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T08 - Stability Analysis of NC Based Systems: Pressure Tube Type BWR and Stea Generators

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STABILITY ANALYSIS OF NC BASED SYSTEMS: PRESSURE TUBE TYPE BWR AND STEAM GENERATORS

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OUTLINE OF THE LECTURE T#8

- INTRODUCTION
- STABILITY ANALYSIS
- STATIC INSTABILITY
- DYNAMIC INSTABILITY
- PARAMETRIC EFFECTS ON 1-Φ DWI
- PARAMETRIC EFFECTS ON 2-Φ DWI
- NONLINEAR ANALYSIS
- NC BASED PRESSURE TUBE TYPE BWR
- STABILITY CONSIDERATIONS IN NC BASED SG
- CLOSING REMARKS ON THE DESIGN PROCEDURE OF NC BWRs

INTRODUCTION

For design and operation, it is necessary to establish the stable and unstable zones of operation of a NCS

This is usually carried out by a linear stability analysis

In many instances there is a possibility that NCSs can land in an unstable zone of operation

How do we establish the operational domain?

What kind of an oscillatory behaviour is expected in such cases?

Can secondary effects like power oscillations/premature CHF be induced?

Limit cycle can be obtained from a nonlinear analysis

Nonlinear analysis can also be used to establish the start-up procedure and the operational domain

Stability Analysis

NCSs experience a large variety of instabilities

Well-established analysis procedures do not exist for all type of instabilities

Design procedures address only the commonly observed static and dynamic instabilities

Ledinegg instability and the DWI are the commonly observed instabilities

Neutronics plays an important role in BWR stability

Hence BWRs also require

- Static analysis
- Dynamic analysis
- Both are to be neutronically coupled

Static Instability

Ledinegg instability

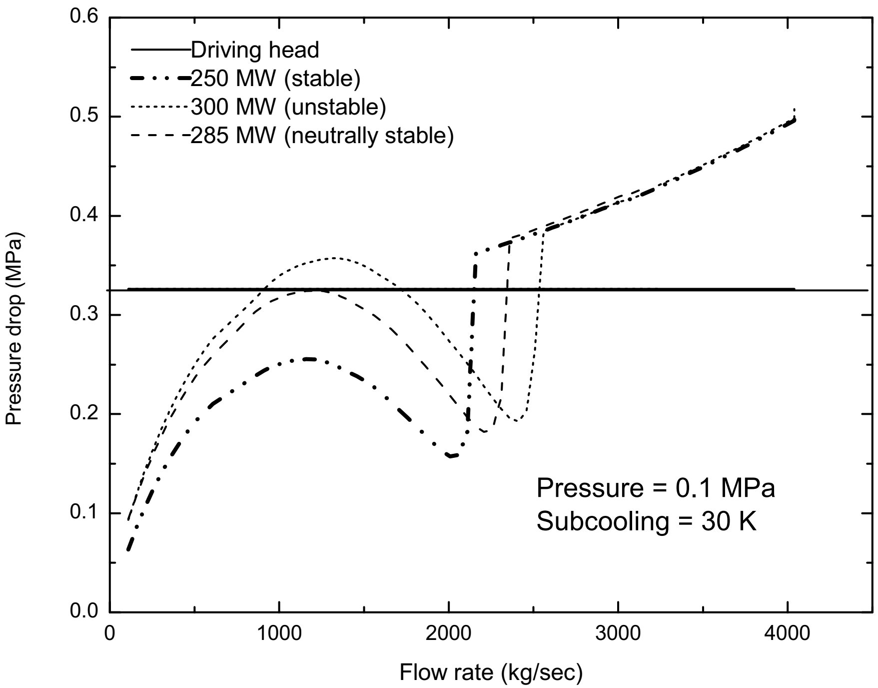


Figure illustrates the method of identification of neutrally stable condition for Ledinegg instability

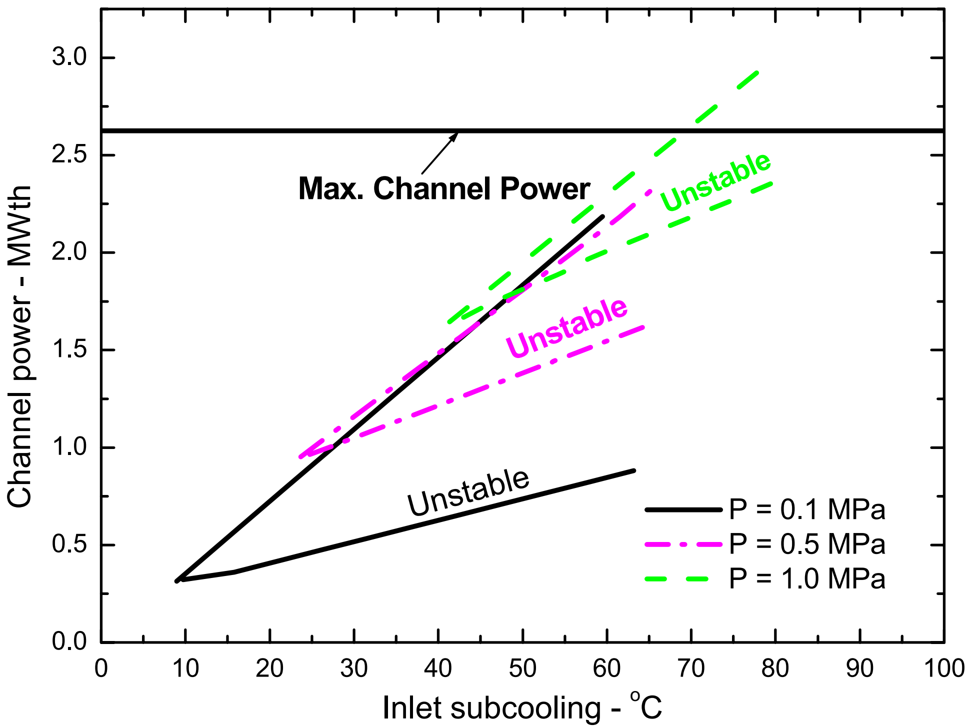
Occurrence of multiple steady states is taken as an indication of instability

Usually there exists a lower and an upper threshold of instability

The neutrally stable condition for the upper threshold can also be established in a similar way

Ledinegg instability – Contd.

The lower and the upper thresholds can be obtained in this way for other values of subcooling to generate a stability map



The instability is not observed below a critical inlet subcooling

With increase in pressure, the unstable zone contracts as well as shifts up

It is found to shift beyond the operating envelope of power beyond a certain pressure

Hence the best way to avoid this instability is to begin boiling at relatively high pressure

Dynamic Instability

Linear and Nonlinear techniques are used to analyse DWI which is the most commonly observed dynamic instability in NCSs

Linear Analysis (Frequency domain analysis)

The time dependent governing equations are perturbed over the steady state. The perturbed equations are linearised and solved analytically to obtain the characteristic equation for stability

If any of the roots of the complex characteristic equation has a positive real part, then the corresponding operating conditions are unstable.

Alternatively, stability is judged from Nyquist plots.

Coupled Neutronic Thermalhydraulic Instability

If the void reactivity coefficient is zero, then the neutronics and thermalhydraulics are decoupled and the instability threshold can be obtained from a pure thermalhydraulic model

In most BWRs, the void reactivity is significantly negative and a coupled stability analysis considering both neutronics and thermalhydraulics is essential

Several modes of power oscillation such as global (in-phase), regional (out-of-phase) and local oscillations are possible in BWRs

Global oscillations	- Point kinetics or 1-D kinetics
Regional oscillations	- 3-D kinetics
Local oscillations	- 3-D kinetics

Linear analysis of 3-D kinetics equation involve complex mathematics with a lot of approximations. Hence simpler models relying on multi point and modal kinetics are sometimes used

Linear Analysis of Two-phase NCSs

The principles of linear analysis is the same as for single-phase NC. However, the equation systems are different for the different two-phase flow models.

Starting from the HEM and progressing towards the two-fluid model a wide choice of two-phase flow models are available

Commonly used linear stability analysis codes

Name of code	Thermalhydraulic model		Neutronics model	Reference
	Channels	TPFM (Eq)		
NUFREQ NP	A few	DFM (4)	Simplified 3-D	Peng (1985)
LAPUR5	1-7	HEM (3)	P-K[1]&M-P-K[2]	Otaudy (1989)
STAIF	10	DFM (5)	1-D	Zerreßen (1987)
FABLE	24	HEM (3)	P-K[1]	Chan (1989)
ODYSY	A few	DFM (5)	1-D	D'Auria (1997)
MATSTAB	All	DFM (4)	3-D	Hănggi (1999)

[1] P-K : point kinetics; [2] M-P-K : modal point kinetics; TPFM: two-phase flow model

Nonlinear Stability Analysis

Linear analysis gives the threshold for infinitesimal disturbances whereas actual operating procedures in nuclear reactors involve finite disturbances.

Achard et al. shows that finite amplitude perturbations can cause instability on the stable side of the linear stability boundary.

Experiments suggest that both single- and two-phase instability thresholds are dependent on the operating procedures

Hence nonlinear analysis is required to establish operational domain. This is carried out by time domain codes, which solves the nonlinear PDEs using FDM

Nonlinear stability analysis is carried out just as a normal transient analysis with steady state (or any specified) initial conditions

Commonly Used Nonlinear Codes

Name of code	Thermalhydraulics model		Neutronics model	Reference
	Channels	TPFM (Eq)		
RAMONA-5	All	DFM (4 or 7)	3-D	RAMONA catalogue
RELAP5/MOD3.2	A few	TFM (6)	Point kinetics	RELAP5 (1995)
RETRAN-3D	4	Slip Eq (5)	1-D	Paulsen (1993)
TRACG	A few	TFM (6)	3-D	Takeuchi (1994)
ATHLET	A few	TFM (6)	Point kinetics	Lerchl (2000)
CATHARE	A few	TFM (6)	Point kinetics	Barre (1993)
CATHENA	A few	TFM (6)	Point kinetics	Hanna (1998)

Comparison of Linear and Nonlinear codes

Frequency domain	Time domain
Linearized PDEs	Nonlinear PDEs
Mathematical derivation of the Ch. Eqn. is very complicated	Simple technique, but tedious computations
Exact analytical solution	Approximate numerical solution
Free from numerical instability	Numerical instability is a concern
Computationally less expensive	More expensive
Best suited for generating stability map	Usually not attempted, but response can be generated
Not useful for establishing limit cycles and OD	Limit cycle and operational domain can be established

Generally both frequency domain and time domain codes are required for the complete stability analysis

Parametric Influences on single-phase DWI

For steady state flow a generalized correlation valid for any loop is possible

However, there is no universal stability map even for uniform diameter loops. For uniform diameter loops, the parametric dependence is given by

$$Stability = f\left(Gr_m, St_m, \frac{L_t}{D}, orientation, length\,scales, flow\,regime\,and\,direction\right)$$

Effect of orientation

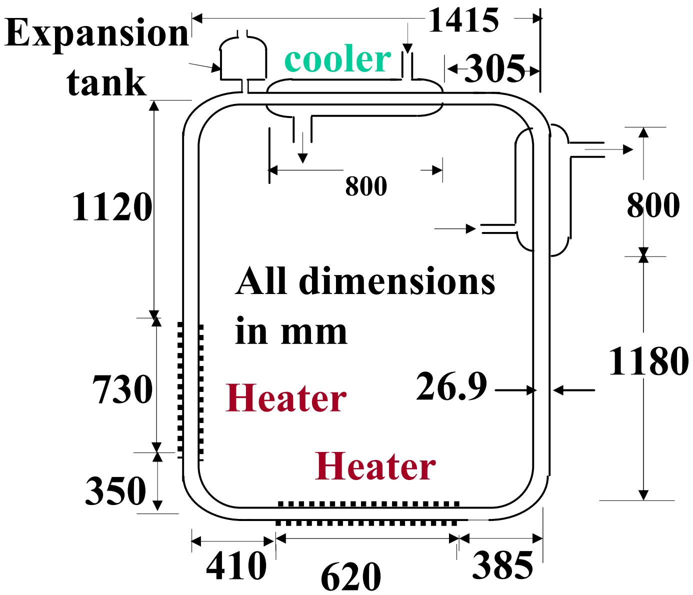
The source and sink orientation are different in different reactor systems

PWR : Both source and sink are vertical

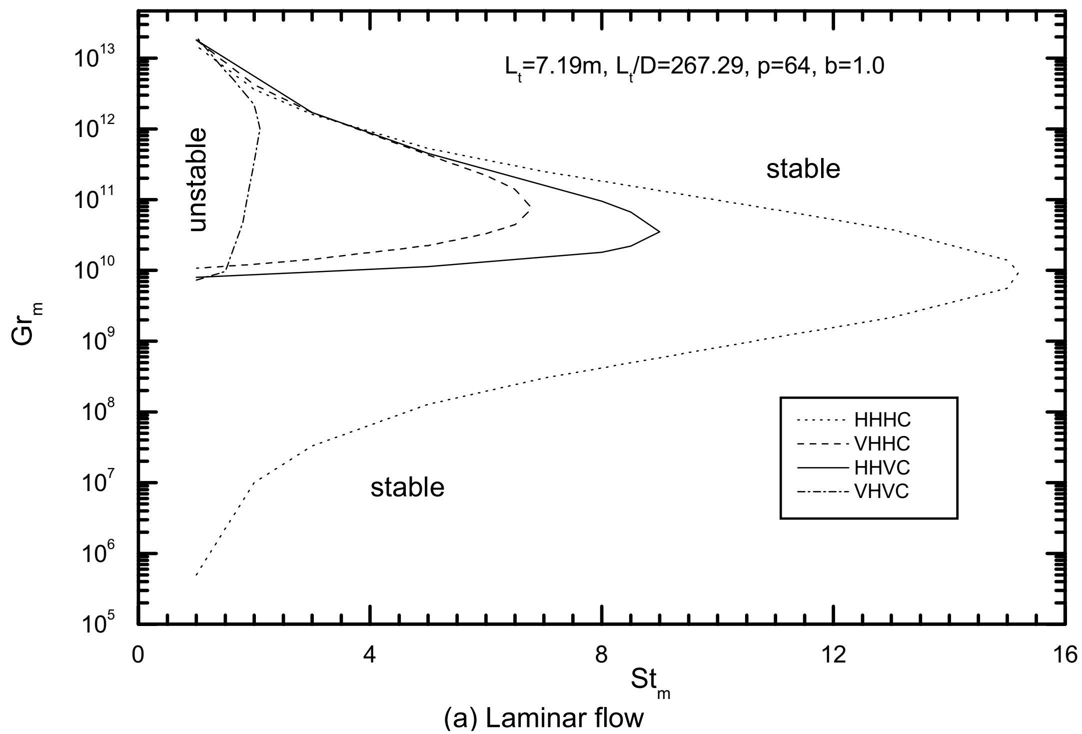
PHWR: Source horizontal and sink vertical

VVER: Source vertical and sink horizontal

Effect of Orientation



Uniform diameter rectangular loop



Predicted stability map for laminar flow

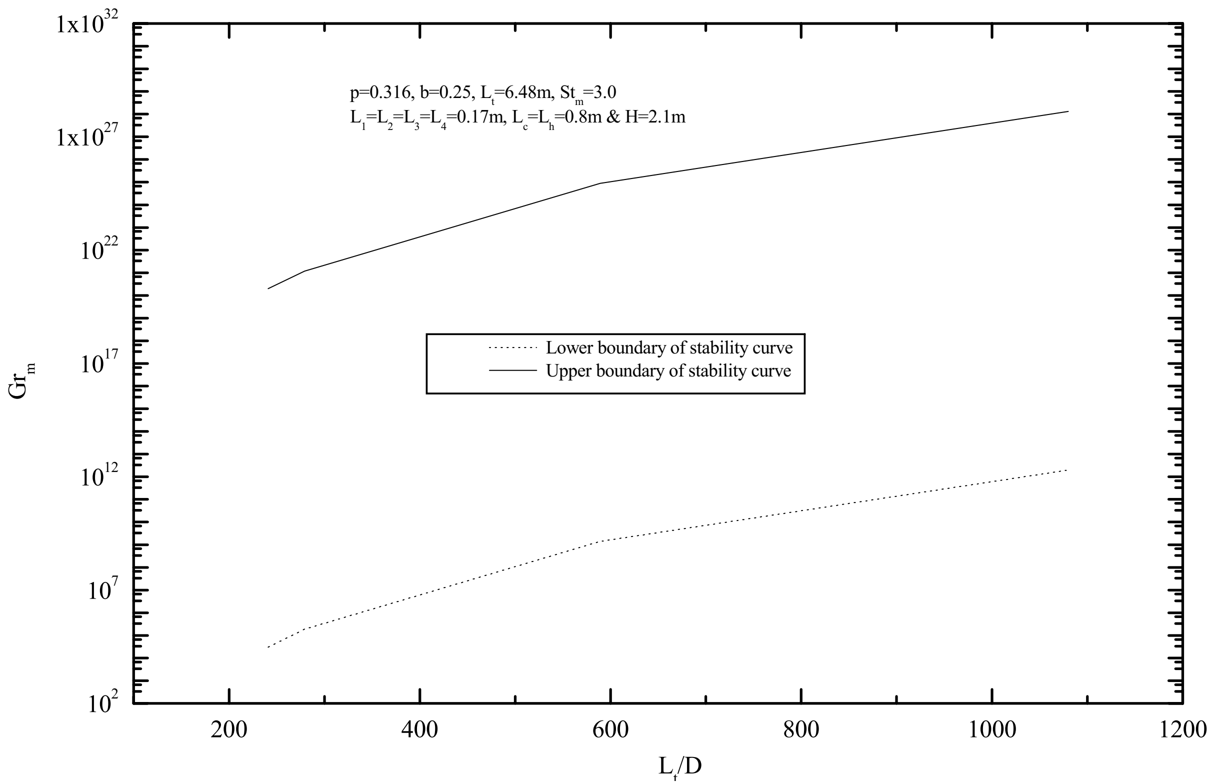
Maximum steady flow can be obtained for the loop with both the source and sink horizontal, but it is the least stable system.

Experimentally, instability was observed only with this orientation

Effect of L_t/D

L_t/D is the contribution of the loop geometry to the friction in a uniform diameter loop.

Increasing L_t/D has a stabilizing effect. Both upper and lower thresholds are found to increase. Most techniques for stabilization results in enhanced L_t/D.

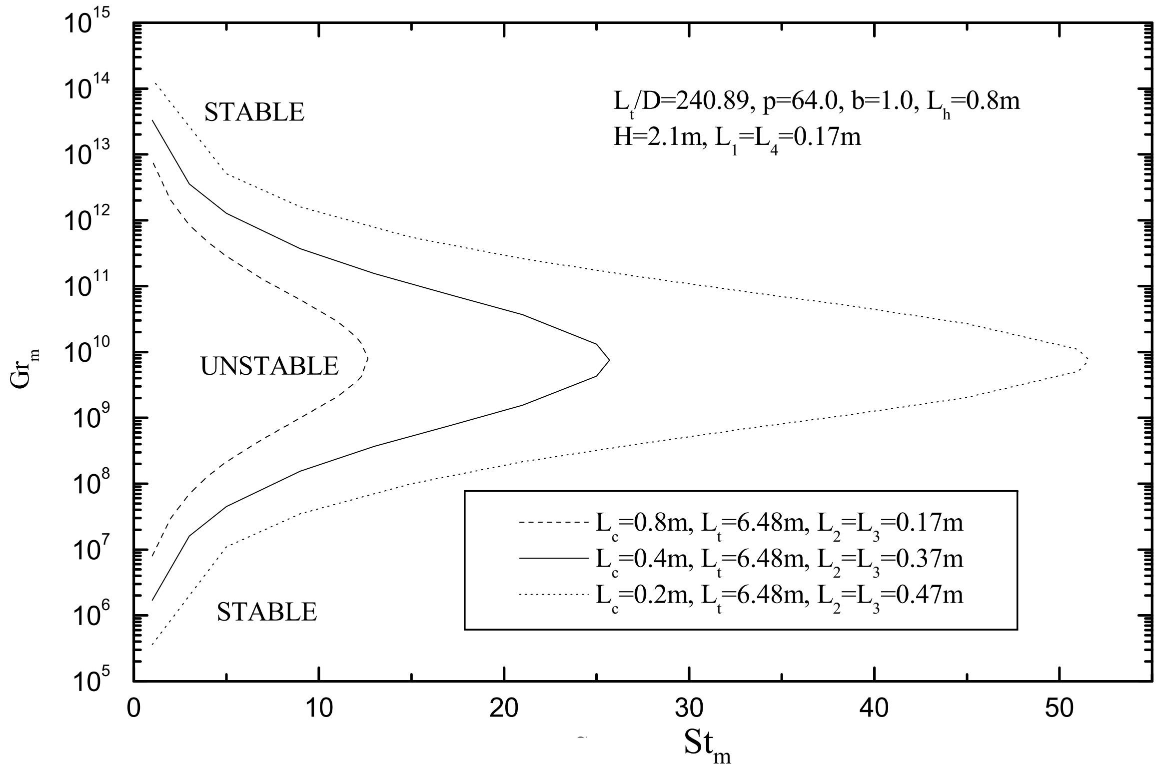


Single-phase instability is observed in loops with $L_t/D < 300$. Most reactor loops operate with L_t/D in the range of several 1000.

Effect of heater and cooler lengths

Reducing the length of heater or cooler has a destabilizing effect.

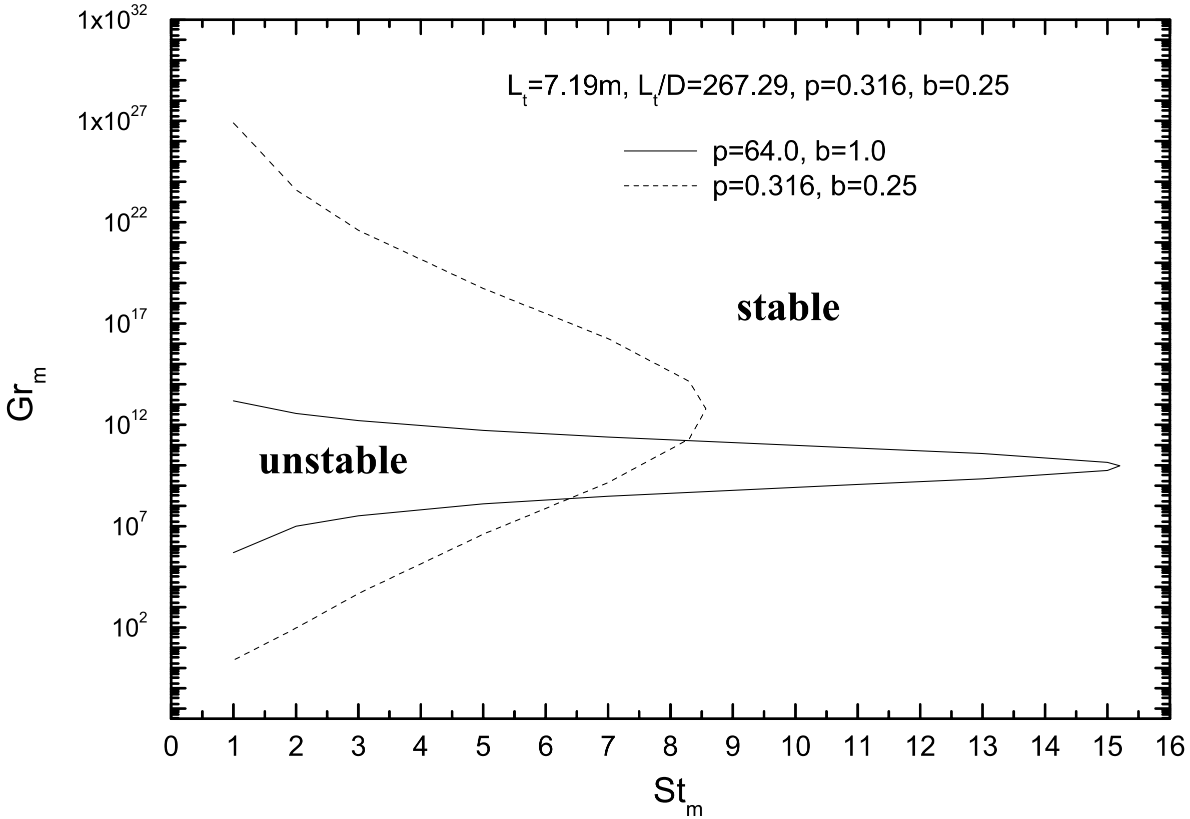
However, the heater length has only a marginal effect whereas the cooler length has significant effect



Effect of cooler length for the HHHC orientation

Effect of flow regime

Significant effect of flow regime is seen from the predictions

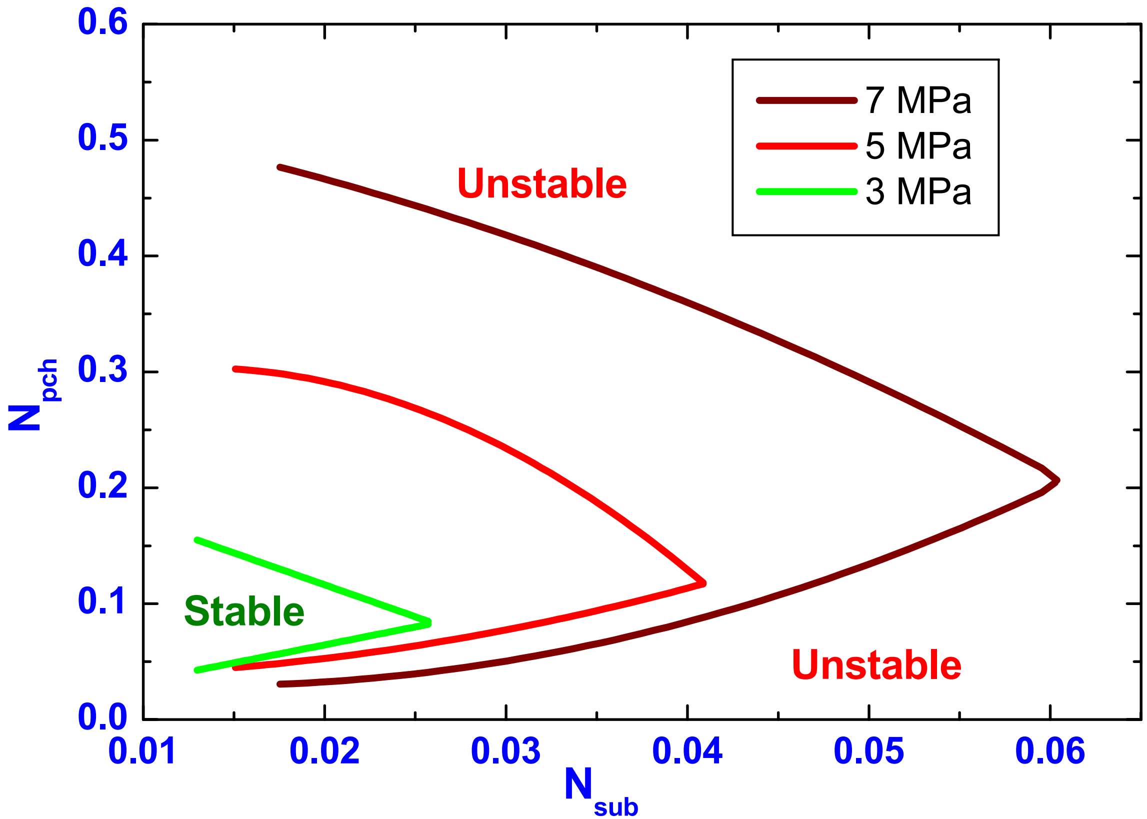


Laminar flow is found to be more stable than turbulent flow

A pathological friction law can show stability

Parametric Effects on the two-phase NC DWI

No universal stability map exists. Instability is affected by a large number of geometric, operational parameters



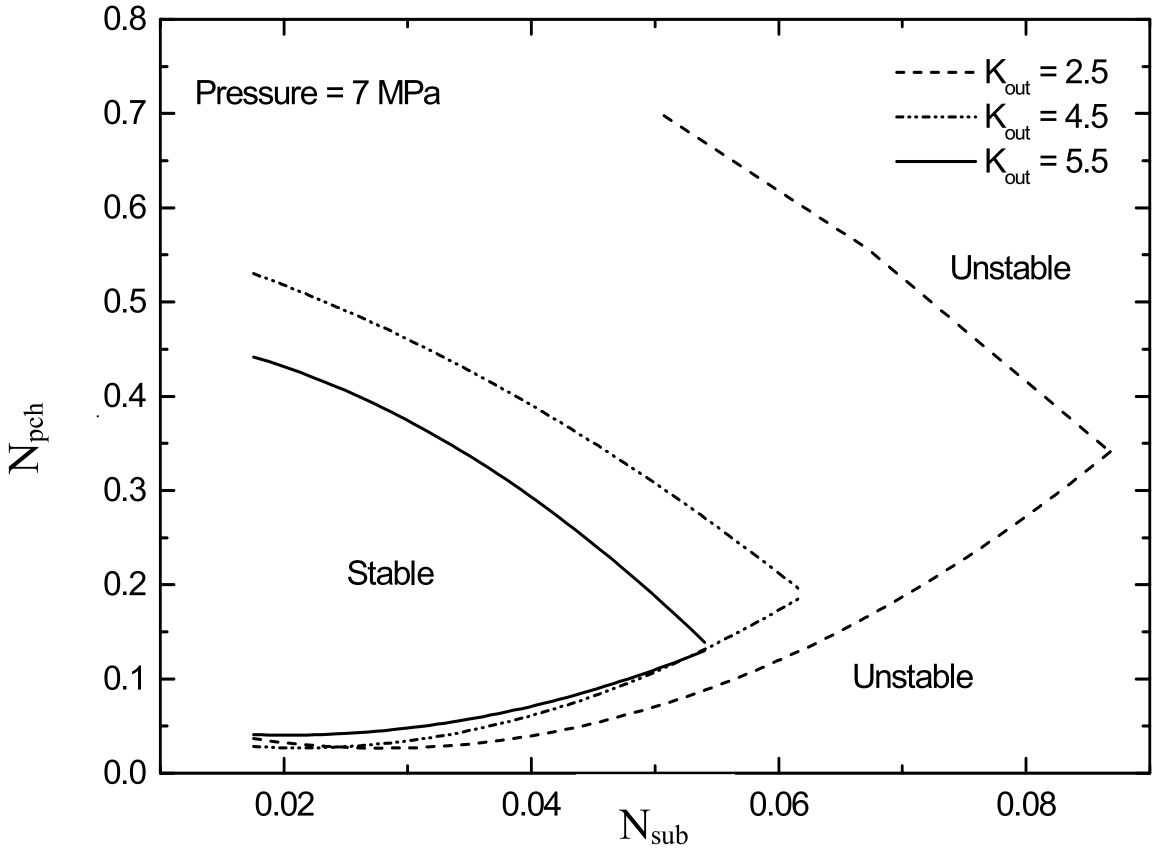
Increasing inlet subcooling has a destabilizing effect

Pressure has a stabilizing effect on DWI

Effect of pressure on stability

Effect of Throttling

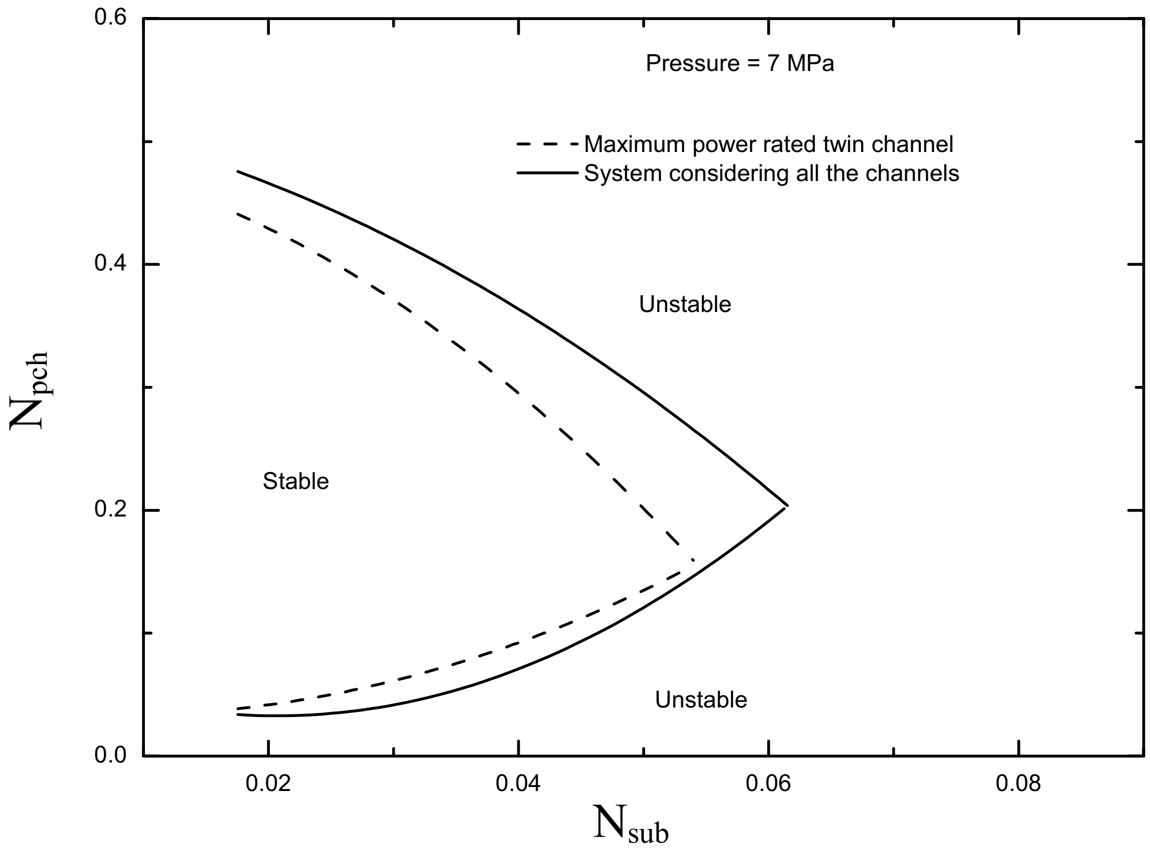
Inlet throttling has a stabilizing effect whereas exit throttling has a large destabilizing effect



Effect of outlet throttling

Parallel Channel Instability

Effect of number of parallel channels



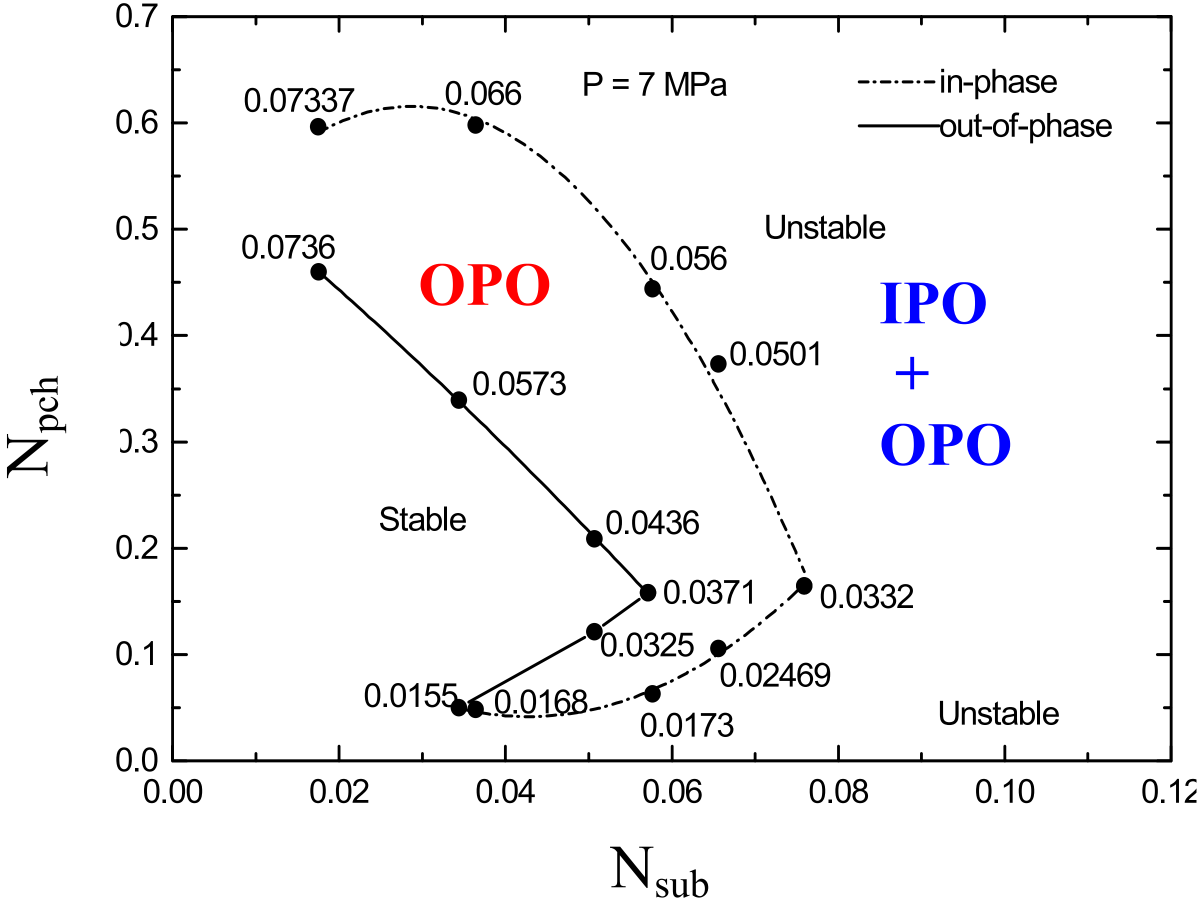
Conservative prediction of parallel channel instability can be carried out with max. rated twin channel system

Effect of number of channels on OPO

Unstable Oscillatory Regimes

Figure shows a comparison of in-phase and out-of-phase instability thresholds. The stable zone for OPO is significantly lower than that of IPO, i.e. OPO is controlling.

In this figure it is easy to identify the various unstable oscillatory regimes.



In the dual oscillation regime both modes of oscillation are possible.

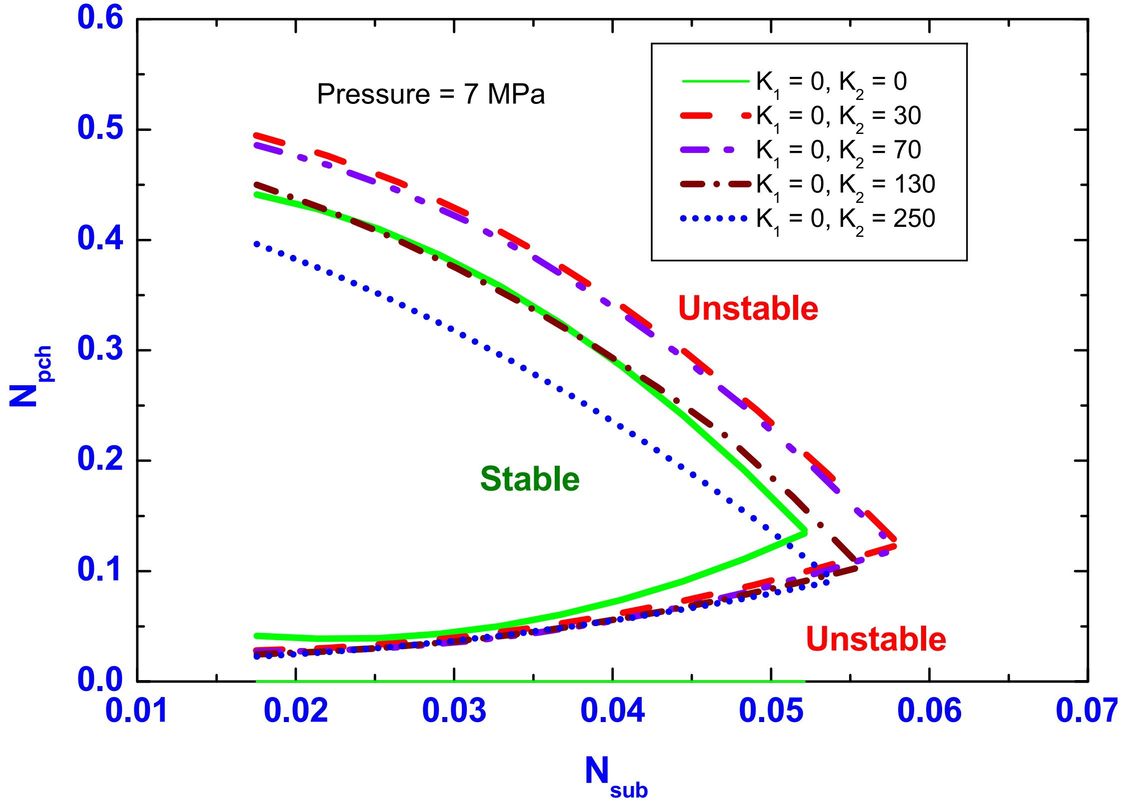
IPO can switch to OPO in this zone.

The decay ratio can show discontinuous behaviour in this zone.

In pure OPO also, this is possible

Effect of Inlet Throttling on OPO

If all channels are uniformly orificed, then it is found to increase stability. However, in a parallel channel system the high power channels are not orificed at all.

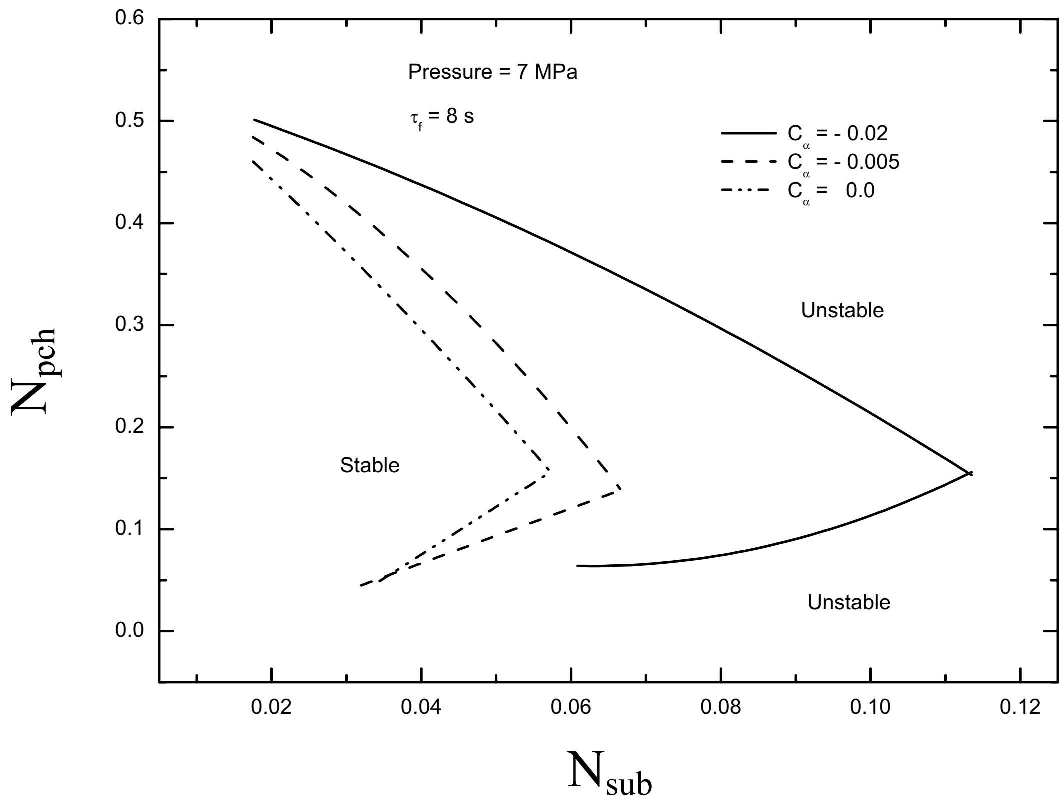


Increasing the inlet loss coefficient of one channel of a twin channel system can have a destabilizing effect beyond a critical value

Coupled Neutronic Thermalhydraulic Instability

Negative void coefficient may stabilise both IPO and OPO so that pure thermalhydraulic stability map is conservative for certain systems

Large fuel time constants have a destabilising effect on OPO



CLOSURE

In most cases, the parametric effects are found to be similar for a forced circulation BWR and a NC BWR

The controlling mode of parallel channel instability is found to be OPO

Differences exist in inlet orificing due to the low value of driving force

For NC BWRs, the reactor power is not limited by stability as in other FC BWRs

The start-up and power raising procedures are to be investigated extensively to ensure stability

Therefore avoiding instability restricts only the start-up procedure and operational domain

Nonlinear Analysis of single-phase NCSs

Nonlinear analysis can be carried out with any initial condition

With the steady state initial condition, the predicted stability maps by the linear and nonlinear analyses were found to be the same

Experience with thermalhydraulic codes

Steady state flow rates could be predicted reasonably well

Effect of nodalization is very important for instability prediction

Instability is not predicted at the same power levels.

Although time series appear to be similar, the predicted limit cycles are vastly different probably due to 3-D effects

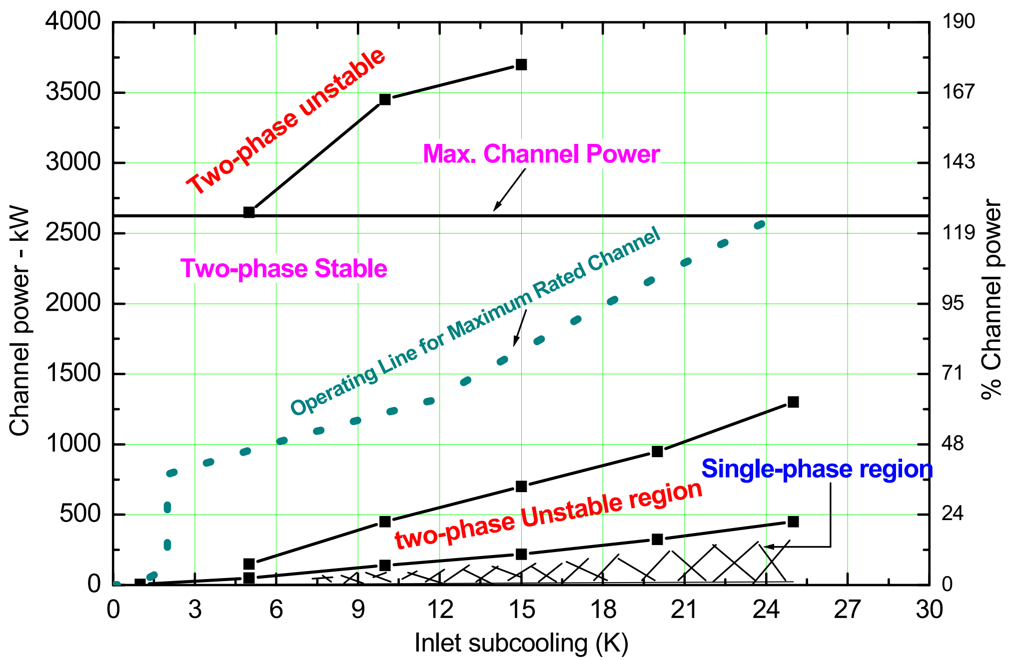
Even simple codes show the same problems

Nonlinear Analysis of NC BWRs

Nonlinear (time domain) codes are useful to establish a stable start-up procedure.

The basic issues during start-up are avoidance of flow reversal and the low power instability (type-I instability)

Flow reversal is expected only at very low power. The lower threshold of instability occurs at reasonably high power and is to be crossed without initiating instability

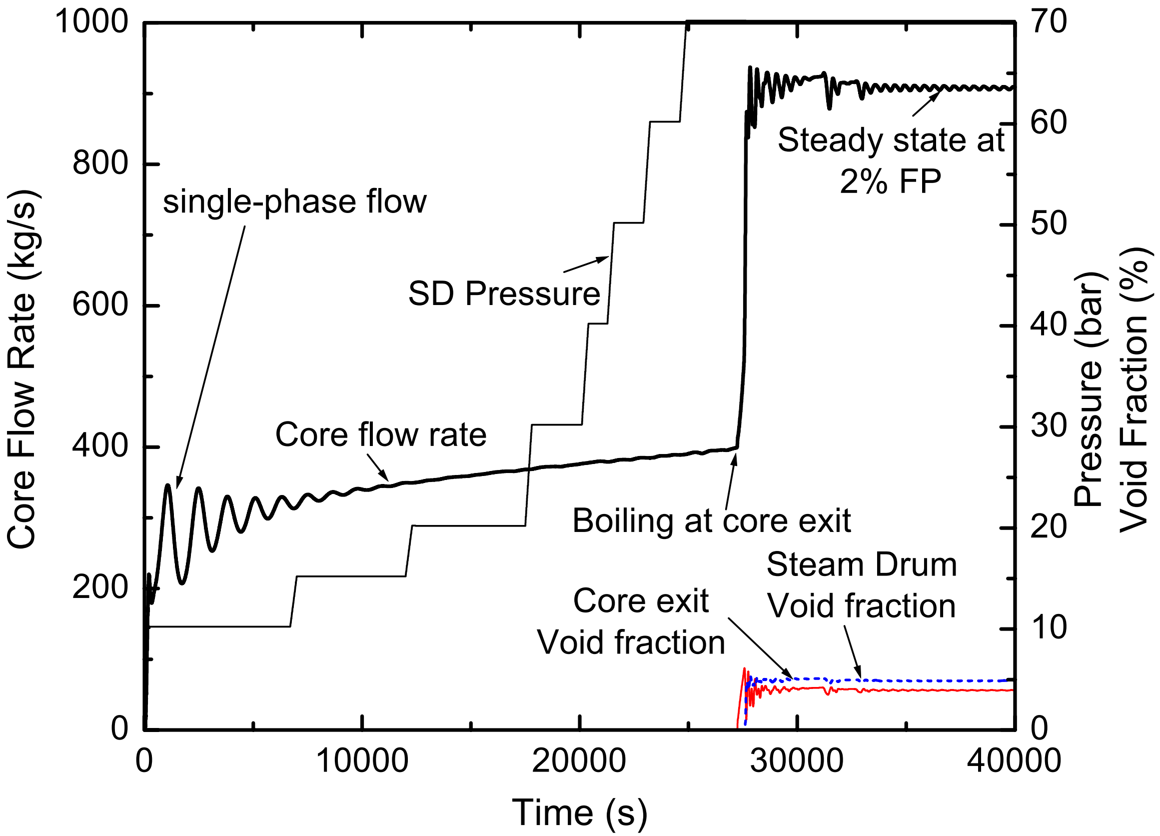


The lower threshold decreases with reduction in subcooling and it disappears if pressure is above a critical value. Hence start-up procedures begins at a low subcooling and then follows a specified pressurization procedure

1) Stage wise pressurisation to the normal value or to a critical value using an external boiler

2) Pressurization using the steam generated within the system ensuring that boiling does not occur in the core

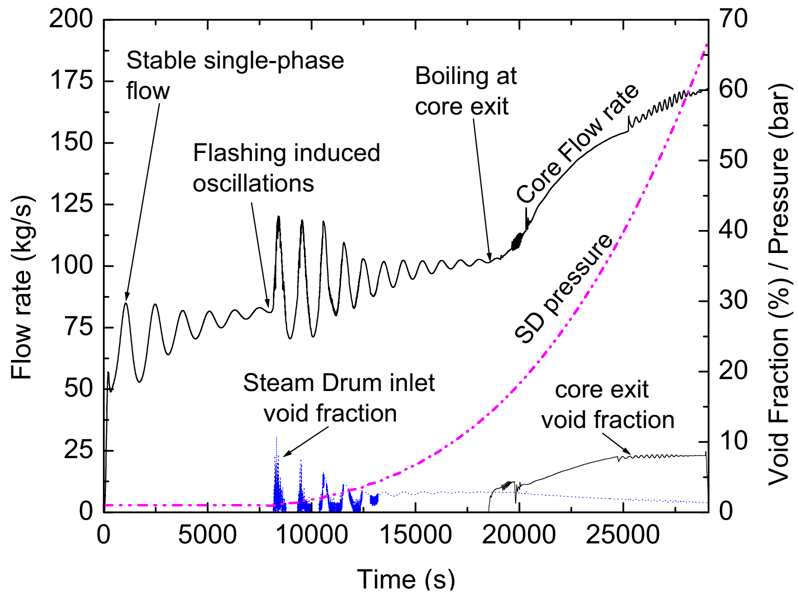
Start-up Procedure with stage-wise pressurization



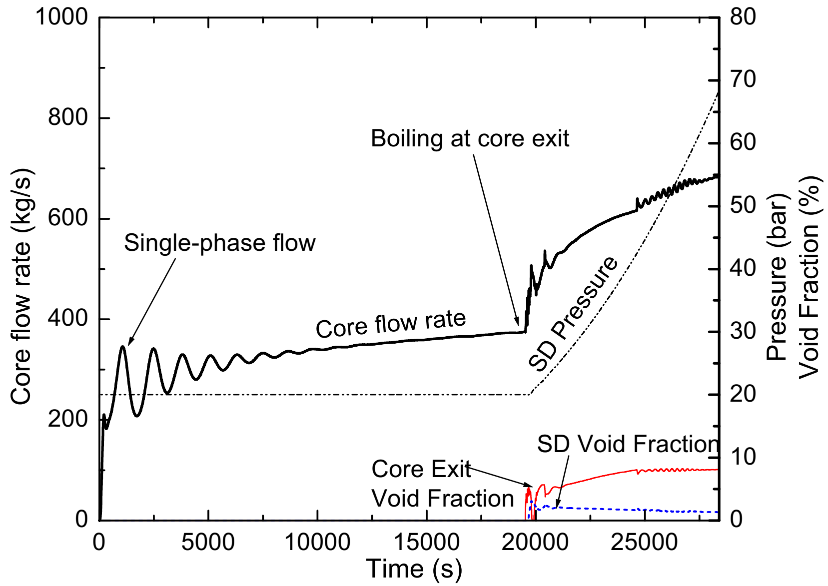
Smooth transition from cold single-phase natural circulation to two-phase is obtained

Simulation of cold start-up procedure with stage-wise pressurization & boiling inception at 7 MPa

Simulation Calculations for Start-up Procedure



(a) Boiling inception at 0.1 MPa



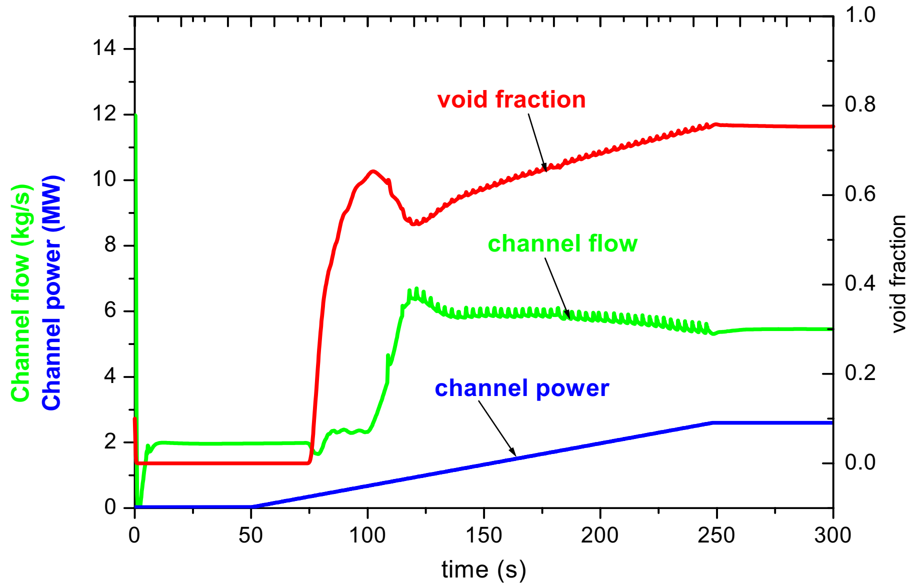
(b) Boiling inception at 2 MPa

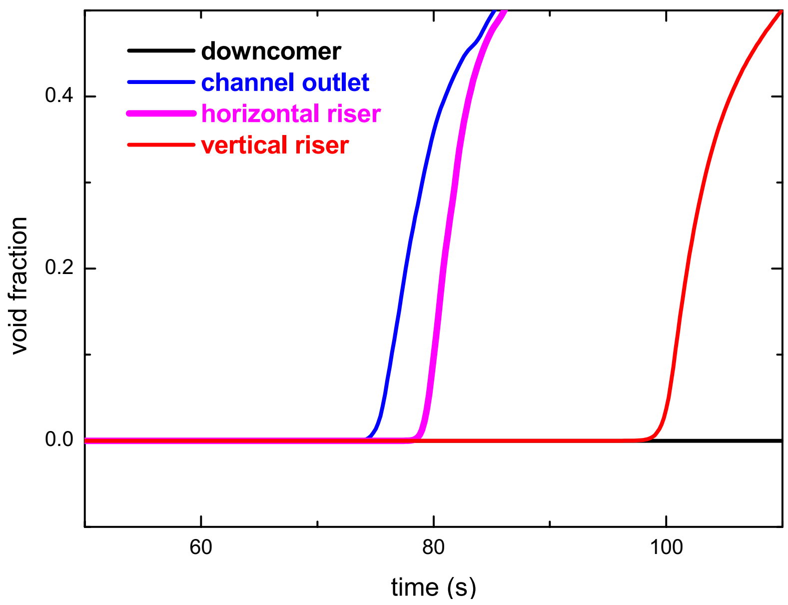
Heat-up, boiling inception and pressurization phases of cold start-up at 2% FP

With increase in pressure the amplitude of oscillations decrease as expected

Power Raising procedure

Due to the possibility of occurrence of the hysteresis phenomenon and islands of instability, the entire operating domain shall be simulated by nonlinear codes





A typical simulation calculation for a 0.5%/sec power raising rate is shown above, which does not show any instability

Closing Remarks on the design Procedure

Stability design of NC BWRs, where several different instability mechanisms can be simultaneously acting is somewhat involved and is not well documented.

Strictly speaking, natural circulation systems shall be analysed for all known instabilities.

However, well-established analysis procedures do not exist for all instabilities.

Design is based on the most commonly observed instabilities such as Ledinegg and Density wave instability

DWI can be in-phase instability or out-of-phase instability and both can be neutronically coupled.

For design, the first issue is which of them is controlling (i.e. having the highest threshold)? Probing calculations may be necessary to identify this.

Closing Remarks on the design Procedure

For NC BWRs, the out-of-phase oscillations can be the controlling mode.

The negative void coefficient could stabilize pure thermalhydraulic instability.

Usually, DWI has a lower and an upper threshold of instability. The upper threshold is generally higher than the CHF threshold and is not expected to occur as CHF limits the power.

The lower threshold can be encountered during start-up and power raising. A start-up procedure needs to be specified for avoiding the unstable zone.

Thank you