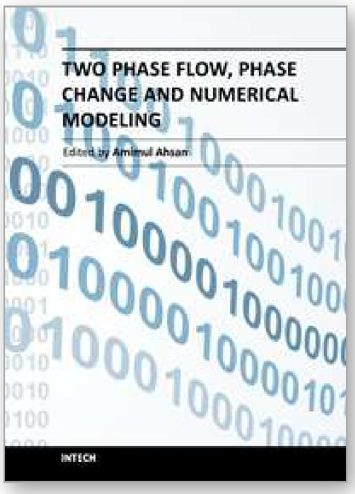

Two Phase Flow, Phase Change and Numerical Modeling

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The heat transfer and analysis on laser beam, evaporator coils, shell-and-tube condenser, two phase flow, nanofluids, complex fluids, and on phase change are significant issues in a design of wide range of industrial processes and devices. This book includes 25 advanced and revised contributions, and it covers mainly (1) numerical modeling of heat transfer, (2) two phase flow, (3) nanofluids, and (4) phase change. The first section introduces numerical modeling of heat transfer on particles in binary gas-solid fluidization bed, solidification phenomena, thermal approaches to laser damage, and temperature and velocity distribution. The second section covers density wave instability phenomena, gas and spray-water quenching, spray cooling, wettability effect, liquid film thickness, and thermosyphon loop. The third section includes nanofluids for heat transfer, nanofluids in minichannels, potential and engineering strategies on nanofluids, and heat transfer at nanoscale. The forth section presents time-dependent melting and deformation processes of phase change material (PCM), thermal energy storage tanks using PCM, phase change in deep CO2 injector, and thermal storage device of solar hot water system. The advanced idea and information described here will be fruitful for the readers to find a sustainable solution in an industrialized society.