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# Experimental investigations on flashing-induced instabilities in one and two-parallel channels: A comparative study

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ABSTRACT

In this investigation, experiments conducted in a natural circulation test facility at low power and low pressure conditions, in the one single and two-parallel channels configuration are presented and discussed in detail. The novel manner of visualizing the results allowed characterizing the facility at any time and position which helped to thoroughly understand the instability mechanisms. Different modes were observed for each configuration. In the case of having two-parallel channels, four different behaviors have been observed: stable flow circulation, periodic high subcooling oscillations, a-periodical oscillations and out-of-phase periodical oscillations. In addition, stability maps were constructed in order to clarify the region in which each mode is dominant. The results obtained from both the one and two-parallel channels configurations are thus analyzed and compared. As a result, some similarities have been observed between the intermittent flow oscillations found in the single channel experiments and the high subcooling oscillations found in the two-parallel channels experiments. Moreover, similarities have also been found between the sinusoidal flow oscillations existing in the single channel experiments and the out-of-phase oscillations from the two-parallel channels experiments. The experiments presented in this work can be used to benchmark numerical codes and modeling techniques developed to study the start-up of natural circulation BWRs.



## 1. Introduction

Natural circulation cooling is a key issue in the design of modern nuclear power plants for simplicity, inherent safety, and maintenance reduction features [21]. For this reason, new generation boiling water reactors (BWRs), which are optimized to be economical and reliable, are cooled with natural circulation in order to improve their competitiveness. The prototypical natural circulation BWR (NCBWR) is the Economic Simplified Boiling Water Reactor (ESBWR) [4,22]. An item of concern of these reactors is the susceptibility to exhibit thermal–hydraulic instabilities since the flow cannot be controlled externally as in forced circulation systems.

Safety concerns of nuclear reactors have attracted the attention of many researchers on flow instabilities in natural circulation boiling loops. Experiments performed on the DANTON facility at start-up conditions (i.e. low pressure-low power) have shown that the pressure increase caused by the steam produced in the reactor vessel is not sufficient to suppress completely the flow oscillations and that without external pressurization, an instability region between single-phase and two-phase operation has necessarily to be crossed [23]. Unstable behavior at low power and low pressure has also been encountered at specific conditions explored in an experimental campaign at the Dutch natural circulation BWR Dodewaard [26,27].

The tall adiabatic chimney, placed on top of the core to enhance the flow circulation, makes flashing phenomenon (the sudden increase of vapor generation due to the reduction in hydrostatic head) likely to occur during the low pressure start-up phase of NCBWRs. The feedback between vapor generation in the chimney and buoyancy in the natural-circulation loop may give rise to self-sustained flow oscillations.

Flashing-induced flow oscillations were first pointed out by the pioneering work of Wissler and colleagues [25], who reported about flashing-induced instabilities in a natural circulation steam/water loop in the 1950s. Since then, several experimental studies have addressed stability of natural circulation two-phase flow systems at low pressure [1,12,13,14,23,15].

These flow oscillations make the operation of the reactor during start-up rather difficult and could cause strong mechanical vibrations of the reactor's internal components. Well-defined start-up procedures are therefore needed to cross the instability region during the transition from single-phase to two-phase flow conditions.

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**Nomenclature**

| | |
|---|---|
| $A$ | section flow area |
| $Cp_l$ | specific heat capacity at constant pressure |
| $D$ | section diameter |
| $E^*_{kin}$ | kinetic energy per unit of volume |
| $M$ | inlet mass flow rate |
| $F^*_{driv}$ | two-phase driving force per unit of area |
| $g$ | acceleration due to gravity |
| $K_{in}$ | inlet friction coefficient |
| $L$ | section length |
| $q$ | applied power |
| $Q$ | time averaged coolant volumetric flow rate |
| $t$ | cross correlation time delay |
| $u_{in}$ | coolant mean inlet velocity |
| $v_{gj}$ | drift velocity |
| $V$ | volume of the section and |
| *Greek letters* | |
| $\alpha$ | void fraction |
| $\Delta P$ | inlet restriction pressure drop |
| $\Delta T_{sub,in}$ | fluid subcooling at the channel inlet |
| $\Delta\rho$ | density difference between liquid and vapor phases |
| $\rho_l$ | coolant inlet density |
| $\tau$ | transfer function from void-fraction fluctuations to flow rate time constant |
| $\tau_{Channel}$ | fluid transit time in the channel |
| $\tau_{bd}$ | boiling delay time |
| $\tau_f$ | period of geysering-induced oscillations |
| $\tau_{b,tt}$ | transit time of the bubbles passing through the chimney |
| *Subscript* | |
| 0 | relative to the steady state condition |
| *C* | relative to the heated section |
| *Ch* | relative to the chimney section |
| *Channel* | relative to the channel |
| *DC* | relative to the downcomer |
| *l* | relative to the liquid phase |
| *model* | referred to model |
| *v* | relative to the vapor phase |
| *Operators* | |
| $\langle\ \rangle$ | time average |

Marcel et al. [17] performed a thoroughly description of the mechanism of flashing-induced oscillations occurring in the CIRCUS test facility with a single chimney configuration. The experiments were presented in a novel manner, allowing observing the dynamic evolution of important parameters which gave an excellent characterization of the phenomenology present in the system.

In natural circulation BWRs the chimney section is usually divided into subchannels to avoid cross flow and to better divide the coolant flowing through the core. Flashing-induced instabilities occurring in parallel channels may occur during the start-up phase of a natural circulation BWR equipped with such adiabatic sections. Such instabilities may be different from the more common flashing-induced oscillations occurring when only one chimney is present. Experimental investigations on this field are still very limited. Aritomi et al. [1,2] studied the low pressure stability of parallel channels with a chimney but in their experiments, the chimneys were too short compared to those from modern natural circulation BWRs, and therefore flashing played a secondary role. Fukuda and Kobori [11] observed two modes of oscillations in a natural-circulation loop with parallel heated channels. One was the U-tube oscillation characterized by channel flows oscillating with 180° phase difference, and the other was the in-phase mode oscillations in which the channel flow oscillated along with the whole loop without any phase lag among them. Out-of-phase oscillations were also observed in the parallel channels of the CIRCUS facility by Marcel et al. [16]. The mechanism of flashing-induced instabilities occurring in two-parallel channels, however, is not fully understood and therefore, more experimental investigations are needed in order to clarify this issue. Such a topic is important to assure a safe start-up process of novel natural circulation BWRs.

## 2. Investigation tools

### 2.1. The CIRCUS facility in the single channel configuration

The CIRCUS facility [9] is a steam/water facility designed to perform studies on two-phase flow dynamics relevant for the starting-up of natural circulation BWRs. CIRCUS is an axially fully scaled, radially lumped version of the Dodewaard reactor [26] . A simplified scheme of the CIRCUS facility including technical details is given in Fig. 1. Further details regarding the CIRCUS facility (e.g. location of sensors, geometry, etc.) can be found in Appendix A.

CIRCUS can be operated in two different ways: the single chimney configuration and the two parallel chimneys configuration. In the first one, CIRCUS is equipped with a single tall adiabatic section representing the reactor chimney which is placed on top of the heated section. The heated section simulates the reactor core and consists of two heated channels with two bypasses. For this reason this section is also referred as the 'core' section.

The steam produced in the heated section and in the chimney is condensed in the heat exchangers and to some extent in the steam dome. A buffer vessel is used to damp temperature oscillations at the downcomer inlet, ensuring a constant inlet subcooling. Two magnetic flow-meters (maximum inaccuracy of ±0.01 l/s) characterize the flow at the heated section inlet and chimney outlet. Several thermocouples (maximum inaccuracy of ±0.5 °C) are located at the inlet and outlet of each heated channel, along the chimney sections, in the heat exchanger and in the steam dome. Two PT100 sensors are located at the inlet of the core section and in the steam dome for more accurate temperature measurements. Absolute pressure sensors are placed at the inlet of the core section, at the chimney outlet and in the steam dome. Differential pressure sensors are mounted across the steam dome, for measuring the water level, and across the core inlet valve. Advanced measuring techniques are used for detailed high sampling rate void-fraction measurements, e.g. conductivity needle probes and capacitance-based sensors. The channels in the facility are made of glass, allowing visual inspection during the operation. To reduce the heat losses to the surroundings, all the sections are covered with removable thermal isolation.

CIRCUS can be operated with a maximum electrical power per rod of 3 kW. By varying the inlet subcooling and the applied power, several configurations can be studied in the power-subcooling plane. The core inlet valve allows changing the inlet restriction coefficient.

### 2.2. The CIRCUS facility in the two-parallel channels configuration

In this configuration, the CIRCUS test facility is operated with two chimneys on top of the core section (see Fig. 1).