Overview on Stability of Natural-circulation-cooled Boiling Water Reactors during Start-up - An Experimental and Modeling Analysis

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This paper provides an overview on numerical and experimental work focused on flashing-induced instabilities. These instabilities may occur in natural circulation two-phase systems when operated at low pressure and low power. Therefore they are of special interest for the start-up phase of natural circulation Boiling Water Reactors. The work presented in this paper has been performed within the framework of the NACUSP project (European-Union Fifth Framework Program). Experiments were carried out on a steam/water natural circulation loop (CIRCUS), built at the Delft University of Technology. Information was gained on the characteristics of the flow oscillations and on the void fraction production during flashing in stationary and transient conditions. A 3-D flow-pattern visualization was achieved by means of advanced instrumentation, namely wire-mesh sensors. On the basis of the experimental results, an assessment of existing drift-flux models was performed for flashing flow. The most suitable drift-flux model was implemented in the 4-equations two-phase model FLOCAL, developed at the Forschunzentrum Rossendorf (FZR, Germany). The model allows for the liquid and steam to be in thermal non-equilibrium and, via drift-flux models, to have different velocities. A detail comparison between simulations and experiments is reported.

KEYWORDS: natural circulation, start-up, flashing, BWR

I. Introduction

The evolution of boiling water reactors leads to designs with larger cores (for instance the ABWR) and to reactors cooled by natural circulation (for instance the SBWR and the ESBWR). Simplification and economy of scale render reactors that are economically competitive, with a high degree of safety. An item of concern for BWRs was their susceptibility to unstable behavior. Fortunately, the experience collected during the years in dedicated research campaigns has reached a level sufficient for eliminating most instability issues. However, two items remain: so-called out-of-phase oscillations in large reactor cores, and flashing induced flow oscillations when relying on natural circulation. The latter instability mode was suggested to be relevant for natural circulation BWRs by Aritomi and colleagues1) It is important during the start-up phase of the reactor, when vessel pressure and power are low.

Triggered by Aritomi’s predictions, the research team at the Delft University of Technology performed a series of dedicated tests on the Dodewaard reactor (cooled by natural circulation), looking for flow instabilities in the start-up phase. Indeed, indications for unstable behavior were found2) (though this reactor was not equipped to measure the flow rate and flow oscillations had to be deduced from neutron flux fluctuations, caused by flow oscillations via void-reactivity feedback). This confirmation of Aritomi’s predictions gave cause for a research campaign in Delft, devoted to analytical modeling of the phenomenon and to experimental research on a dedicated test facility CIRCUS.

An overview of the modeling and experimental results obtained during this research campaign on flashing-induced instabilities is presented in this paper. The research has been carried out within the framework of the EU project NACUSP.

II. The mechanism of flashing-induced instabilities

With flashing it is referred to the void production that takes place in a fluid when no external heat source is supplied. In this conditions void production occurs due to superheating of the liquid phase (for instance if the local pressure decreases or if hot water is transported from a higher to a lower pressure region). At start-up conditions both system pressure and heating power are low. The low system pressure implies large differences in saturation temperature between the inlet and the outlet of the adiabatic section (in a natural circulation BWR this difference can easily exceed 10°C). At low powers the coolant, which is heated up in the heated section of the natural circulation loop, may not reach saturation conditions in the core itself. However, due to the strong pressure gradient, flashing can occur in the adiabatic section (see Fig. 1), leading to an enhancement of the natural circulation flow rate. In dynamic conditions this phenomenon can cause self-sustained flow oscillations: if only single-phase is present in the system, a low flow rate circulates into the system. If the temperature of the coolant entering the adiabatic section is high enough, flashing takes place. The occurrence of flashing will cause an increase of the loop buoyancy and a decrease of the pressure below the location of bubbles formation. The decrease in local pressure will trigger...
additional void formation, leading to a large variation of the flow rate in the system. The increase of flow rate will cause a subsequent decrease of the coolant temperature entering the adiabatic section, so that the process of flashing may eventually stop and the flow rate will be low again. The coolant temperature entering the adiabatic section will therefore increase leading to a new flashing cycle. In this way a self-sustained flow oscillation will take place. The occurrence of flashing will also cause an increase of the condensed water level in the steam dome, so that the gravitational pressure head in the system will increase, leading to a decrease of the void production in the riser. Hence, the presence of the steam dome has a feedback effect that reduces the flow-oscillation amplitude.

The steam possibly produced in the heated channels and in the riser section is condensed in heat exchangers. A steam dome, containing a steam-water mixture at saturation conditions, is used to simulate the steam dome of a reactor; here a small heater compensates for heat losses. A buffer vessel is used to damp out temperature oscillations in order to assure a constant temperature at the inlet of the heated section. A simplified scheme of the facility is shown in Fig. 2; its main characteristics are reported in Table 1. Besides conventional instrumentation, the facility is equipped with wire-mesh conductance sensors\(^3\) that enable the measurements of two-dimensional void-fraction profiles with a sampling rate of 1200 frames per second. The temperature along the riser section is measured by means of thermocouples equidistantly located along the riser’s vertical axis. Needle conductivity probes\(^4\) are located at the same positions as the thermocouples to measure the void fraction distribution along the riser.

<table>
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<th>Table 1 Characteristics of the test facility</th>
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<td>Power range per rod</td>
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**III. Experimental facility and instrumentation**

The CIRCUS facility is a natural-circulation water/steam loop. The heated section (1.95 m) consists of four parallel heated channels and four bypass channels. On top of the heated channels a 3-m long adiabatic riser section is present.

**IV. The thermal-hydraulic code FLOCAL**

FLOCAL\(^5\) is a one-dimensional 4-equations two-phase thermal-hydraulic code originally developed to model the dynamic behavior of the AST-500 reactor, a Russian design nuclear reactor based on natural circulation. The system of partial differential equations (PDEs) solved in the code consists of a momentum balance, an energy balance and a mass balance equation for the two-phase mixture with in addition a separate mass balance equation for the vapor phase. A evaporation/condensation model is used to couple the two mass balance equations.

The core is modeled as a series of parallel coolant channels associated to one or more fuel assemblies. On top of the core both individual (parallel) risers and a common riser can be modeled. The parallel channels are coupled by a boundary condition of equal pressure drops over their total length. A detailed description of the model and the numerical schemes used for the integration of the set of PDEs can be found in Refs. 5) and 6).

To simulate the CIRCUS facility both heated and adiabatic sections have been divided in 30 axial nodes. As boundary conditions, the coolant temperature at the inlet of the heated section and the pressure at the outlet of the adiabatic section are kept constant. The boundary condition on the coolant temperature is exact, since the inlet temperature is kept constant also during the experiments. This is not the case for the condition on the outlet pressure. In the experimental set-up the loop is connected to a steam dome, where a mixture
of steam and water is present. During flow instabilities, the production of steam in the adiabatic section causes an equivalent volume of water to enter the steam dome leading to a compression (and partially condensation) of the steam cushion in the steam dome itself. This has as effect a temporary increase of the system pressure that limits the steam production and expansion in the adiabatic section and therefore the amplitude of the flow oscillations. Since the feedback of the steam dome is not considered in this analysis with the code FLOCAL, one should expect higher amplitude of the flow oscillation in the simulations. In any case, neglecting the feedback of the steam dome does not affect the reproducibility of the phenomenology of flashing-induced instabilities. The k-factors that define the concentrated frictional pressure drops have been evaluated on the basis of standard geometry-based correlations\(^2\). The k-factor corresponding to the valve at the inlet of the heated section has been determined experimentally.

From a detail analysis of experiments performed on the CIRCUS facility, the most suitable drift-flux model for the prediction of void fraction during flashing was selected\(^8\) and implemented in the code FLOCAL. Moreover, the important effects to be modeled in order to reproduce flashing-induced instabilities were identified as\(^9\):

1. Pressure dependency on the axial location along the system and evaluation of the fluid thermodynamic properties as function of the local pressure. If the local pressure is not considered, the model cannot predict the occurrence of flashing.
2. Velocity slip between the phases. It is of great importance for a reliable prediction of the void fraction, which is one of the most important variables in flashing systems because it determines the buoyancy of the natural circulation loop.
3. Thermal non-equilibrium between the phases. This includes subcooled boiling in the heated section and liquid in superheating conditions in the adiabatic section.
4. Effect of heat structures.
5. Effect of turbulent diffusion on the temperature profile during single-phase circulation.

### IV. Experiments and numerical simulations

A series of experiments\(^10\) was carried out at the CIRCUS facility to study the characteristics of flashing-induced flow instabilities and to provide a database on which basis thermal-hydraulic codes can be validated. The experiments were performed at pressures of 1 and 2 bar and for different heights of the steam cushion in the steam dome. During each experiment the power level and the temperature at the inlet of the heated section were kept constant. In Fig. 3 examples are shown of time-traces of the flow rate measured at the CIRCUS facility at a pressure of 1 bar and at a power of 8 kW. The temperature at the inlet of the heated section is reported separately for each case. The results of the FLOCAL simulations are also shown. Four different types of behaviors can be observed both in the experiments and in the simulations: stable single-phase circulation (Fig. 3.a), intermittent natural circulation (Fig. 3.b through Fig. 3.f), unstable two-phase circulation (Fig. 3.g) and stable two-phase circulation (Fig. 3.h).

At single-phase circulation the liquid temperature always remains below saturation. The intermittent natural circulation occurs as soon as the system passes from single-phase to two-phase operation and is characterized by an alternate presence of liquid and two-phase mixture in the adiabatic section. Within a cycle an incubation period exists before the flow-rate increases, needed to the liquid to reach saturation conditions. The incubation period becomes shorter and shorter with increasing inlet temperature and disappears in the unstable two-phase natural circulation region. In the latter condition, two-phase mixture is always present in the riser section due to flashing, but the location at which flashing starts (flashing boundary) oscillates, giving rise to an oscillatory driving force in the system and thus to a flow instability. Finally, when the flashing boundary stabilizes, stable two-phase circulation takes place; in this case a much higher flow rate is achieved with respect to single-phase natural circulation due to the considerable density difference between liquid in the downcomer and two-phase mixture in the heated and adiabatic sections. Same trends are experienced if the inlet temperature is kept constant and the power is increased instead. It is thus clear that to transit from single-phase to two-phase operations and unstable region has to be crossed.

![Fig. 3 Typical flow-rate time traces.](image-url)
A better physical insight in the instabilities is achieved if the time evolution of the void fraction in the adiabatic section is also analyzed. This is shown in Fig. 4. Again the time traces were recorded at a total heating power of 8 kW and a system pressure of 1 bar. Different cases are shown corresponding to different temperatures at the inlet of the heated section. The magnitude of the void fraction is represented by means of contour plots. In Fig. 4 both simulated (bottom picture) and experimental (top picture) time traces are reported. At low inlet temperatures (Fig. 4.a) flashing starts relatively high in the riser and later on the flashing front expands and propagates both in the upward and downward directions. As soon as the inlet temperature increases, steam bubbles are generated first in the heated section (subcooled boiling) below the riser inlet. These bubbles collapse in the riser (contributing to the heating up of the fluid) before flashing starts (Fig. 4.b and Fig. 4.c). Increasing the inlet temperature flashing in the riser is directly triggered by the voids coming from the heated section (Fig. 4.d and Fig. 4.e).

Also with regard to the void fraction, fair agreement is found between the model predictions and the experiments and the phenomenology is well reproduced.

1. Main characteristics of the instabilities

The physical origin of the instability suggests that the transit time of the mixture through the heated and adiabatic sections is a dominant factor in determining the oscillation period. This transit time is a function of the coolant flow rate and of the void content in the system. Fig. 5 shows that the oscillation period decreases monotonously with increasing average flow rate, although this graph contains cases recorded at different subcooling, heating power and system pressure. Clearly, the relation between oscillation period and average flow rate depends only on the geometrical characteristics of the system. The results of the FLOCAL simulations, also reported in Fig. 5 support this idea.

In Fig. 6 the relation between the driving pressure in the loop and the kinetic pressure is shown. All experimental points, both stable and unstable, lie approximately on a straight line passing through the origin. In Ref. 10) it was argued that the reason for this behavior is the fact that driving pressure and friction are the major terms in the momentum balance of the loop, while inertia and acceleration pressure drops play a small role in the determination of flow magnitude. This argument has been confirmed by the FLOCAL calculations, since it is found that inertia and acceleration pressure drops are orders of magnitude smaller with respect to frictional and gravitational pressure drops.
The oscillation period is well predicted at low subcoolings (i.e. high flow rates and absence of single-phase circulation) and underestimated at high subcoolings (i.e. at low flow rates and presence of alternate single-phase/two-phase circulation). The reason could lie on both heat losses to the environment, neglected in the calculation presented here, and on the smearing of the temperature front during the single-phase circulation. Calculations including heat losses have been performed with FLOCAL but, though they cause an increased incubation period, they do not justify the extent of under-estimation of the incubation period. The smearing of the temperature front seems to be caused by turbulent diffusion in presence of a negative temperature gradient along the vertical axis of the adiabatic section. It has been shown that indeed this has a strong effect on the incubation period at high inlet subcooling and has no effect at low inlet subcooling\textsuperscript{9}). Thus this effect explains the trends observed in Fig. 7.

![Fig. 6 Driving pressure vs kinetic pressure.](image)

![Fig. 7 Oscillations period as function of the inlet subcooling. The effect of the heat structures on the simulations results is shown.](image)

The strong effect of the energy accumulated in the heat structures, namely the walls of riser and heated section is clearly visible (Fig. 7, “no wall” calculations).

Several experiments have been carried out at the CIRCUS facility to derive so-called stability maps. These maps are represented in the power-subcooling plane in the present discussion since power and subcooling are the variables directly controlled during the measurements. Stability maps have been constructed at a pressure of 1 bar and 2 bar. In the former case, two different compressible volumes in the steam dome have been considered. The results are shown in Fig. 8. In agreement with other experimental results reported in literature\textsuperscript{(11)-(13)}, the range of inlet subcoolings for which instabilities occur increases with power and decreases with pressure. Increasing system pressure has a stabilizing effect also because it reduces the relative amplitude of flow oscillations\textsuperscript{10}).

![Fig. 8 Stabilities boundary for different pressures p and steam dome volumes in the steam dome. H indicates the height of the steam cushion in the steam dome.](image)

The extension of compressible steam volume in the steam dome does not influence the behavior of the system in steady state conditions since in this case no variation of the compressible volume in the steam dome occurs. In dynamic conditions, however, flashing in the riser will cause a larger pressure increase when a smaller compressible volume is available in the steam dome. The pressure increase in its turn will lead to vapor collapse and to an increase of saturation temperature. This feedback limits the amplitude of the flow oscillation\textsuperscript{10}). However,
the effect on the extension of the unstable two-phase region is not significant, as can be seen in Fig. 8 (stability boundaries at 1 bar with 18 and 26 cm height of the steam cushion respectively).

V. Flow pattern visualization

During a flashing cycle, the flow pattern changes from bubbly flow to slug/churn flow and finally to bubbly flow again. This can be seen by visual inspection of the test section and by flow pattern visualization\(^3\) on the basis of data collected with two wire-mesh sensors. These sensors are located in the adiabatic section between T5 and T6 indicated in Fig. 2 at an axial distance from each other of 27.5 mm.

The wire-mesh sensor has the same diameter of the pipe in which it is mounted (47 mm for the CIRCUS facility) and delivers the two-dimensional void fraction distribution in the pipe (on a square matrix of 16x16 points) with a spatial resolution of 2.8 mm and at a rate of 1200 frames per second. The result is a three-dimensional matrix of instantaneous void-fractions. The time sequence of instantaneous void fraction distributions over the tube diameter is plotted in a vertical column. To convert the time coordinate in the spatial coordinate perpendicular to the pipe cross-section, the time-dependent steam velocity is used. This is evaluated by means of cross correlation techniques using the data from the two wire-mesh sensors located in the adiabatic section. A simplified light-ray tracking algorithm was applied to the three-dimensional matrix of void-fraction data. The data column was assumed to be illuminated from the left side by parallel white light. For both water and steam phases individual absorption and dispersion coefficients for the three colors components red, green and blue were assumed, and composition and intensity of the light departing in the direction of the observer was calculated. The result is presented in Fig. 10 for a case corresponding to a power of 10.8 kW and an inlet temperature of 72.8°C.

The height and width of the columns are in scale so that the bubbles are displayed in their realistic shape (within the accuracy of the velocity assumption).

The light-ray tracking supplies a very illustrative, spatial impression of the shape of the bubbles in the different stages of the flashing cycle. In the beginning just a few bubbles appear; some of them soon reach the size of cap bubbles. The flow soon transits to slug flow. Before flashing stops, the flow regime again transits to bubbly flow.

Similar trend can be seen by analyzing the position of the transient working point in the \(J_G-J_L\) plane shown in Fig. 9. The flow maps according to Taitel et al.\(^{14}\) and to Mishima-Ishii\(^{15}\) are also reported.

VI. Conclusions

An experimental and modeling analysis on flashing-induced flow instabilities, which are important during the startup phase of natural circulation BWRs, lead to the following findings:

- an unstable operational region exists between stable single-phase and two-phase operation; flashing is the main cause of these instabilities;
- the oscillation period is directly related to the propagation of enthalpy perturbations;
- increasing pressure has a stabilizing effect.

The physical effects that need to be taken into account to correctly model flashing instabilities were identified as:

- Pressure dependency on the axial location along the system and evaluation of the fluid thermodynamic properties as function of the local pressure. If the local pressure is not considered, the model cannot predict the occurrence of flashing.
- Velocity slip between the phases. It is of great importance for a reliable prediction of the void fraction, which is one of the most important variables in flashing systems because it determines the buoyancy of the natural circulation loop.
- Thermal non-equilibrium between the phases. This includes subcooled boiling in the heated section and liquid in superheating conditions in the adiabatic section.
- Effect of heat structures.
- Effect of turbulent diffusion on the temperature profile during single-phase circulation.

The code FLOCAL, which contains all the effects reported above, was found to reproduce very well the experimental data available on flashing-induced instabilities.

A three-dimensional visualization of the transient flow pattern during flashing instabilities was obtained on the basis of wire-mesh sensors data and it was possible to shown that the flow pattern transit from bubbly to slug/churn flow regime and ends back to bubbly flow in the last phase of a flashing cycle.
Nomenclature

\[ J = \text{superficial velocity [m/s]} \]
\[ G = \text{flow rate [l/s]} \]
\[ L = \text{riser length [m]} \]
\[ H = \text{steam cushion height [cm]} \]
\[ u = \text{velocity [m/s]} \]

Subscripts

\[ l = \text{liquid} \]
\[ g = \text{gas} \]
\[ in = \text{inlet} \]
\[ sat = \text{saturation} \]

Greek

\[ \rho = \text{density [kg/m}^3\text{]} \]
\[ \alpha = \text{void fraction} \]
\[ \Delta = \text{amplitude} \]

Operators

\[ <> = \text{time/spatial average} \]

Abbreviations

ABWR  Advance Boiling Water Reactor
ESBWR  European Simplified Boiling Water Reactor
SBWR  Simplified Boiling Water Reactor

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References


Fig. 10 Flow pattern visualization reconstructed from wire-mesh data.