Low-pressure dynamics of a natural-circulation two-phase flow loop

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Abstract
Flashing induced oscillations in a natural circulation loop are studied as function of heating power and inlet subcooling in symmetrical and asymmetrical power conditions. To unveil the effects of power/velocity asymmetries on the two-phase flow stability at low power and low pressure conditions different signals at several locations in the loop are recorded. In particular a Laser Doppler Anemometry set-up is used to measure the velocity simultaneously in two parallel channels and a wire-mesh sensor is used to measure the 2D void fraction distribution in a section of the ascendant part of the loop.

Introduction

Natural circulation is of importance for several industrial applications such as steam generators, boilers and chemical industrial processes. Passive cooling by means of natural circulation has been recently considered as a challenging principle to be applied to next generation Boiling Water Reactors (BWRs) in order to simplify these systems and improve at the same time their inherent safety. A long adiabatic section is built at the top of the heated section (core) to enhance the buoyancy of the loop and achieve high flow rates. Unfortunately, the presence of a long adiabatic section (riser) makes the system susceptible to so-called flashing-induced instabilities. Flashing-induced instabilities in a natural circulation system occur as soon as the heating power is sufficient to bring the coolant at the exit of the heated section at a temperature equal or larger than the corresponding saturation temperature at the exit of the riser. In fact, at low-pressure conditions the saturation temperatures corresponding to the core exit pressure and to the riser exit pressure respectively can differ by several degrees. Therefore, even if no boiling occurs in the core, void production can take place in the adiabatic section due to a decrease of the local pressure along the axis of the system.

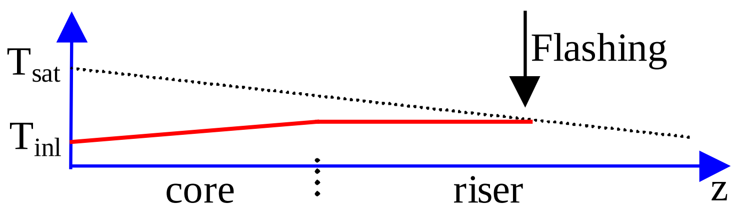

Fig. 1 Flashing in the riser at low power and low pressure conditions

This process is schematically illustrated in Fig. 1: at low pressure the local saturation temperature decreases considerably along the vertical axis of the system, from the inlet of the heated region to the end of the adiabatic section. If the power is low, the coolant that enters the heated section with a given temperature T_{inl} can still be in subcooled conditions at the exit of the heated section (core), but it can attain saturation conditions in the adiabatic section giving rise to void production due to flashing. The rapid void production due to flashing leads to a sudden imbalance between the coolant density in the downcomer and core/riser sections causing an abrupt increase of the mass flow rate. As a consequence of the increased mass flow rate, the temperature at the outlet of the core will decrease to a value too low to allow flashing in the riser. The buoyancy of the loop will decrease due to the suppression of void production in the riser; consequently the fluid temperature at the core exit will again increase leading again to flashing in the riser. This process can become self-sustained resulting in constant amplitude flow oscillations.

During flashing-induced instabilities the quality at the exit of the core is generally negative (subcooled conditions) or very close to zero and the instability process is directly correlated to the oscillations of the hydrostatic pressure head in the ascendant part of the loop.

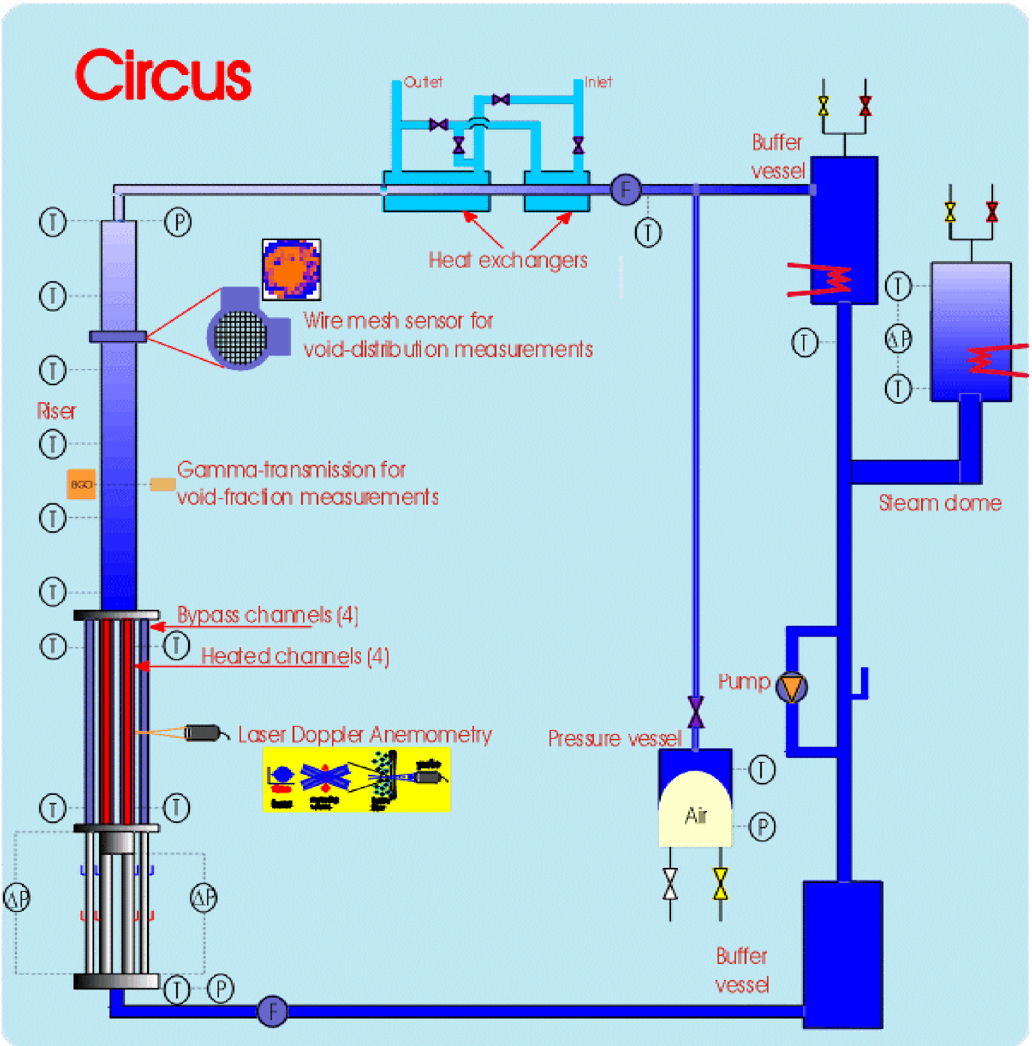

Fig. 2 Schematic view of the CIRCUS facility

To avoid or reduce the effects of flashing during the start-up of a natural circulation BWR suitable procedures need to be defined. In order to gain more physical insight into the phenomena involved during flashing oscillations and to enlarge the experimental database needed to validate analytical models and advanced thermalhydraulic codes the CIRCUS facility has been built at the Delft University of Technology[1]. A schematic view of the facility is represented in Fig. 2. The facility consists of four parallel separately heated channels and four parallel non-heated bypass channels above which a long adiabatic section (riser) is present. The steam produced in the system is condensed in a heat exchanger. The pressure of the system is regulated by means of a steam dome (see Fig. 2) where a two-phase mixture is kept in equilibrium at saturation conditions. The facility is equipped with several thermocouples, flowmeters, pressure and pressure-drop sensors. Two laser doppler anemometry set-ups are used to measure the local velocity in two parallel channels simultaneously (data rate between 1000 and 5000 Hz) and a wire mesh sensor[2] located in the riser is used to measure the 2D void fraction distribution on a 16x16 grid with a frequency of about 1000 Hz.

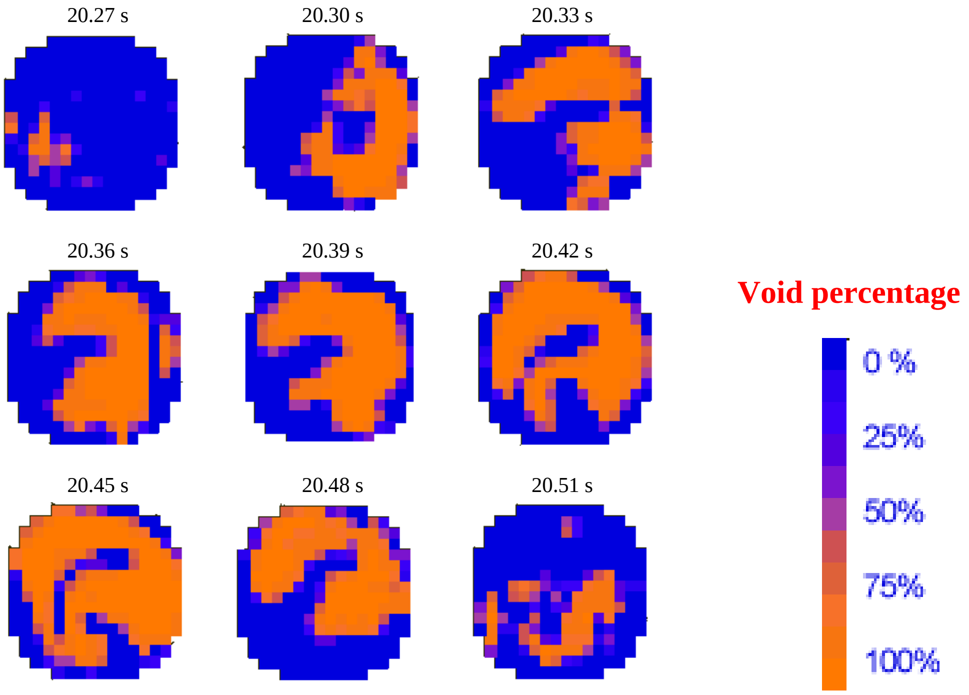

Fig. 3 Void fraction distribution measured by the wire mesh located in the riser

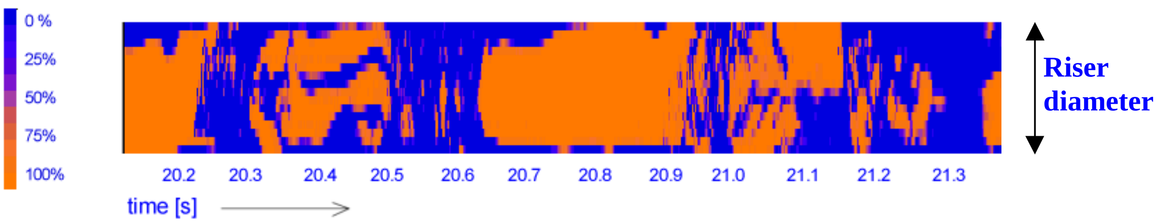

Fig. 4 Void fraction projection on time axis

In Fig. 3 a measurement of the void fraction during a flashing-induced instability performed with the wire mesh sensor located at the top of the riser is shown at different time instants. A graphical reconstruction of the average radial void fraction in the section where the wire mesh is located is shown as function of time in Fig. 4.
From Fig. 3 and Fig. 4 it can be seen how rapidly the void distribution changes during flashing. Fast alternation of liquid and steam is in fact observed, giving rise to strong

void fraction fluctuations. This is also shown in Fig. 5, where the time series of the average void fraction in the riser section as measured by the wire-mesh is reported. The periodic character of the flashing instabilities is clearly visible.

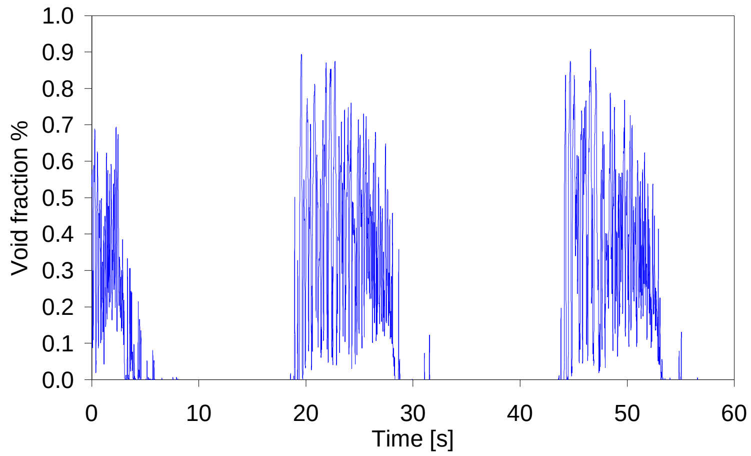

Fig. 5 Average void fraction time series in a section of the riser

The occurrence of periodic void production in the riser is originated by enthalpy perturbations that travel from the heated section to the top of the riser. A confirmation that the feedback mechanism for this kind of instabilities is linked to "enthalpy waves" travelling upward in the system can be found in Fig. 6, where typical time traces of the temperature at the inlet and the exit of the riser encountered during flashing-induced oscillations are presented. The two time series are out of phase, indicating the wavy character of travelling enthalpy variations.

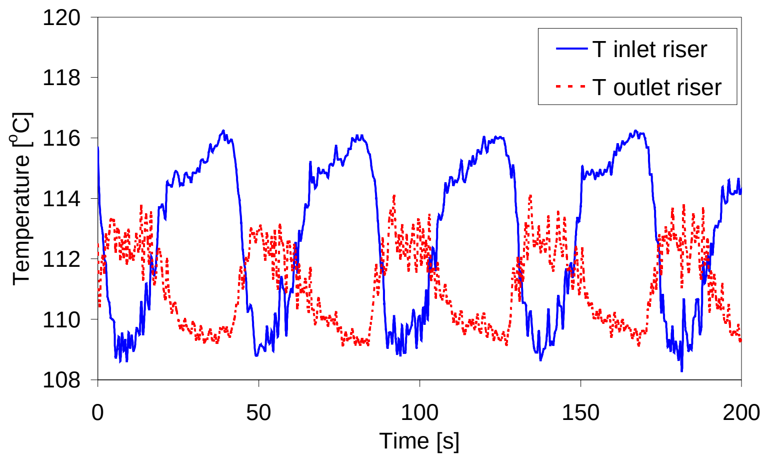

Fig. 6 Typical time traces of inlet and outlet temperatures in the riser during flashing-induced oscillations

The maximum values of the two temperature signals differ by several degrees from each other. This difference comes from energy conservation; in fact to produce void in an adiabatic section the fluid temperature has to decrease.

LDA set-up

Two LDA set-ups are used to measure the velocity in two heated parallel channels simultaneously. The reference beam technique is applied (see Fig. 7): a laser beam of a given frequency f_0 is divided in two parallel beams by means of a beam-splitter. The two beams are focused on the location where the fluid velocity has to be measured. One of the two beams (the so-called reference beam) is sent directly to the detector. The detector will detect the reference beam together with the light of the other beam (the scatter-beam) scattered by the fluid moving in the channel. The frequency of the scattered light depends on the fluid velocity according to the Doppler principle. The output of the detector will oscillate with a frequency $|f_0 - f_S|$, where f_S is the frequency of the Doppler shifted scattered light given by:

$$f_S = f_0 + \frac{2\sin\frac{\theta}{2}}{\lambda_0}\left|\vec{v}\right|\cos\alpha \qquad (1)$$

where v is the scattering particle velocity forming an angle α with the channel axis, θ is the angle formed between the reference and the scattered beam, as illustrated in Fig. 7, and λ_0 is the wave length of the laser used.

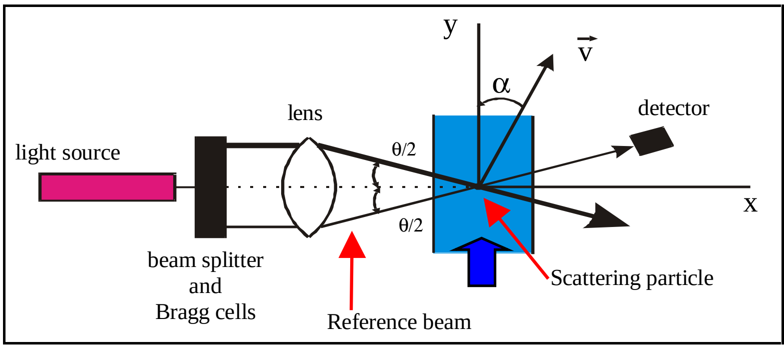

Fig. 7 Schematic representation of the reference beam set-up implemented

In principle, light scattered along the entire path of the scatter-beam will be seen by the detector. However, in practice only scattered light coming from the intersection of the two beams will give rise to a detectable frequency containing the Doppler shift.
As the detector only detects the absolute values of the Doppler shift, no negative velocities can be measured in this way. The measurement of negative velocities is made possible by pre-shifting one of the two beams. This is done by sending each of the two beams through a Bragg cell. The two cells modulate the beams at two chosen frequencies, whose difference is called the shift frequency f_{shift}. In this case the frequency experienced by the detector can be expressed as:

$$f = f_{shift} + \frac{2\sin\frac{\theta}{2}}{\lambda_0}\left|\vec{v}\right|\cos\alpha \qquad (2)$$

With an appropriate choice of the shift frequency negative velocities can be measured. In the specific case of the CIRCUS facility a green crystal light laser is used (wavelength of about 530 nm) and a shift frequency of 90kHz has been chosen.
A clear advantage of the LDA technique in comparison with other fast velocity measurement devices (such as, for example, orifice flowmeters) lays in the fact that LDA is not intrusive. The use of forward mode gives an optimal intensity for the

scattered light to be detected, so that no seeds are needed for the detection of the scattered light. This is of particular importance in the study of flashing-induced instabilities since seeds can act as nucleation sites, triggering void production.

Experimental results

Two sets of experiments have been carried out to study the characteristics of natural circulation at low pressure and low power conditions. In both series of measurements the total power has been varied from 5.6 kW to 9.8 kW and the inlet temperature has been ranged from about 98 to 102 ^{o}C. In the first set of measurement a symmetric power distribution has been adopted in the four channels, while in the second series of measurements an asymmetric power distribution has been applied. In particular, in the second set of measurements two channels have been kept at constant power equal to 2.8 kW while the power in the other two channels has been varied from 0 to 2.1 kW. Details on the power distributions set during the measurements are reported in Table 1, where P_i indicates the power in the i-th heated channel.

Total power	Series I	Series II
5.6 kW	$P_1 = P_2 = P_3 = P_4 = 1.4$ kW	$P_2 = P_4 = 0$ kW; $P_1 = P_3 = 2.8$ kW
7.0 kW	$P_1 = P_2 = P_3 = P_4 = 1.75$ kW	$P_2 = P_4 = 0.7$ kW; $P_1 = P_3 = 2.8$ kW
8.4 kW	$P_1 = P_2 = P_3 = P_4 = 2.1$ kW	$P_2 = P_4 = 1.4$ kW; $P_1 = P_3 = 2.8$ kW
9.8 kW	$P_1 = P_2 = P_3 = P_4 = 2.45$ kW	$P_2 = P_4 = 2.1$ kW; $P_1 = P_3 = 2.8$ kW

Table 1 Power distribution used during the two set of measurements

From Fig. 8 it can be seen that the oscillation period decreases with increasing power or inlet subcooling for symmetric as well asymmetric power distribution. This is consistent with the increase of average flow rate, reported in Fig. 9 since, as mentioned previously, the period of the oscillation is directly related to the travelling of enthalpy perturbations along the loop.

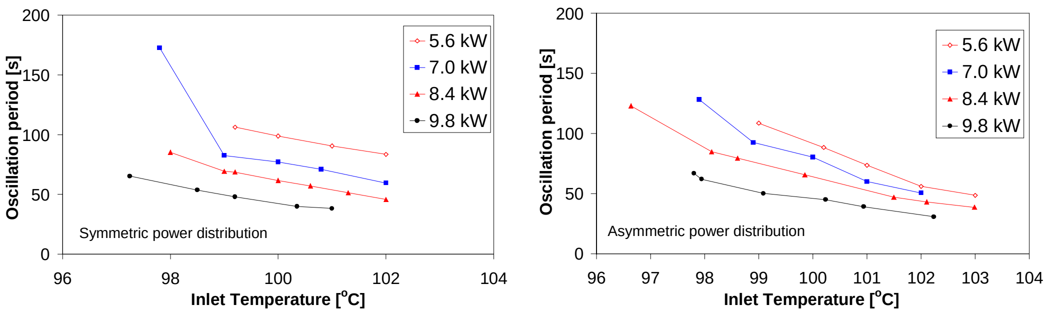

Fig. 8 Period of oscillation as function of power and inlet temperature for symmetric (left) and asymmetric (right) power distribution

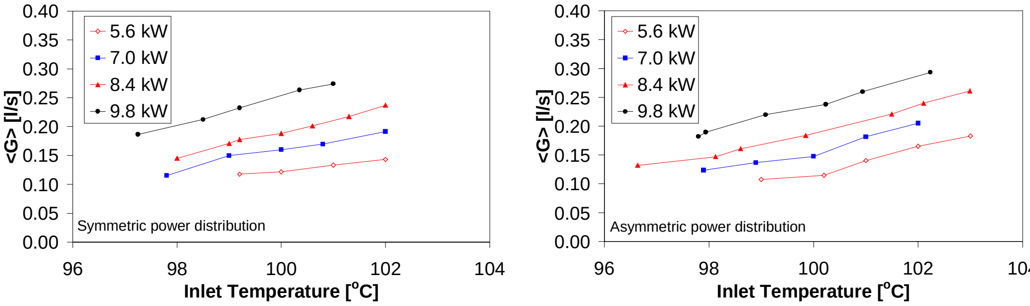

Fig. 9 Average inlet flow as function of power and inlet temperature for symmetric (left) and asymmetric (right) power distribution

In Fig. 10 the oscillation periods recorded during all the experiments performed in the two series of measurements are reported as function of $\tau_{1\phi}$ defined as:

$$\tau_{1\phi} = \frac{V_{core} + V_{riser}}{\langle G \rangle}, \tag{3}$$

where V_{core} and V_{riser} are the volumes of the core and riser section respectively and <G> is the average total flow rate in a period of the oscillation. $\tau_{1\phi}$ is the time needed for the single-phase flow to travel from the inlet of the core to the outlet of the riser with a flow equal to the total average flow rate <G>. It can be seen that, despite the difference in power and in inlet temperatures, most of the cases lay on the same line indicating a relation between period of oscillation and average flow rate. Similar results were already found by Aritomi and Chiang[3,4,5] both in case of natural and forced circulation, although experiments were limited to symmetric power distributions in natural circulation conditions.

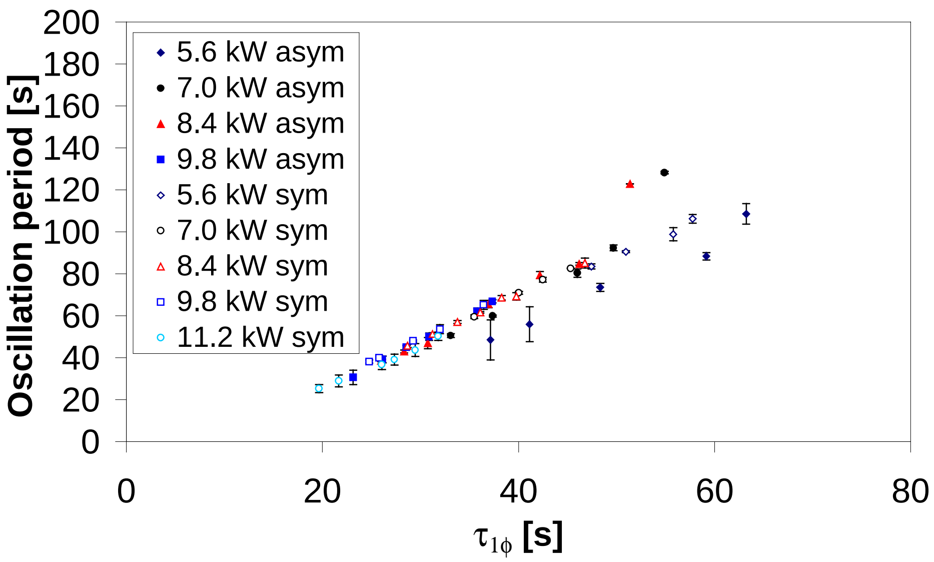

Fig. 10 Relation between oscillation period and average flow rate

Exception to the trend is found at lower flow rates (high $\tau_{1\phi}$) for asymmetric power distributions and all over the experimented range of flow rates for the case of the asymmetric power distribution at 5.6 kW, where the power of two channels is set to zero. The reason for this behaviour is not clear yet. However, in view of the different flow velocities in asymmetric conditions, it is not surprising that the relation between average flow rate and oscillation period is not linear any longer. As an example, in Fig. 11 the flow velocities measured in two heated channels in case of an asymmetric power distribution are shown. Channel 1 (as well as channel 3) is heated at a power level of 2.8 kW, while channels 2 and 4 are unheated in the case presented. It can be seen that for a long part of the oscillation period the velocity in the unheated channels is much lower than the velocity in the heated channels.

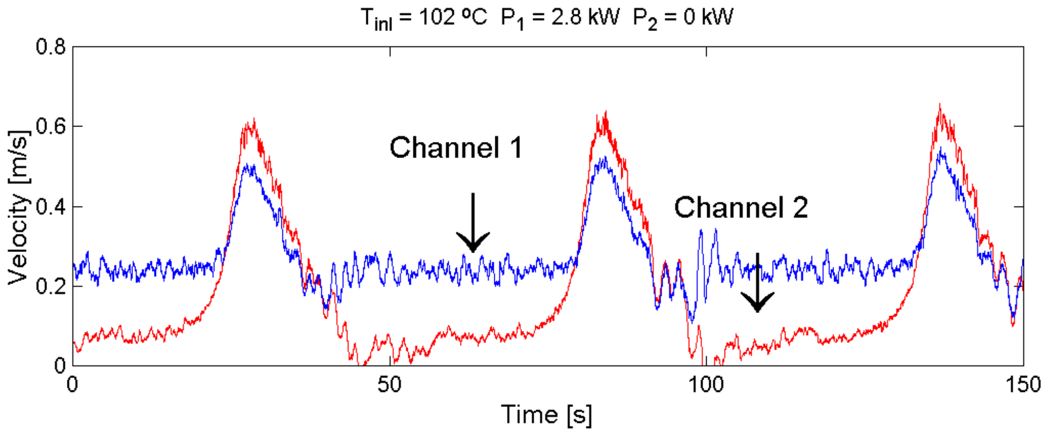

Fig. 11 Lda velocity measurements in two parallel channels for asymmetric power distribution

Conclusions

Different measurements techniques are used simultaneously to study in detail the dynamics of natural circulation cooled systems during flashing-induced instabilities at low pressure and low power conditions. Measurements of the 2D void fraction distribution by means of a wire mesh sensor located at the top of the riser section unveils the complex and fast dynamics of void production due to flashing during natural circulation instabilities. Two sets of experiments carried out at different powers and subcoolings point out a clear dependence of the oscillation period of the instabilities on the average flow rate circulating in the loop. Exceptions are found for some of the asymmetric cases studied.

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