The Abdus Salam International Centre for Theoretical Physics

United Nations Educational, Scientific and Cultural Organization
IAEA
International Atomic Energy Agency

**2291-16**

**Joint ICTP-IAEA Course on Science and Technology of Supercritical Water Cooled Reactors**

***27 June - 1 July, 2011***

# FLOW STABILITY OF HEATED CHANNELS WITH SUPERCRITICAL PRESSURE FLUIDS

Walter AMBROSINI
*Universita' degli Studi di Pisa*
*Dipartimento di Ingegneria Meccanica, Nucleare e della Produzione*
*Largo Lucio Lazzarino, 1*
*56122 Pisa*
*ITALY*

# Flow stability of heated channels with supercritical pressure fluids

**Joint ICTP-IAEA Course on Science and Technology of SCWRs**
**Trieste, Italy, 27 June - 1 July 2011**

**Walter Ambrosini**
**Università di Pisa**
**Dipartimento di Ingegneria Meccanica Nucleare e della Produzione**

IN SUPREMÆ DIGNITATIS
1343
UNIVERSITÀ DI PISA

# Objectives

Objectives of this Lecture are:

- To review the basic mechanisms of flow instability
- To shortly describe techniques and tools adopted to predict unstable behaviour
- To present a comparison of unstable behaviour in two-phase and SC fluid systems

# Introduction

- **Assuring a stable flow behaviour of industrial equipment is one of the important design objectives**
  - **instability may perturb operation, challenging control systems**
  - **the inadvertent occurrence of oscillations may endanger sensitive equipment**
    - **fatigue**
    - **exceeding thermal margins**

- **Nevertheless, instabilities are often encountered in fluid systems because of**
  - **presence of delays between causes and effects due to transport of perturbations (advection)**
  - **non monotonic trends in pressure drop vs. flow characteristics**
  - **nonlinear behaviour of governing equations (advection terms)**
  - **intrinsically unstable flow regimes in multiphase flow**

# Introduction

- **Classical control theory concepts constitute a useful basis for understanding and modelling linear stability in fluid systems**
  - **approach applicable to study the effect of small perturbations, i.e. for linear behaviour**
  - **zeroes and poles of transfer functions define stability conditions**
  - **practical stability criteria available (Nyquist, Routh-Hurwitz)**

- **When nonlinear behaviour is addressed, often transition to chaos by different routes is observed**
  - **generally, periodic behaviour is first observed (limit cycles)**
  - **chaos is a deterministic but unpredictable aperiodic behaviour arising due to sensitivity to initial conditions (SIC) by different routes**

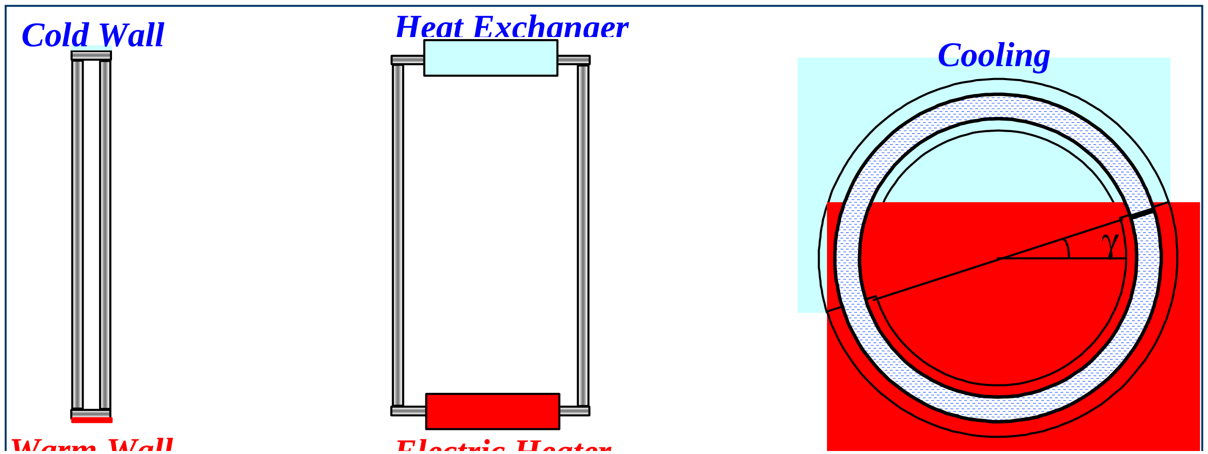
# Introduction

- In nuclear reactors unstable behaviour may be favoured or affected in its nature by the presence of neutronic feedback
  - power production is affected by flow oscillations
  - fluid density variations in moderated systems affect the closed loop gains (e.g., higher gain --> lower stability)
  - spatial harmonic modes in nuclear reactor core are affected by the thermal-hydraulic feedback
- Flow oscillations in nuclear reactors are unwanted because they perturb the power production and the heat transfer capabilities
- Unstable behaviour must be therefore prevented or mitigated in NPPs by different means:
  - designing for stable normal operation
  - avoiding known unstable operating conditions
  - suppressing instabilities by corrective actions
  - shutting down the reactor, whenever needed

# Basic mechanisms of flow instability

## Single-Phase Natural Circulation

- **Even in single-phase natural circulation flow oscillations may take place as a consequence of delays due to fluid transit along the loop**
- **Typical configurations of the more frequently studied loops are reported hereafter**



# Basic mechanisms of flow instability
## Welander's mechanism

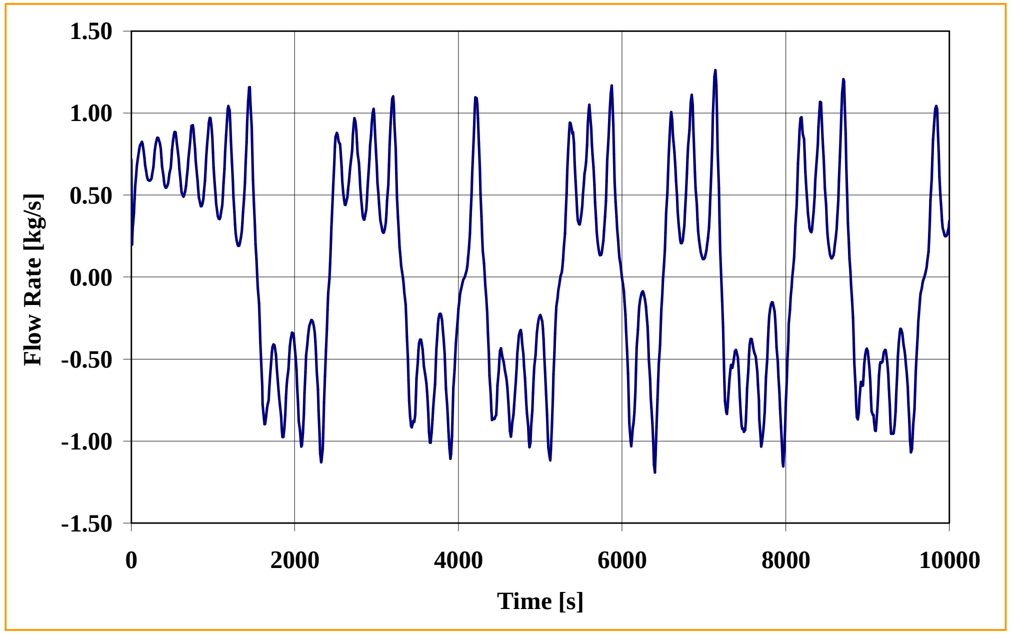
- **Unstable behaviour was predicted by Welander in (1967) and then observed in many experimental loops**

- **An intuitive explanation for this behaviour was also provided in Welander's paper:**
  - **pockets of fluid with perturbed temperature emerging from the source and the sink result in a perturbation of the flow rate**
  - **this, in turn, affects the residence time of the pockets in the source and the sink at the subsequent passages;**
  - **thus, for different combinations of physical parameters, temperature perturbations may be damped or amplified.**

# Basic mechanisms of flow instability
## Flow rate oscillations

**Typical observed or predicted behaviour:**

**the flow oscillates with repeated <u>flow reversals</u>**




**This mechanism may be possibly active also in supercritical fluid systems**

# Basic mechanisms of flow instability

## Boiling channels

**Boiling channel instabilities have a great concern for our discussion, since unstable phenomena occurring in them are closer to those envisaged in heated channels with supercritical fluids**

**Both static and dynamic instabilities are considered:**

- **Static: Ledinegg type, flow regime relaxation, geysering**
- **Dynamic: density-wave, pressure drop, flow regime, acoustic**

**The pressure drop oscillations occur when a system that would be prone to the static Ledinegg instabilities is coupled with compressible devices allowing for dynamic oscillations of the system**

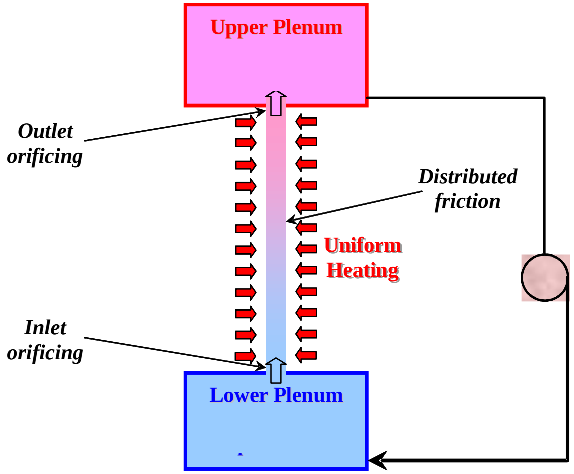
**We will shortly review only the Ledinegg type and the density wave oscillations**

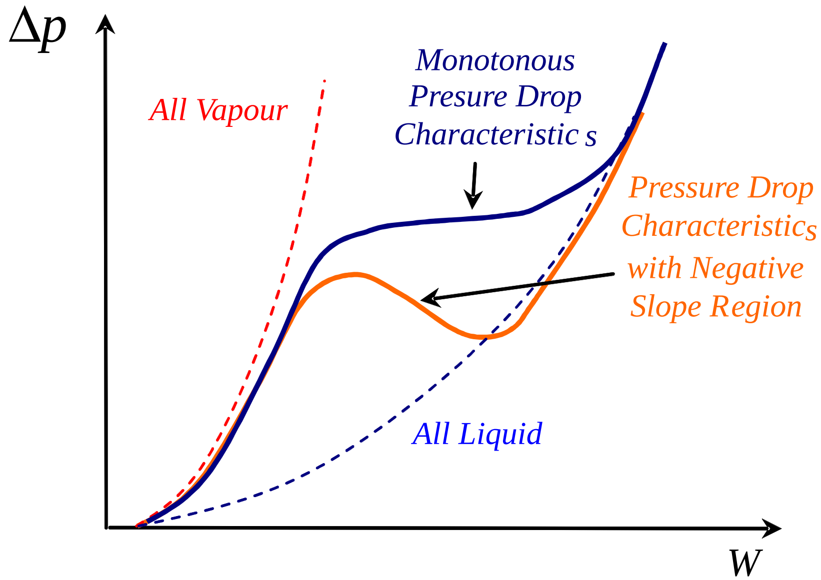
# Basic mechanisms of flow instability

## Static Ledinegg type instability

**For a single channel, the Ledinegg instability can be expected when the internal pressure drop to flow characteristics has a non monotonous trend**

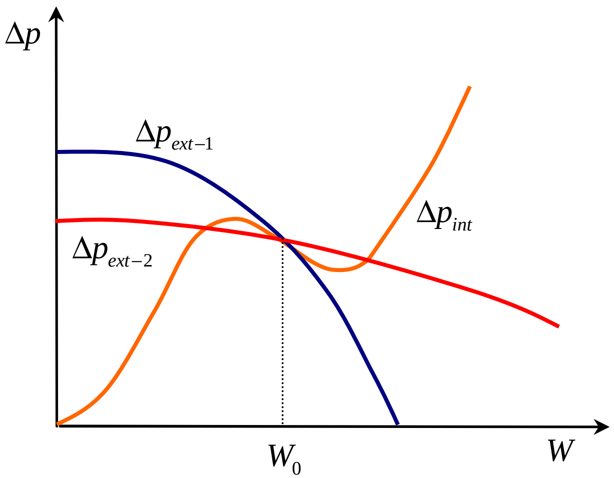
**The reference situation is depicted below**



# Basic mechanisms of flow instability
## Static Ledinegg-type instability (cont'd)

**Depending on the slope of the static external and internal pressure drop-to-flow characteristics, the system can be found stable or unstable in an excursive way**




**In fact, representing the system dynamics by**

$$I\frac{dW}{dt} = \Delta p_{ext}(W) - \Delta p_{int}(W)$$

**and linearising by perturbation the equation, it is found**

$$\delta W(t) = \delta W(0)\exp\left\{\left[\left.\frac{d(\Delta p_{ext})}{dW}\right|_{W=W_0} - \left.\frac{d(\Delta p_{int})}{dW}\right|_{W=W_0}\right]\frac{t}{I}\right\}$$

**The pure exponential trend explains the classification of "excursive" instability. Therefore, the system is stable or unstable if**

$$\boxed{\left.\frac{d(\Delta p_{ext})}{dW}\right|_{W=W_0} < \left.\frac{d(\Delta p_{int})}{dW}\right|_{W=W_0}}$$

**or**

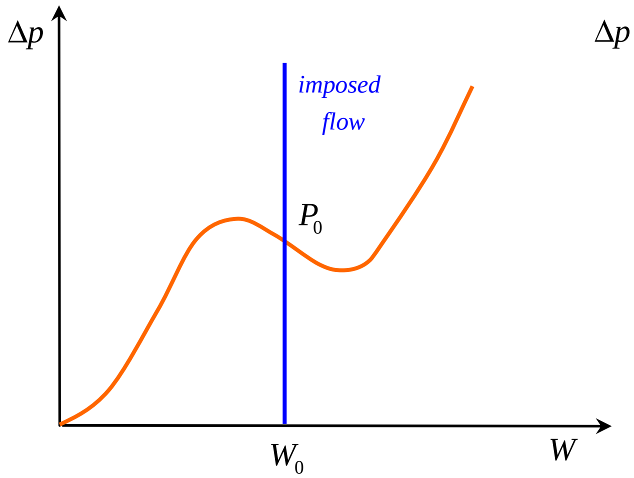
$$\boxed{\left.\frac{d(\Delta p_{ext})}{dW}\right|_{W=W_0} > \left.\frac{d(\Delta p_{int})}{dW}\right|_{W=W_0}}$$

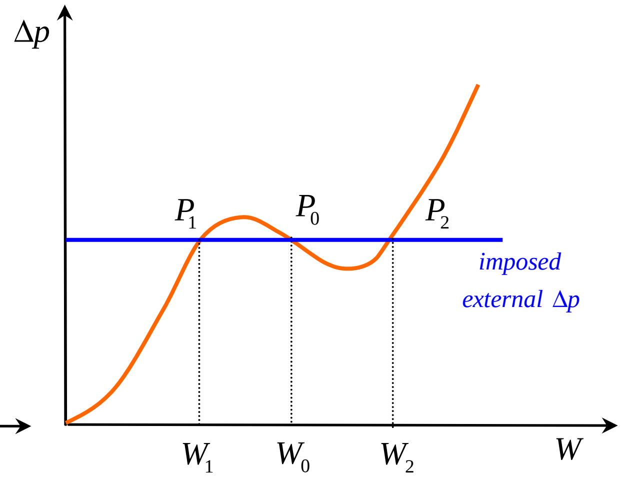
# Basic mechanisms of flow instability

## Static Ledinegg type instability (cont'd)

**Different boundary conditions may result in different stability characteristics:**

- **an imposed flow condition (e.g., positive displacement pump) always stabilizes the system**
- **an imposed external pressure drop condition (single channel in a bunch of many) may make the system unstable**




**In the latter case, the system drifts from the unstable $P_0$ point to either $P_1$ or $P_2$, which are stable**

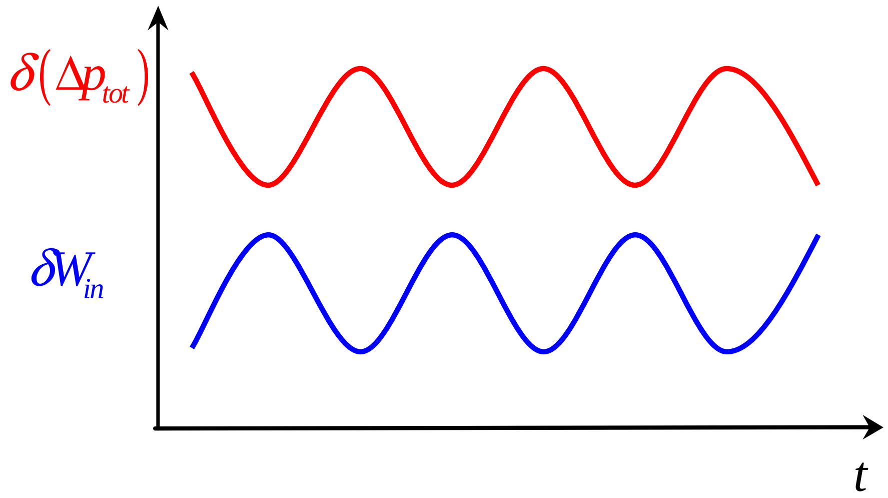
# Basic mechanisms of flow instability

## Density-wave oscillations

**Unlike Ledinegg instability, density-wave oscillations represent a dynamic phenomenon, i.e., their occurrence depends on the dynamic characteristics of the systems**

**Simplified Rational Explanation:**

**If sinusoidal flow perturbations having different frequency are applied to the system, for a given frequency the perturbation in pressure drop may be out-of-phase with the flow perturbation → THE PERTURBATION IS AMPLIFIED**

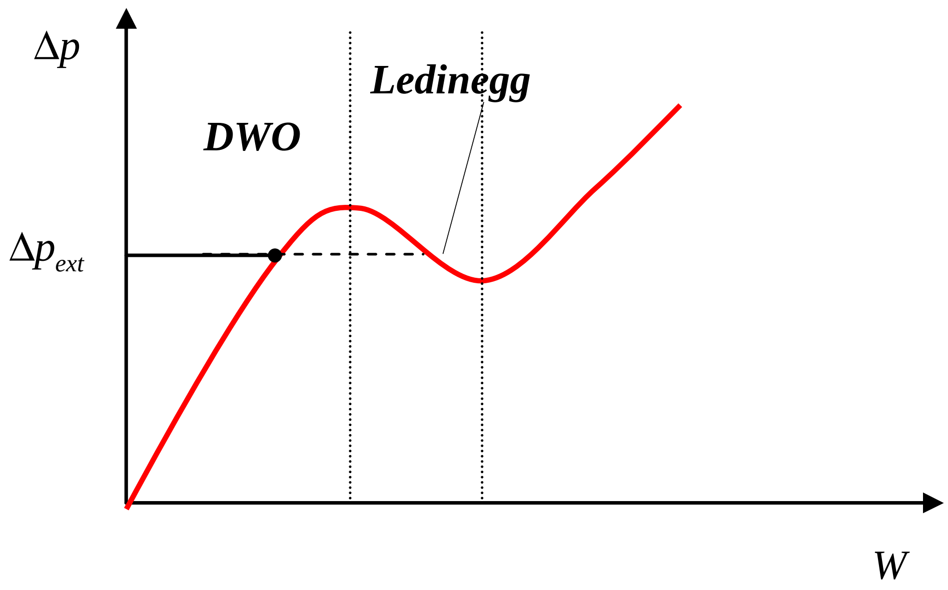


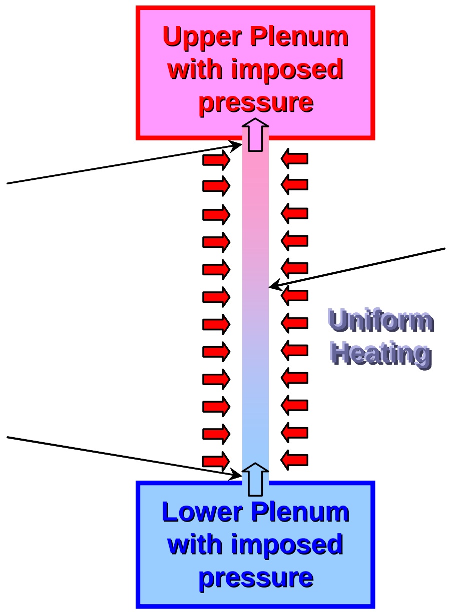

**In fact, at that frequency the system reacts as it had a negative hydraulic impedance**

**IF A SYSTEM IS UNSTABLE AT SOME SELECTED FREQUENCY IT MUST BE CONSIDERED UNSTABLE**

# Basic mechanisms of flow instability
## Density-wave oscillations

**Though the static pressure drop vs. flow rate characteristics does not help to decide if a system is stable or not under certain conditions, it identifies the region where instability may occur; i.e., for a a constant pressure drop:**



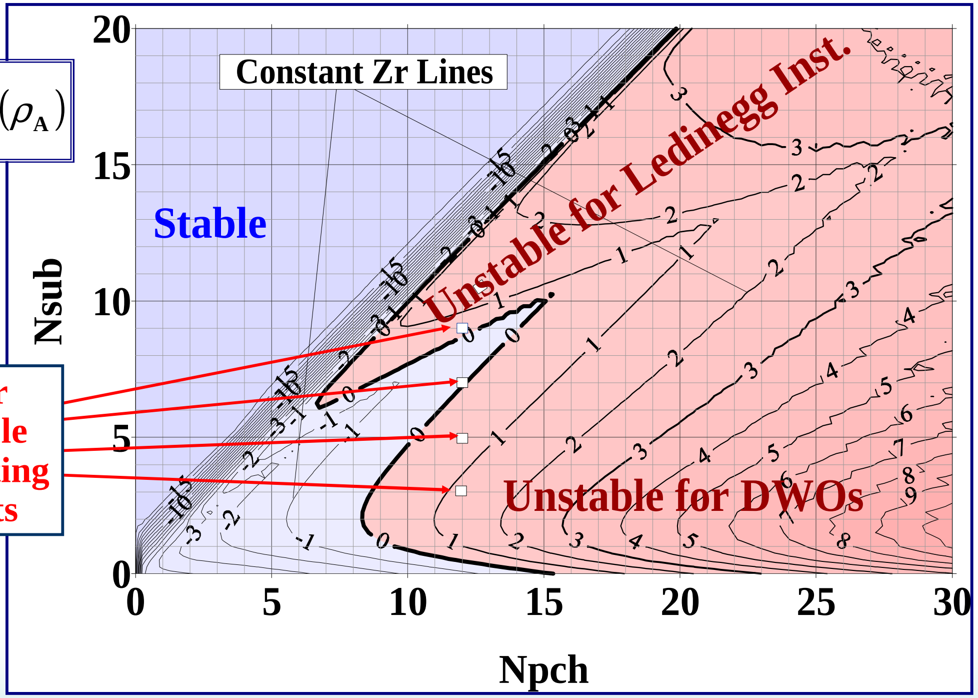
# Basic mechanisms of flow instability

## Stable and unstable behaviour in boiling channels

- **If properly linearised, the governing equations for two-phase flow may be used to provide stability maps in the Ishii-Zuber plane, i.e. the plane of the *phase change number* and the *subcooling number*, for selected values of the other dimensionless parameters (Λ, Fr, $K_{in}$, $K_{out}$, etc.)**

$$z_R = \frac{1}{\Delta t} \ln(\rho_A)$$

**Four Sample Operating Points**




$$N_{pch} = \frac{\dot{Q}}{W\, h_{lv,sat}} \frac{v_{lv,sat}}{v_{l,sat}}$$

**Dimensionless power-to-flow ratio**

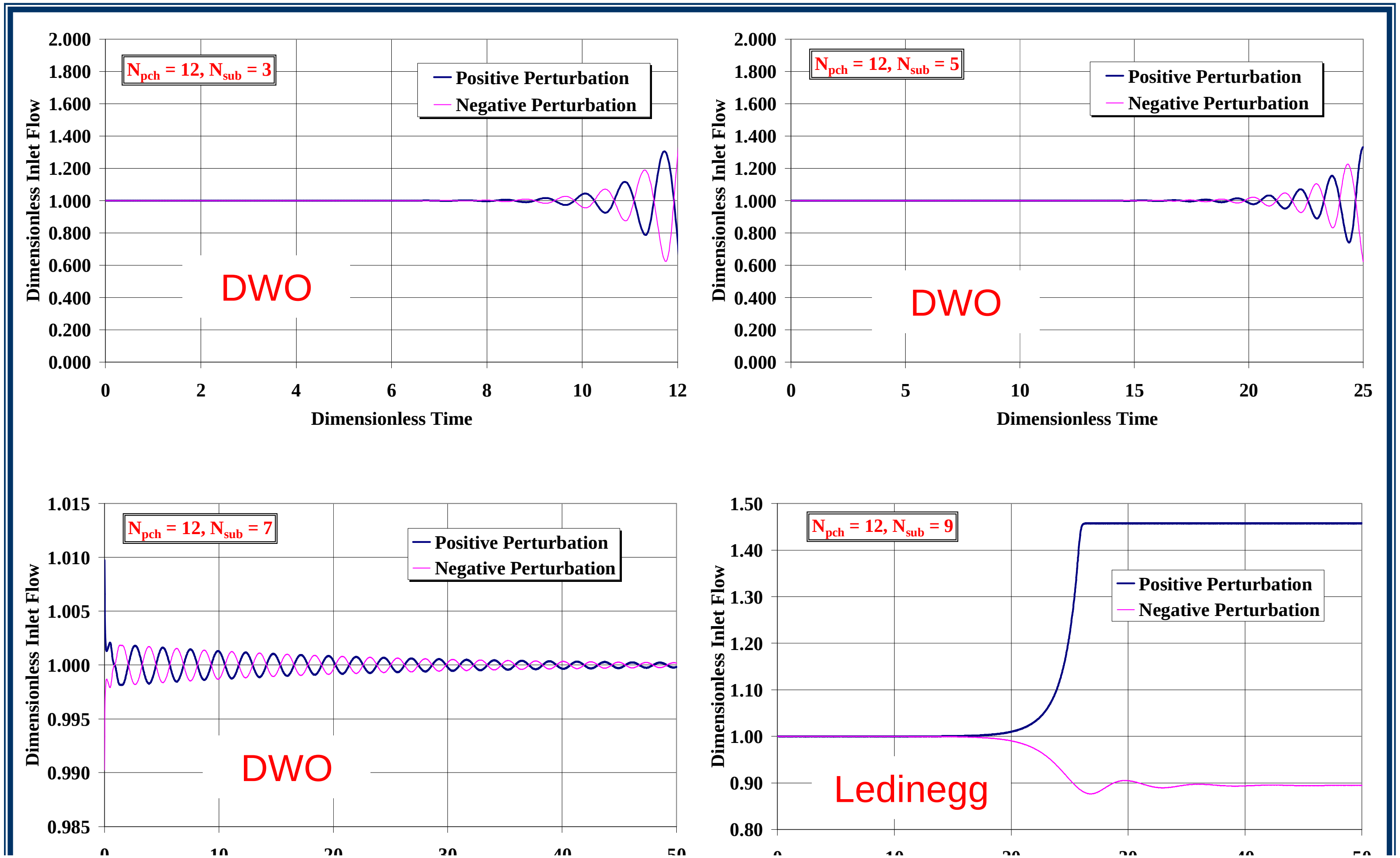
$$N_{sub} = \frac{h_{l,sat} - h_{in}}{h_{lv,sat}} \frac{v_{lv,sat}}{v_{l,sat}}$$

**Dimensionless degree of subcooling**

**In this figure, $Z_R$ is a dimensionless amplification factor positive for unstable and negative for stable conditions**

# Basic mechanisms of flow instability

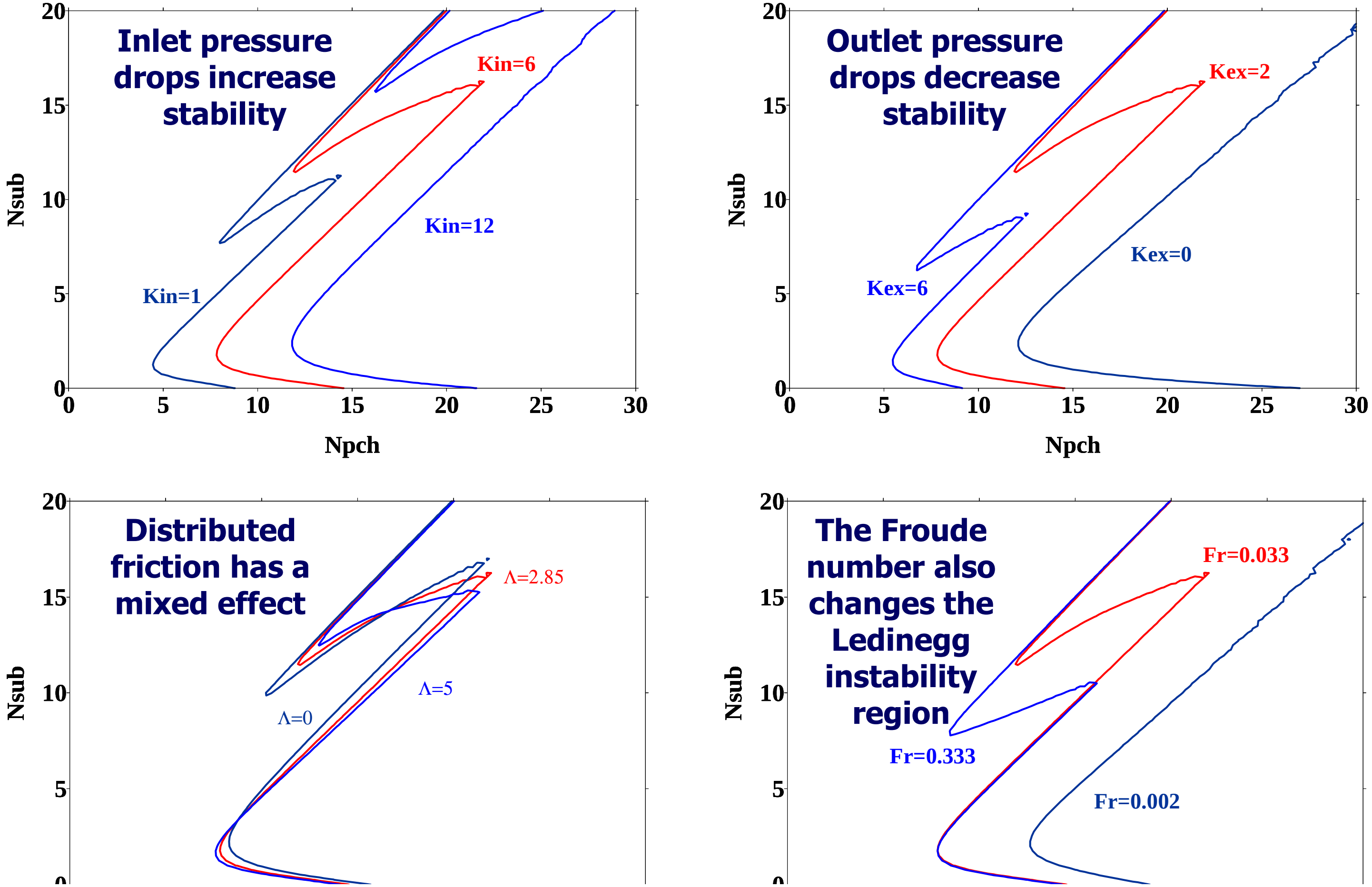
## Stable and unstable behaviour in boiling channels




**See the definition of the operating points in the previous page**

# Basic mechanisms of flow instability

## Parametric effects for boiling instabilities



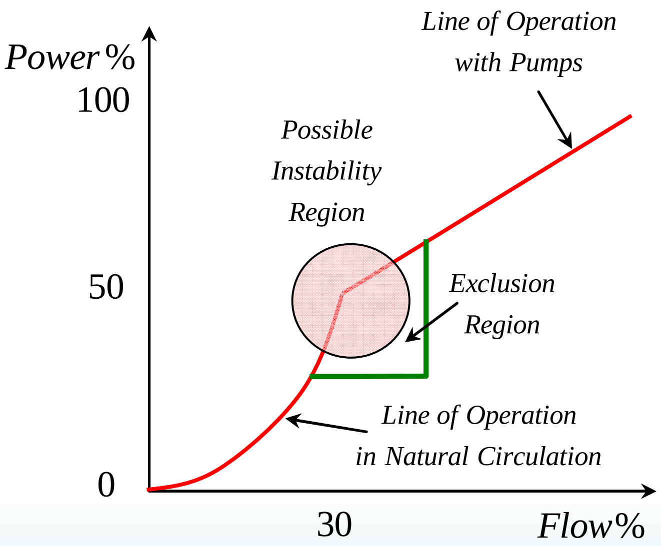
# Basic mechanisms of flow instability

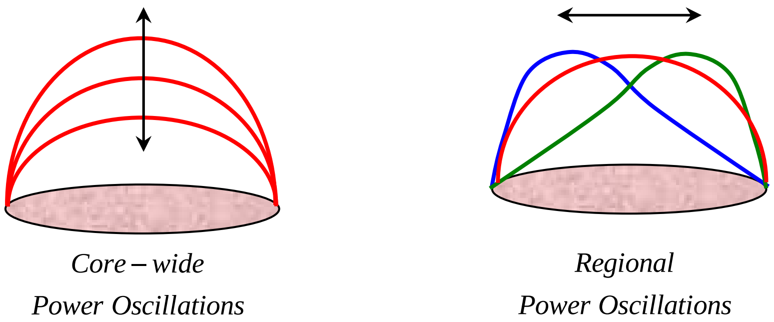
## Coupled neutronic and thermal-hydraulic effects

**Harmonic modes of neutron distribution in BWR cores**

$$\nabla^2 \varphi_n + B_n^2 \varphi_n = 0$$

**may change their level of subcriticality due to thermal-hydraulic feedback, resulting in CORE WIDE or OUT-OF-PHASE (regional) power oscillations, triggered by density waves, at relatively high power-to-flow ratios**




**when the fundamental mode is the most unstable**

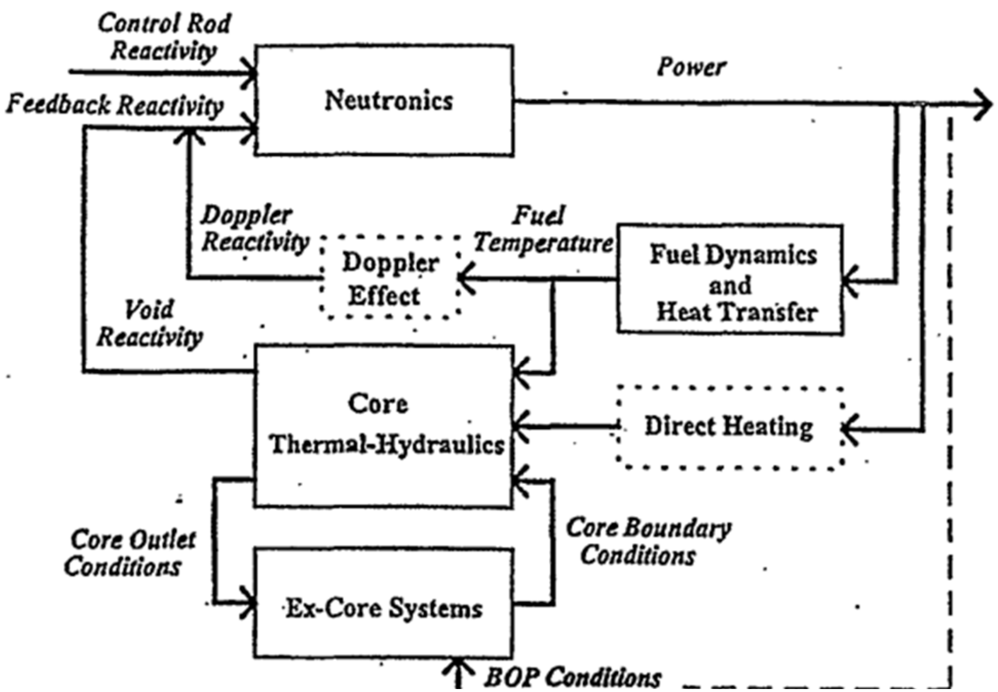
**when higher order modes are most unstable**

# Basic mechanisms of flow instability

## Coupled neutronic and thermal-hydraulic effects

**A functional sketch of the interaction between thermal-hydraulic and neutronic effects in reactor cores is reported hereafter.**

**This is also a sketch of the aspects requiring a proper modelling**



# Basic mechanisms of flow instability
## SCWR phenomena

- **Stability is addressed as an issue of great importance for SCWR design**
- **Heated channels with supercritical pressure fluids are assumed to be susceptible to similar instability phenomena as observed in boiling channels**
- **The transition across the pseudocritical temperature can be considered as a sort of "pseudo-boiling" phenomenon, giving rise to denser fluid at channel inlet and lighter one at the outlet**
- **This is one of the reasons why the basic understanding and the numerical tools developed for two-phase flow instabilities are found immediately available for being converted into understanding and numerical tools to be applied to supercritical pressure instabilities**
- **The scarcity of relevant experimental data on instabilities in supercritical pressure systems is presently a problem to be coped with in order to ascertain that this process of knowledge transfer from one research field to another is made without forgetting any important difference**

# Tools for predicting unstable behaviour
## Governing equations

**While two-phase flow models must be used for the thermal-hydraulic analyses of BWR stability, single-phase flow governing equations with allowance for strong property changes are sufficient for SCWRs**

$$\frac{\partial \rho}{\partial t} + \frac{\partial \rho w}{\partial z} = 0$$

$$\frac{\partial \rho w}{\partial t} + \frac{\partial \rho w^2}{\partial z} + \frac{\partial p}{\partial z} = -\rho g - \left[\frac{f}{D_{\mathrm{h}}} + K_{\mathrm{in}}\delta_{\mathrm{d}}(z) + K_{\mathrm{ex}}\delta_{\mathrm{d}}(z - L)\right]\frac{\rho w^2}{2}$$

$$\frac{\partial \rho h}{\partial t} + \frac{\partial \rho h w}{\partial z} = q_0'' \frac{\Pi_{\mathrm{h}}}{A}$$

**This remarkable simplification should not mislead:**

- **the heavy (liquid-like) and light (gas-like) fluid may be unevenly distributed in the channel cross section giving rise to buoyancy phenomena affecting transfers in a complex way**
- **specific constitutive laws are required (and still under development) to represent supercritical fluid phenomena**

**So, a complex behaviour is anyway expected even if the governing equations are simpler with respect to the two-phase flow case**

# Tools for predicting unstable behaviour
## General classification

**"Codes" is the name adopted for complex computer programs adopted in nuclear reactor analysis**

- **Time domain codes**

  **They are based on some kind of numerical discretisation and integration in time**

  **They are suitable for predicting the transient behaviour in a free or forced evolution of a system, even beyond the stability limit**

  **They are affected at different extent by truncation error effects**

- **Frequency domain codes**

  **They are so called because they are based on linearised equations that are converted to transfer functions by Laplace transform**

  **They are therefore suitable to predict the stability threshold**

  **The classical control theory principles are therefore used to study stability**

  **The algebra they are based on is sometimes very cumbersome**

**Codes of both categories can be very complex addressing many real plant details (see the previous sketch of coupled effects)**

# Tools for predicting unstable behaviour
## Models and codes

**Classical two-phase flow system codes can be adopted for supercritical fluid analyses provided their property packages allow for the calculation at supercritical pressure; only the single-phase version of governing equations is obviously necessary**

**As mentioned, they should be upgraded for application at supercritical pressures by appropriate constitutive laws for heat transfer and friction**

**At the moment, classical transient codes for the safety analysis of LWRs (RELAP5, TRACE, etc.) are applied to supercritical pressures with no major numerical problem, unless the critical pressure is crossed or the operating pressure is too close to the critical one**

**In addition to heat transfer and friction, critical flow from supercritical pressure conditions is another field needing development**

# Two-phase vs. SC flow stability phenomena
## Basic reasons for similarity

- **As mentioned heated channels with boiling and supercritical fluids share a common basic feature**

**THE FLUID ENTERS THE CHANNEL AT HIGH DENSITY AND GETS OUT OF IT AT LOW DENSITY BECAUSE OF HEATING**

- **The related instability phenomena can be considered quite similar because of this basic similarity**

- **Dimensionless numbers to study stability were proposed by various Authors in similarity with the classical phase change and subcooling numbers adopted for boiling channels**

# Two-phase vs. SC flow stability phenomena
## Dimensionless numbers for SC flow stability
## Zhao et al. (2005)

**1 - "Heavy fluid" region**

$$u^* = \frac{u}{\Omega_1\lambda_1},\ z^* = \frac{z}{\lambda_1},\ \rho_A^* = \frac{\rho}{\rho_A},\ u_{in}^* = \frac{u_{in}}{\Omega_1\lambda_1},\ h^* = \frac{h}{h_{AB}},\ q'''^* = \frac{q''}{Gh_{AB}},\ P_h^* = \frac{P_h}{\lambda_1}$$

$$A_c^* = \frac{A_c}{\lambda_1^2},\ t^* = t\Omega_1,\ p^* = \frac{p}{(\Omega_1\lambda_1)^2\rho_A},\ D_e^* = \frac{D_e}{\lambda_1},\ g^* = \frac{g}{\Omega_1^2\lambda_1}$$

$$N_1 = \frac{\Omega_1\lambda_1}{u_{in}} = \frac{(h_A - h_{in})}{h_{AB}}\frac{\rho_A - \rho_B}{\rho_B} = N_{psub}$$

$$\Omega_1 = \frac{v_{AB}}{h_{AB}}\frac{q''P_h}{A_c}$$

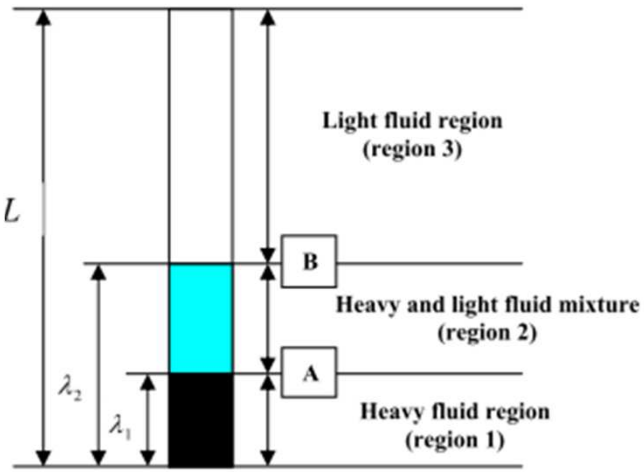
$$\frac{\partial u^*}{\partial z^*} = 0$$

$$\rho_A^*\frac{\partial h^*}{\partial t^*} + \rho_A^* u_{in}^*\frac{\partial h^*}{\partial z^*} = \frac{1}{N_1}\frac{q'''^* P_h^*}{A_c^*}$$

$$-\frac{\partial p^*}{\partial z^*} = \rho_A^*\frac{du_{in}^*}{dt^*} + f_1\frac{\rho_A^* u_{in}^{*2}}{2D_e^*} + \rho_A^* g^*$$

pseudo saturation temperatures

$$T_A = 350^o C. \qquad T_B = n_2 + \left(\frac{p - n_3}{n_1}\right)^{0.5} \text{ (Kelvin)}$$




**2 - "Heavy and light fluid mixture" region**

$$u_m^* = \frac{u_m}{\Omega_1\lambda_2},\ z^* = \frac{z}{\lambda_2},\ \rho_m^* = \frac{\rho_m}{\rho_A},\ h_m^* = \frac{h_m}{h_{AB}},\ q'''^* = \frac{q}{Gh_{AB}},\ P_h^* = \frac{P_h}{\lambda_2},\ \Omega_1^* = \frac{\Omega_1}{\Omega_1}$$

$$A_c^* = \frac{A_c}{\lambda_2^2},\ t^* = t\Omega_1,\ p^* = \frac{p}{(\Omega_1\lambda_2)^2\rho_A},\ D_e^* = \frac{D_e}{\lambda_2},\ g^* = \frac{g}{\Omega_1^2\lambda_2}$$

$$N_2 = \frac{\Omega_1\lambda_2}{u_{in}} = \frac{(h_B - h_{in})}{h_{AB}}\frac{\rho_A - \rho_B}{\rho_B} = N_1 + \frac{\rho_A - \rho_B}{\rho_B}$$

$$\frac{\partial u_m^*}{\partial z^*} = \Omega_1^*$$

$$\rho_m^*\left(\frac{\partial u_m^*}{\partial t^*} + u_m^*\frac{\partial u_m^*}{\partial z^*}\right) = -\frac{\partial p_m^*}{\partial z^*} - f_2\frac{\rho_A^* u_m^{*2}}{2D_e^*} - \rho_m^* g^*$$

$$\rho_m^*\left(\frac{\partial h_m^*}{\partial t^*} + u_m^*\frac{\partial h_m^*}{\partial z^*}\right) = \frac{1}{N_2}q^*$$

# Two-phase vs. SC flow stability phenomena
## Dimensionless numbers for SC flow stability
## Zhao et al. (2005)

**3 - "Light fluid" region**

$$u^* = \frac{u}{\Omega_2 L},\; z^* = \frac{z}{L},\; \rho^* = \frac{\rho}{\rho_A},\; h^* = \frac{h}{h_{AB}},\; q'''^* = \frac{q''}{G h_{AB}},\; P_h^* = \frac{P_h}{L},\; \Omega_2^* = \frac{\Omega_2}{\Omega_2}$$

$$A_c^* = \frac{A_c}{L^2},\; t^* = t\Omega_2,\; p^* = \frac{p}{(\Omega_2 L)^2 \rho_A},\; D_e^* = \frac{D_e}{L},\; g^* = \frac{g}{\Omega_2^2 L}$$

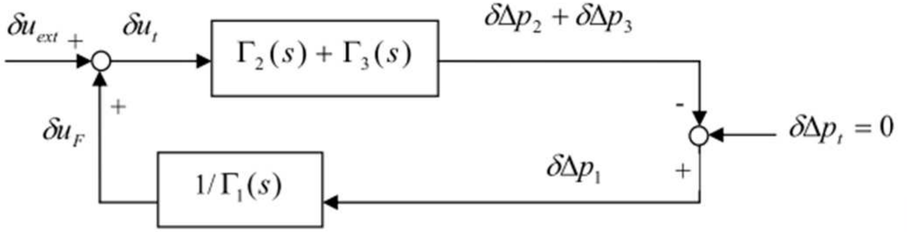
$$\Omega_2 = \frac{R}{p c_p}\frac{q'' P_h}{A_c} \qquad N_3 = \frac{\Omega_2 L}{u_{in}} = \frac{R}{p c_p}\frac{q'' P_h}{A_c}\frac{L}{u_{in}} = N_{exp}$$

$$\frac{\partial u^*}{\partial z^*} = \Omega_2^*$$

$$\rho^*\left(\frac{\partial u^*}{\partial t^*} + u^*\frac{\partial u^*}{\partial z^*}\right) = -\frac{\partial p^*}{\partial z^*} - f_3\frac{\rho_f^* u^{*2}}{2D_e^*} - \rho^* g^*$$

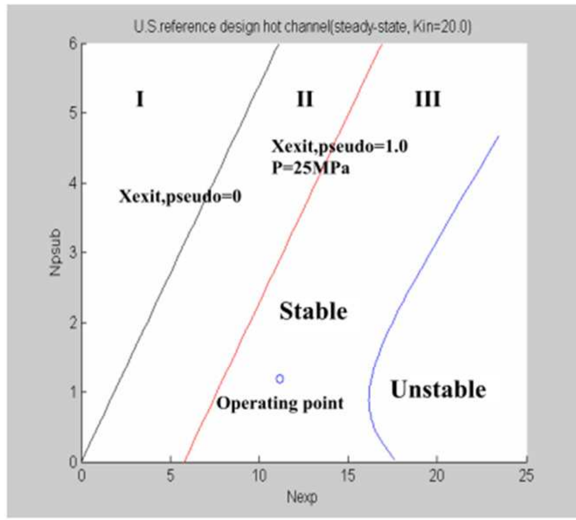
$$\rho^*\left(\frac{\partial h^*}{\partial t^*} + u^*\frac{\partial h^*}{\partial z^*}\right) = \frac{1}{N_3} q_w'''^*$$

- **Feedback loop of the transfer functions for the pressure drops in the three regions**




- **Typical stability map**

U.S. reference SCWR design for hot channel



# Two-phase vs. SC flow stability phenomena
## Dimensionless numbers for SC flow stability
## Ortega Gómez et al. (2006)

- **These authors propose two dimensionless numbers similar to the ones adopted for boiling channels**

$$z^* = \frac{z}{L}, \qquad g^*_{eff} = \frac{g_{eff}}{\overline{\Omega}^2_\rho L}, \qquad t^* = t\overline{\Omega}_\rho.$$

$$\overline{q}''^* = \frac{\overline{q}''}{\rho_{inlet} u_{inlet} h_{inlet}}, \quad P^*_H = \frac{P_H}{L}, \quad u^* = \frac{u}{\overline{\Omega}_\rho L};$$

$$A^*_{x-s} = \frac{A_{x-s}}{L^2}, \ \rho^* = \frac{\rho}{\rho_{inlet}}, \ v^* = \frac{v}{v_{inlet}}, \ D^*_H = \frac{D_H}{L}.$$

$$h^* = \frac{h}{h_{inlet}}, \ \Omega^*_\rho = \frac{\Omega_\rho}{\overline{\Omega}_\rho}, \ p^* = \frac{p}{\overline{\Omega}^2_\rho L^2 \rho_{inlet}};$$

$$N = \frac{\overline{\Omega}_\rho L}{u_{inlet}} \tag{2e}$$

$$N_{P-PCH} = \frac{\overline{\Omega}_\rho L_H}{u_{inlet}} = \frac{\left[v(L_H) - v_{inlet}\right]}{v_{inlet}} = \frac{\left[u(L_H) - u_{inlet}\right]}{u_{inlet}}$$

$$N_{P-SUB} = \frac{\overline{\Omega}_\rho \lambda}{u_{inlet}} = \frac{\left[v(L_H) - v_{inlet}\right]\lambda}{v_{inlet} L_H} = \frac{\left[u(L_H) - u_{inlet}\right]\lambda}{u_{inlet} L_H} = N_{P-PCH}\frac{\lambda}{L_H}$$

Continuity Equation [see Appendix-I]:

$$\frac{\partial u^*}{\partial z^*} = \Omega^*_\rho$$

Momentum Equation:

$$\rho^*\left[\frac{\partial u^*}{\partial t^*} + u^*\frac{\partial u^*}{\partial z^*}\right] = -\frac{\partial p^*}{\partial z^*} - f\frac{\rho^*(u^*)^2}{2D^*_H} - \rho^* g^*_{eff}$$

Energy Equation:

$$\rho^*\left[\frac{\partial h^*}{\partial t^*} + u^*\frac{\partial h^*}{\partial z^*}\right] = \frac{(\overline{q}'')^* P^*_H}{A^*_{x-s} N}$$

State Equation:

$$\rho^* = \rho^*(h^*) = \frac{1}{v^*(h^*)}$$

$$\overline{\Omega}_\rho = \frac{\left[u(L_H) - u_{inlet}\right]}{L_H}$$

$L = \lambda$ is where $T_{bulk} = 350°C$

# Two-phase vs. SC flow stability phenomena
## Dimensionless numbers for SC flow stability
## Ortega Gómez et al. (2006)

- **The balance equations are discretised by FEMLAB**

$$\underline{\underline{A}}\frac{\partial \underline{\Psi}}{\partial t}+\underline{\underline{B}}\frac{\partial \underline{\Psi}}{\partial z}=\underline{c}$$

- **Typical stability map**

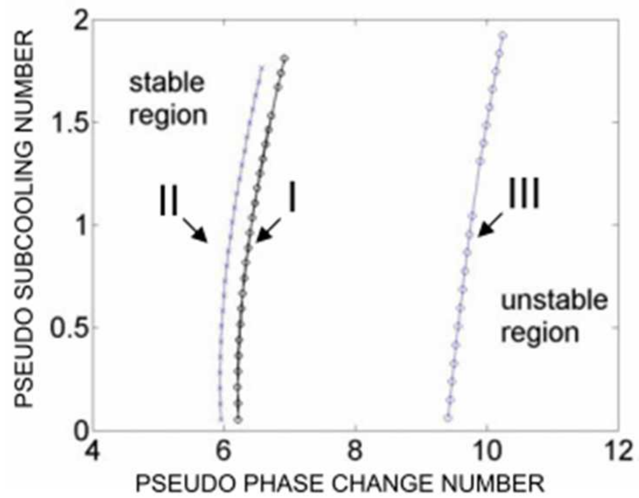



FIGURE 8: LINEAR STABILITY MAP FOR A UNIFORMLY HEATED PIPE AT SUPERCRITICAL WATER PRESSURE, 25MPa (LINE I: NO INLET OR EXIT LOSSES; LINE II: WITH EXIT LOSS, 0.5; LINE III: WITH INLET LOSS, 50.)

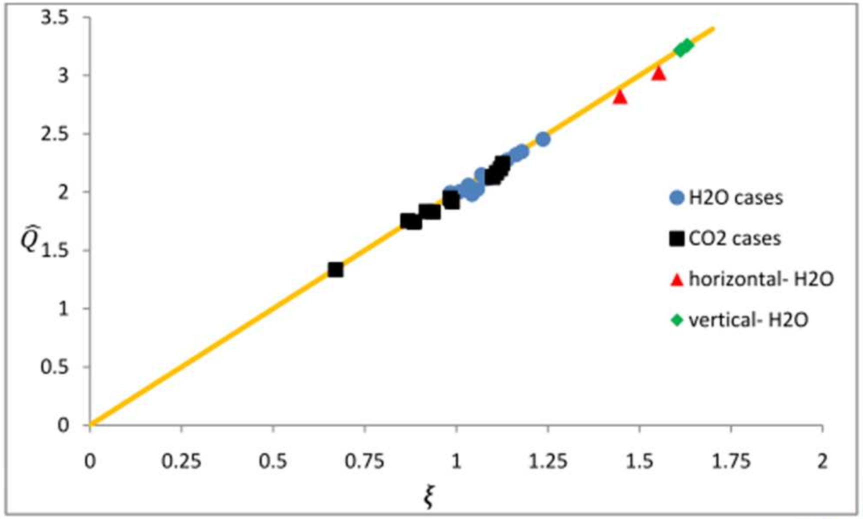
# Two-phase vs. SC flow stability phenomena
## Dimensionless numbers for SC flow stability
## Yeylaghi et al. (2011)

- **The Authors use a very compact and simple dimensionless formalism derived from balance equations applied in the prediction of static instabilities**

$$\hat{Q} = 2\xi \qquad \hat{Q} = \frac{Q\theta_e}{GA} \qquad \theta_e = -\frac{1}{\rho_e}\frac{\partial \rho_e}{\partial h_e} \qquad \xi = \left(1 - \frac{\rho_e}{\rho_i}\right) + \frac{\rho_e}{2}\left(\frac{1}{G}\frac{\partial p_e}{\partial G}\right)$$

**(*e = exit, i = inlet*)**

- **Typical results show a very successful prediction of stability boundaries, for different fluids and also for different channel orientations**
- **The outlet temperature at the onset of excursive instabilities is also found close to the pseudocritical value**



# Two-phase vs. SC flow stability phenomena
# Dimensionless numbers for SC flow stability
# Ambrosini and Sharabi (2006)

- **In analogy with the case of the boiling channel, the following dimensionless parameters were introduced (Ambrosini and Sharabi, ICONE14, 2006):**

$$\rho^* = \frac{\rho}{\rho_f} \to \rho^* = \frac{\rho}{\rho_{pc}}$$

$$h^* = \frac{h - h_f}{h_{fg}} \frac{v_{fg}}{v_f} \to h^* = \frac{1}{v_{pc}} \left(\frac{\partial v}{\partial h}\right)_{p,pc} (h - h_{pc}) = \frac{\beta_{pc}}{C_{p,pc}} (h - h_{pc})$$

$$p^* = \frac{p}{\rho_f w_{in}^2} \to p^* = \frac{p}{\rho_{pc} w_{in}^2}$$

$$N_{sub} = \frac{h_f - h_{in}}{h_{fg}} \frac{v_{fg}}{v_f} \to N_{SPC} = \frac{\beta_{pc}}{C_{p,pc}} (h_{pc} - h_{in})$$

$$N_{pch} = \frac{q_0'' \Pi_h L}{\rho_f w_{in} h_{fg} A} \frac{v_{fg}}{v_f} \to N'_{TPC} = \frac{q_0'' \Pi_h L}{\rho_{pc} w_{in} A} \frac{\beta_{pc}}{C_{p,pc}}$$

$$N_{TPC} = \frac{N'_{TPC}}{\rho^*_{in}} = \frac{q_0'' \Pi_h L}{\rho_{in} w_{in} A} \frac{\beta_{pc}}{C_{p,pc}}$$

- **These definitions do not need introducing any fictitious pseudo-saturated state and make reference to the single thermodynamic state that really matters in supercritical fluids: the pseudocritical point**

# Two-phase vs. SC flow stability phenomena
# Dimensionless numbers for SC flow stability
# Ambrosini and Sharabi (2006)

**The 1D dimensionless balance equations therefore become**

$$\frac{\partial \rho^*}{\partial t^*} + \frac{\partial \rho^* w^*}{\partial z^*} = 0$$

$$\frac{\partial \rho^* w^*}{\partial t^*} + \frac{\partial \rho^* w^{*2}}{\partial z^*} + \frac{\partial p^*}{\partial z^*} = -\frac{\rho^*}{Fr} - \left[ \Lambda + K_{in} \delta^*(z^*) + K_{ex} \delta^*(z^* - 1) \right] \rho^* w^{*2}$$

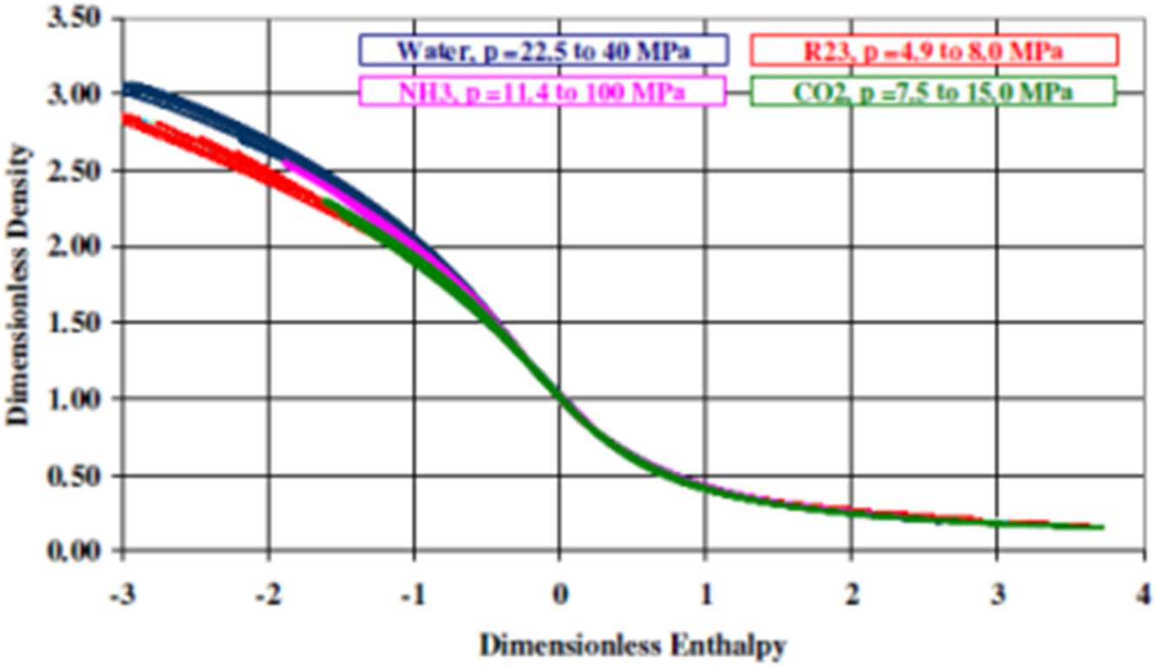
$$\frac{\partial \rho^* h^*}{\partial t^*} + \frac{\partial \rho^* w^* h^*}{\partial z^*} = N'_{TPC} f_q^*(z^*)$$

**with the inlet boundary condition**

$$h_{in}^* = \frac{\beta_{pc}}{C_{p,pc}} \left( h_{in} - h_{pc} \right) = -N_{SPC}$$

# Two-phase vs. SC flow stability phenomena
## Dimensionless numbers for SC flow stability
## Ambrosini and Sharabi (2006)

**One of the useful features of the definition of dimensionless density is its capability to collapse all the trends as a function of dimensionless enthalpy nearly into a single line no matter the pressure**



# Two-phase vs. SC flow stability phenomena
## Dimensionless numbers for SC flow stability
## Ambrosini and Sharabi (2006)

**The trans-pseudocritical number is defined as**

$$N_{TPC} = N'_{TPC} \Big/ \rho_{in}^{*} = \frac{q_0'' \Pi_h L}{\rho_{in} w_0 A} \frac{\beta_{pc}}{C_{p,pc}}$$

**having the meaning of a power-to-flow dimensionless ratio; in fact, it is:**

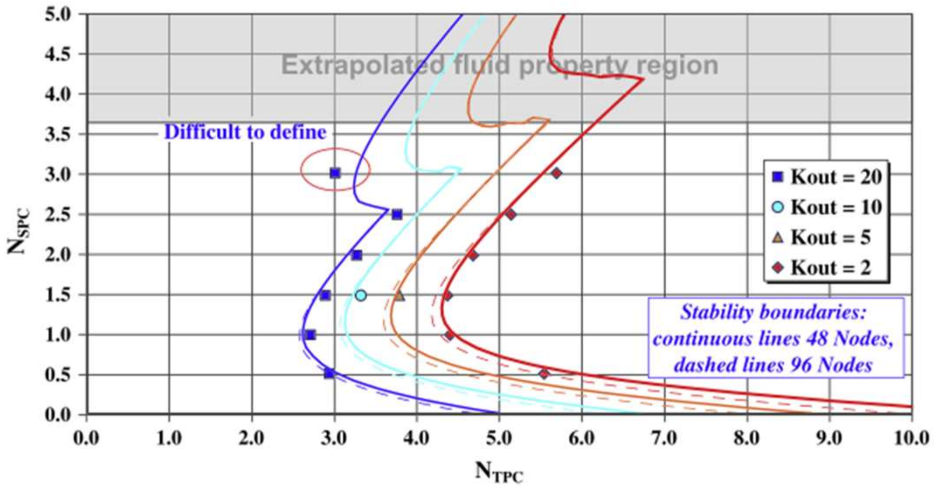
$$N_{TPC} = \frac{\dot{Q}_{channel}}{W_{channel}} \frac{\beta_{pc}}{C_{p,pc}}$$

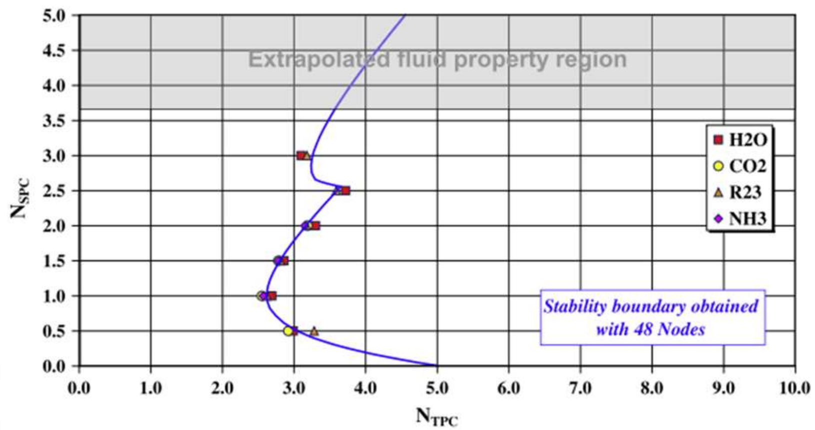
**Therefore, in similarity with boiling channels for $N_{PCH}$ and $N_{SUB}$, in the $N_{TPC}$ - $N_{SPC}$ plane the lines for which $N_{SPC} = N_{TPC}$ + const. represent the loci at constant exit dimensionless enthalpy**

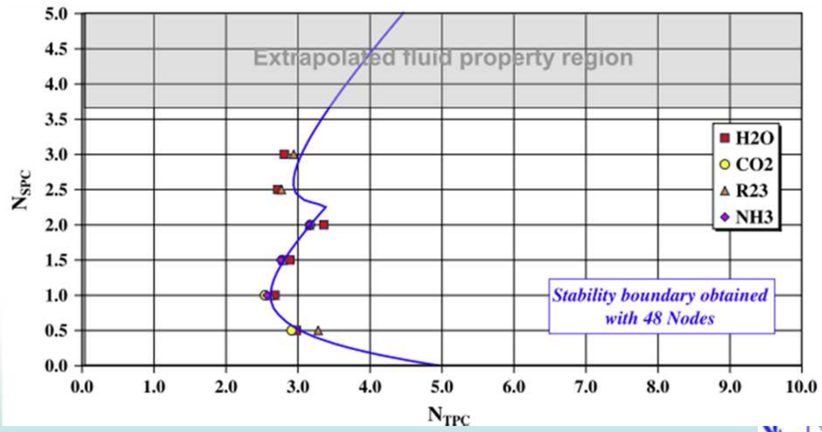
# Two-phase vs. SC flow stability phenomena
## Dimensionless numbers for SC flow stability
## Ambrosini and Sharabi (2006)

**Comparison between transient code behaviour with stability maps produced for an IAEA Code Comparison Benchmark**

**RELAP5 is used in comparison with in house codes**

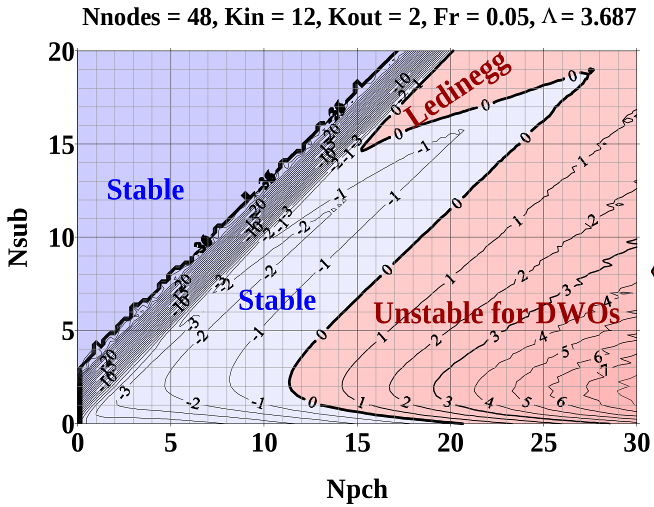



**In-house transient code and for vertical and horizontal channel**

# Two-phase vs. SC flow stability phenomena
## Comparison of Stability Maps



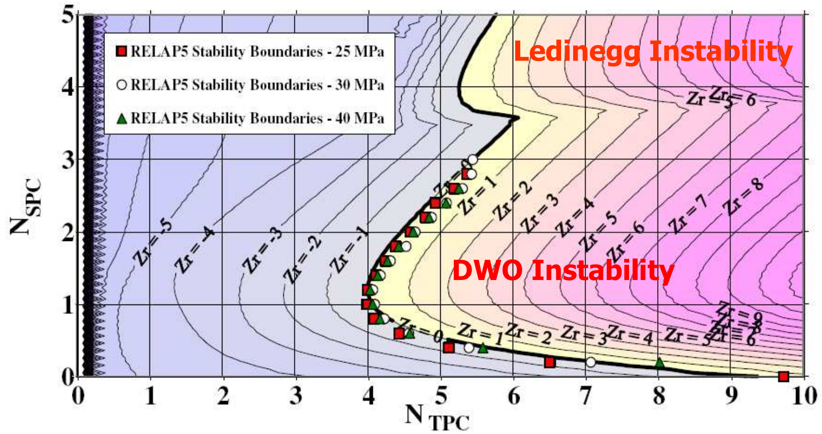



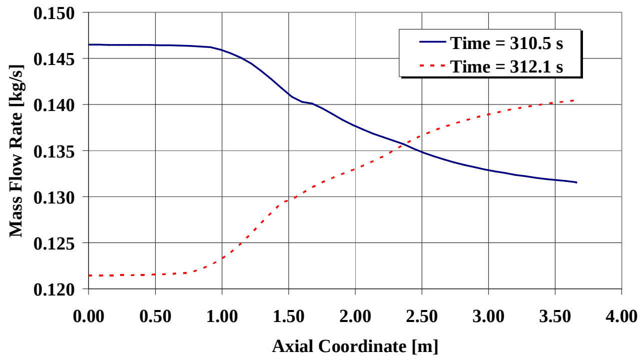

Fig. 3 *Comparison between RELAP5 stability boundaries for the nominal conditions at 25, 30 and 40 MPa and the stability map by the simplified model with 48 nodes, $\Lambda$=14, Fr=0.030, $K_{in}$=10.5, $K_{out}$=0, $C_{max}$= 0.9*

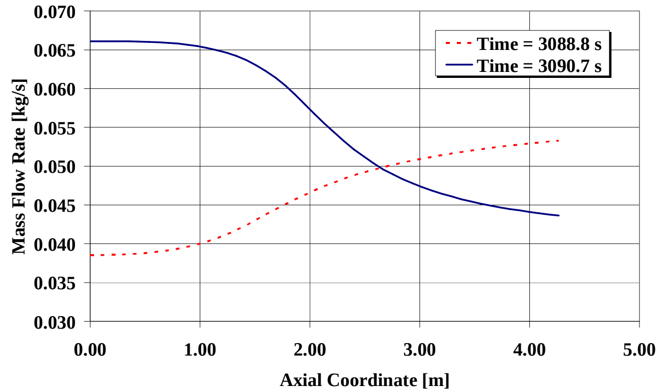
**Boiling Channels** | **Heated Channels with Supercritical Fluids**

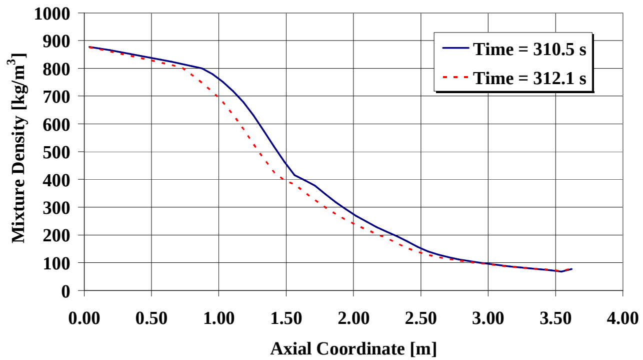
**Bearing in mind the boiling channel paradigma,**
**heated channels with supercritical fluids are also predicted to show both density-wave oscillations and Ledinegg excursive instabilities**

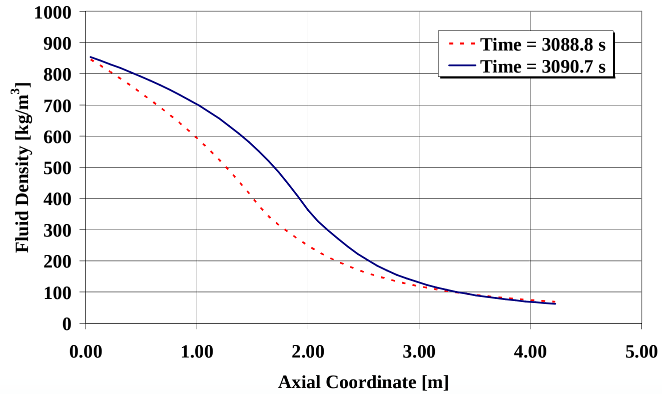
# Two-phase vs. SC flow stability phenomena
## Comparison of Transient Behaviour
## System codes

**Density waves appear as a sort of flow wave phenomenon in both cases**



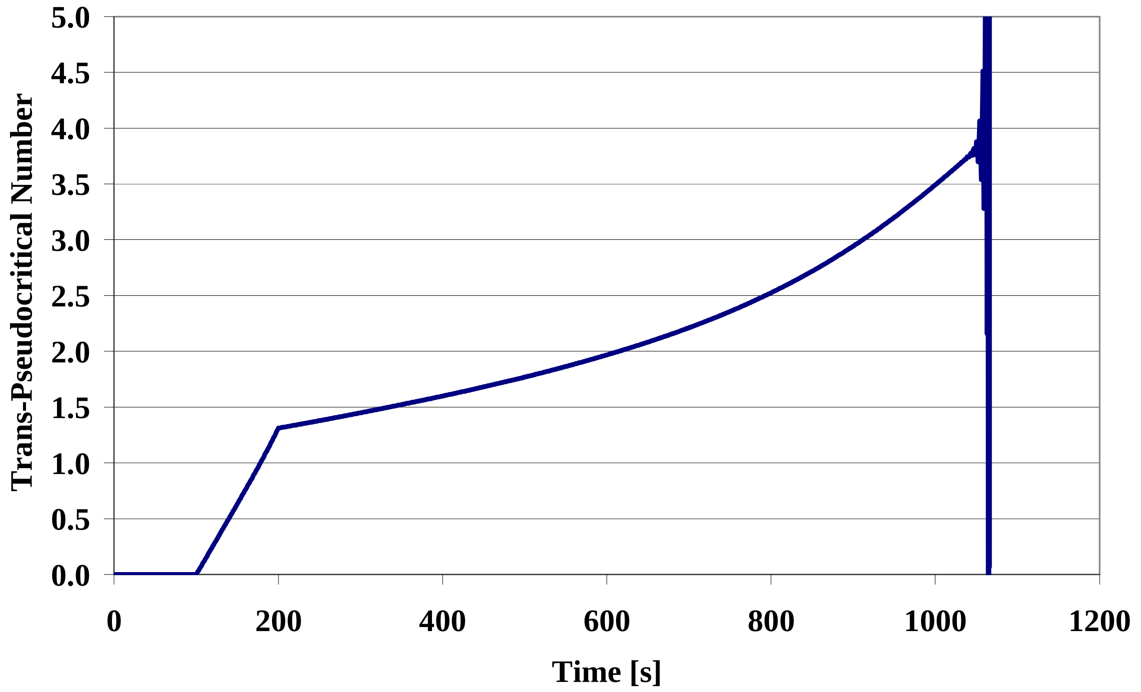




Boiling Channel

Heated Channels with Supercritical Water

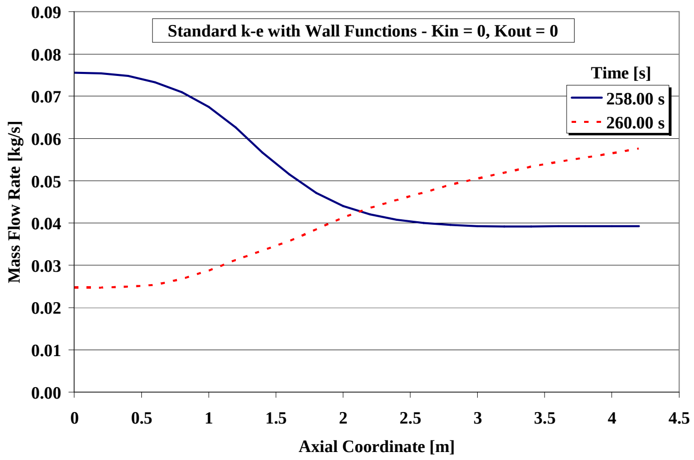
# Two-phase vs. SC flow stability phenomena
# Comparison of Transient Behaviour
# System codes

**To study stability with a system code, time histories of $N_{TPC}$ vs. time are obtained while power is slowly increased and an automatic or visual criterion is used to identify the threshold for unstable behaviour**

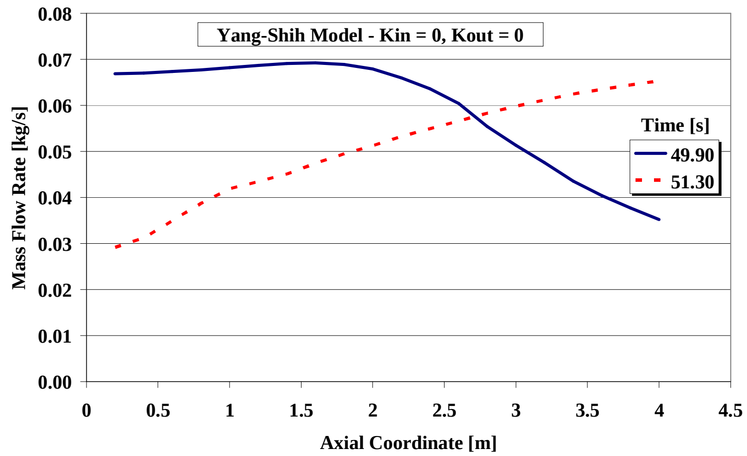


# Two-phase vs. SC flow stability phenomena
## Comparison of Transient Behaviour
## CFD Codes – Circular Pipes

**Also the FLUENT code was applied to study density wave oscillation instabilities**




**k-ε with wall functions**

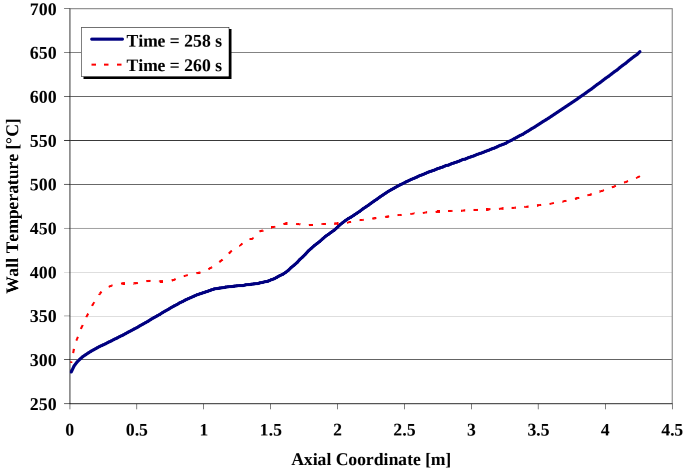


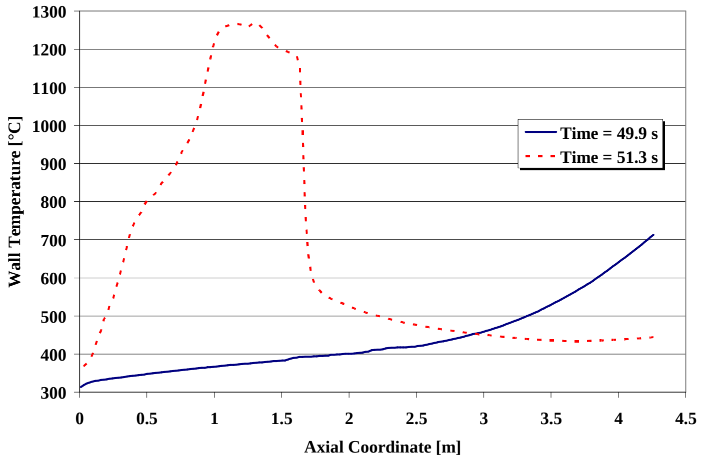

**low-Re Yang & Shih model**

**Both models show swings of flow rate distribution similar to those predicted by 1D codes:**

**<u>again, the global instability mechanism appears the same</u>**

# Two-phase vs. SC flow stability phenomena
# Comparison of Transient Behaviour
# CFD Codes – Circular Pipes




**k-ε with wall functions**

**Yang & Shih model**

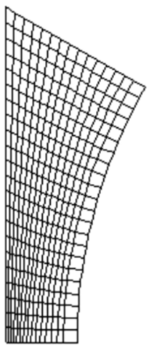
**A major difference is found in the capability of the low-Re model to identify heat transfer deterioration during oscillations:**

**<u>wall functions cannot catch the occurrence of this phenomenon</u>**

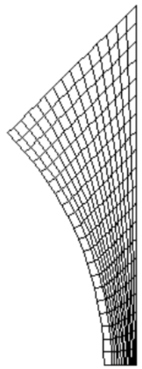
**that resembles Boiling Transition occurring during instabilities in BWRs**

# Two-phase vs. SC flow stability phenomena
## Comparison of Transient Behaviour
## CFD Codes – Fuel Bundle Slices

**The standard k-ε model of FLUENT was used with wall functions addressing the following cases**



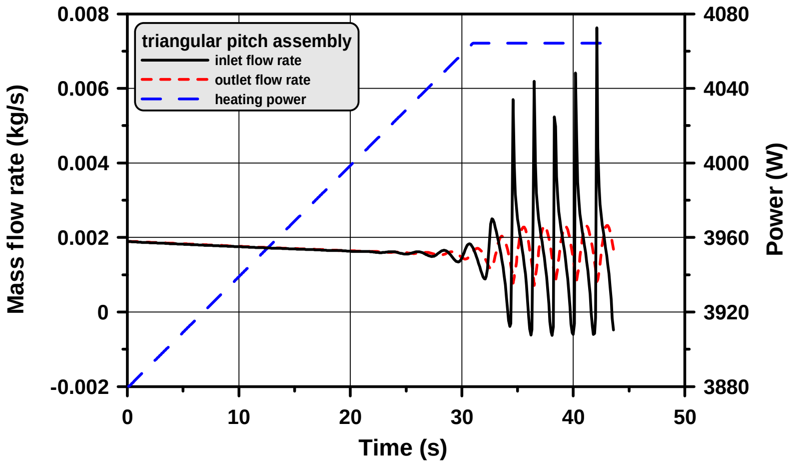
for the triangular pitch subchannel:
- rod diameter: 7.6 mm;
- pitch: 8.664 mm;
- active height: 3 m.

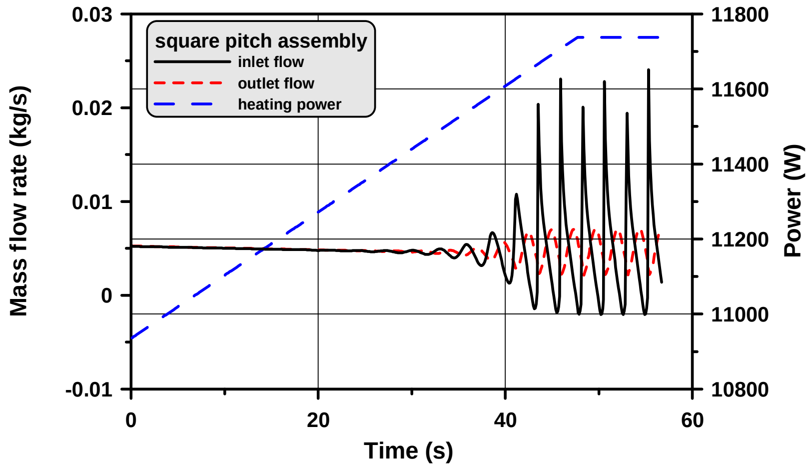


for the square pitch subchannel:
- rod diameter : 10.2 mm;
- pitch: 11.2 mm;
- active height: 4.2 m;

# Two-phase vs. SC flow stability phenomena
## Comparison of Transient Behaviour
## CFD Codes – Fuel Bundle Slices

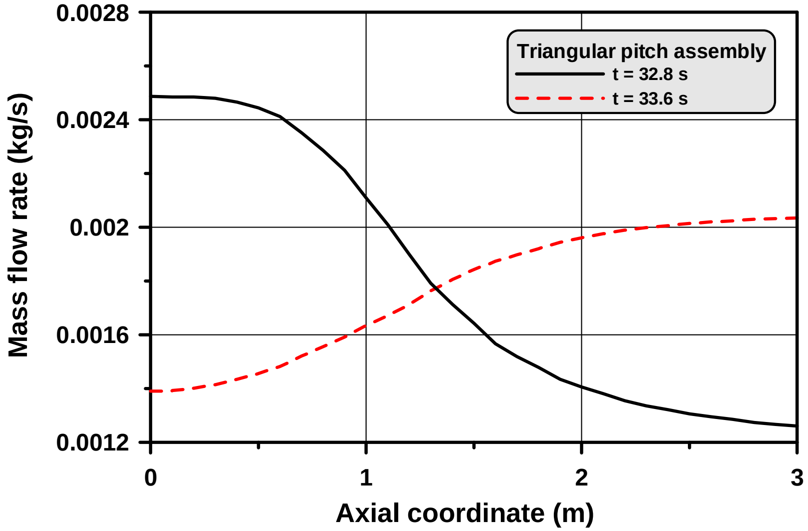
**By raising the power to appropriate levels, while keeping constant the pressure drop across the channel, unstable behaviour is observed in both cases**

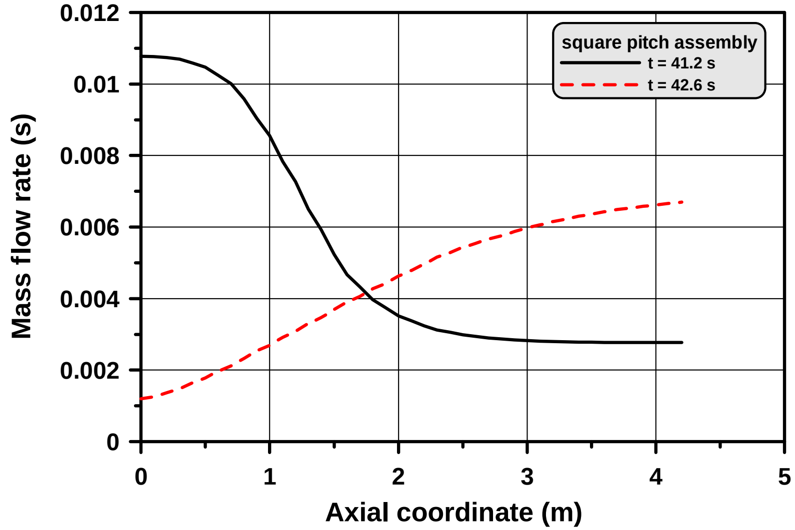


# Two-phase vs. SC flow stability phenomena
## Comparison of Transient Behaviour
## CFD Codes – Fuel Bundle Slices

**The same mechanism of flow oscillations is observed as in the case of circular pipes**




**AGAIN, IT SEEMS THAT THE OVERALL INSTABILITY MECHANISM IS SIMILAR AS PREDICTED BY 1D MODELS**

# Conclusion

**Flow instabilities in supercritical pressure fluid systems are predicted in close similarity with those observed in two-phase flow**

**A plenty of tools and theories developed for boiling channel instabilities is available to be used with supercritical fluids**

**Though this lecture covered only basic aspects, in comparison with the two-phase flow case, the complexity of these tools can be considerable, including the coupling with neutronics and the different relevant reactor systems as reported in some of the works whose reading is suggested in the References**

**Experimental data are presently needed to confirm the predictions obtained by available tools**

Thank you for your attention,

Walter Ambrosini

# References

**Description of Basic Phenomena related to Boiling Channel Instabilities**

Bourè, J.A., Bergles, A.E., Tong, L.S., 1973 **"Review of Two-Phase Flow Instability“,** *Nuclear Engineering and Design*, 25, (1973), pp.165-192.

D'Auria, F., (Editor) et al., 1997 **"State-of-the-Art Report on Boiling Water Reactor Stability"**, NEA/CSNI/R(96)21, OCDE/GD(97)13, OECD/NEA Paris, 1997.

Lahey, R.T., and Moody, F.J., 1993, **"The thermalhydraulics of a boiling water reactor"**, American Nuclear Society 1993.

March-Leuba, J., and Rey, J.M., 1993 **"Coupled Thermohydraulic-Neutronic Instabilities in Boiling Water Nuclear Reactors: A Review of The State of the Art"**, *Nuclear Engineering and Design*, 145, (1993), pp. 97-111.

**Specific works mentioned in the lecture**

Ortega Gómez, T., Class, A., Lahey, R.T., Jr., Schulenberg, T., 2006 and 2008, **"Stability analysis of a uniformly heated channel with supercritical water"**, *Nuclear Engineering and Design* 238 (2008) 1930–1939. Also published in 2006 at ICONE-14.

Yeylaghi, S., Chatoorgoon, V., and Leung, L., 2011, **"Assessment of non-dimensional parameters for static instability in supercritical down-flow channels"**, The 5th Int. Sym. SCWR (ISSCWR-5), P69, Vancouver, British Columbia, Canada, March 13-16, 2011

Zhao, J., Saha, P., Kazimi, M.S., 2005. **Stability of supercritical water-cooled reactor during steady-state and sliding pressure start-up.** The 11th International Topical Meeting on Nuclear Reactor Thermal-Hydraulics (NURETH-11), Paper:

# References


<u>**Works on Supercritical Pressure Instabilities whose reading is particularly suggested**</u>

Cai, J., Ishiwatari, Y., Ikejiri, S., Oka, Y., 2009, **"Thermal and stability considerations for a supercritical water-cooled fast reactor, with downward-flow channels during power-raising phase of plant startup"**, *Nuclear Engineering and Design* 239 (2009) 665–679.

Yi, T.T., Koshizuka, S., Oka, Y., 2004. "**A linear stability analysis of supercritical water reactors, (I) thermal–hydraulic stability",** Journal of Nuclear Science and Technology 41, 1166–1175.

Yi, T.T., Koshizuka, S., Oka, Y., 2004. **"A linear stability analysis of supercritical water reactors, (II) coupled neutronic thermal–hydraulic stability",** Journal of Nuclear Science and Technology 41, 1176–1186.

Zhao, J., Saha, P., Kazimi, M.S., 2008, **"Core-wide (in-phase) stability of supercritical water-cooled reactors - I: Sensitivity to design and operating conditions"**, Nuclear Technology Volume 161, Issue 2, February 2008, Pages 108-123

Zhao, J., Saha, P., Kazimi, M.S., 2008, **"Core-wide (in-phase) stability of supercritical wayer-cooled reactors - II: Comparison with boiling water reactors"**, Nuclear Technology, Volume 161, Issue 2, February 2008, Pages 124-139

Zhao, J., Saha, P., Kazimi, M.S., 200c, **"Coupled neutronic and thermal-hydraulic out-of-phase stability of supercritical water-cooled reactors, Nuclear Technology"**, Volume 164, Issue 1, October 2008, Pages 20-33

Zuber, N., 1966, **"An analysis of thermally induced flow oscillation in the near-critical and supercritical thermal-dynamic region"**, Report no. NASA-CR-80609, General Electric Co., NY, USA.

# References

**Works by the Lecturer**

W. Ambrosini, P. Di Marco and J.C. Ferreri, **"Linear and Non-Linear Analysis of Density-Wave Instability Phenomena",** *International Journal of Heat and Technology*, Vol. 18, No. 1, 2000, pp. 27-36

W. Ambrosini, M. Sharabi, 2006 and 2008, **"Dimensionless parameters in stability analysis of heated channels with fluids at supercritical pressures"**, *Nuclear Engineering and Design* 238, (2008) 1917–1929. Also published in 2006 at ICONE-14.

W. Ambrosini **"On the analogies in the dynamic behaviour of heated channels with boiling and supercritical fluids"**, *Nuclear Engineering and Design*, Vol. 237/11 pp 1164-1174, 2007.

W. Ambrosini and M. Sharabi, **"Assessment of Stability Maps for Heated Channels with Supercritical Fluids versus the Predictions of a System Code"**, *Nuclear Engineering and Technology*, Vol. 39, No. 5, October 2007.

M. Sharabi, W. Ambrosini, S. He, J.D. Jackson **"Prediction of turbulent convective heat transfer to a fluid at supercritical pressure in square and triangular channels"**, *Annals of Nuclear Energy*, Volume 35, Issue 6, June 2008, Pages 993-1005.

M. Sharabi, W. Ambrosini, S. He, Pei-xue Jiang, Chen-ru Zhao, "**Transient 3D Stability Analysis of SCWR Rod Bundle Subchannels by a CFD Code**", ICONE-16, 16th International Conference on Nuclear Engineering, May 11-15, 2008, Orlando, Florida USA.

Walter Ambrosini, "**Discussion on the stability of heated channels with different fluids at supercritical pressures"**, *Nuclear Engineering and Design*, 239 (2009) 2952–2963.

Walter Ambrosini, **"Assessment of flow stability boundaries in a heated channel with different fluids at supercritical**