STABILITY OF NATURAL CIRCULATION COOLED BOILING WATER REACTORS DURING START-UP

Annalisa Manera [1], Ulrich Rohde, and Frank Schaefer

1. Introduction

The evolution of boiling water reactors leads to designs with larger cores and to reactors cooled by natural circulation. An item of concern for BWRs was their susceptibility to unstable behavior. Fortunately, the experience collected during the years 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 in natural circulation. The latter instability mode was suggested to be relevant for natural circulation BWRs by Aritomi et.al. [1]. It is important during the start-up phase of the reactor, when pressure and power are low. In a series of dedicated tests on the Dodewaard reactor, indications for unstable behavior during the start-up phase were found [2]. 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 experiments and the modeling of flashing-induced instabilities with the codes FLOCAL and ATHLET is presented in this paper. The research has been carried out within the framework of the EU project NACUSP.

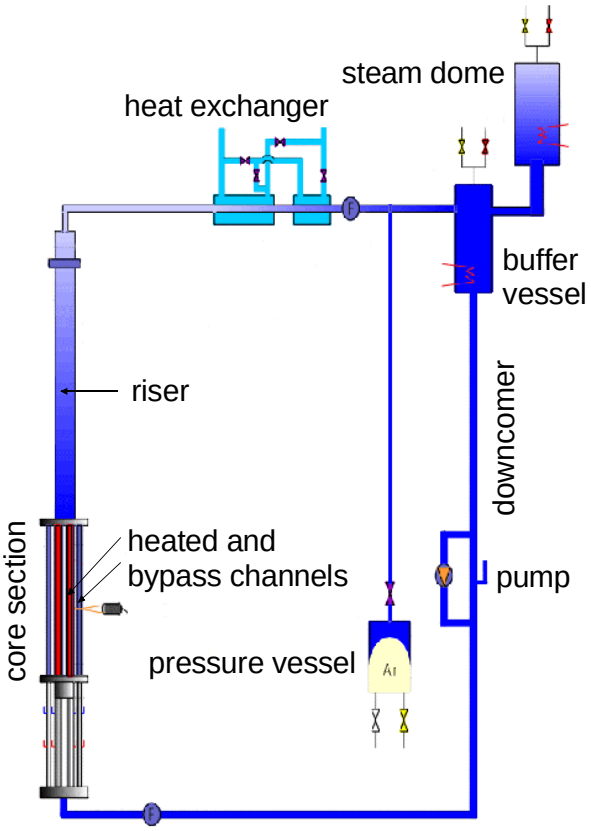

Fig. 1: The CIRCUS test facility

2. The CIRCUS test facility

The CIRCUS facility (Fig. 1) 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. 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 detailed description of the test facility is given in [3].

[1] Interfaculty Reactor Institute, Delft University of Technology, The Netherlands

3. 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 condition 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. 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. 2), 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 bubble 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.

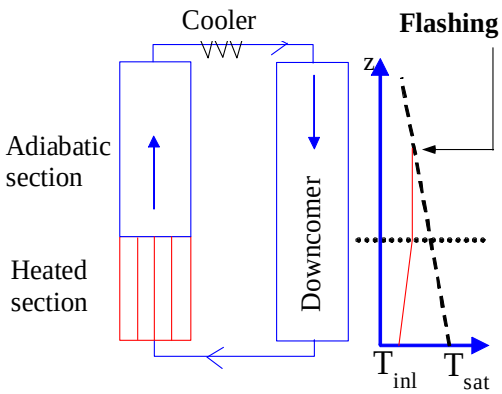

Fig. 2: Flashing in the riser (adiabatic section) of the CIRCUS test facility

4. Experiments and FLOCAL simulations

FLOCAL [4] is a one-dimensional 4-equation two-phase thermal-hydraulic code, originally developed to model the dynamic behavior of the AST-500, a Russian design nuclear reactor. The system of partial differential equations consists of a momentum, energy and mass balance equation for the two-phase mixture and a separate mass balance equation for the vapor phase. An 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, individual (parallel) risers or a common riser can be modeled. The parallel channels are coupled by a boundary condition of equal pressure drops over their total length. As boundary conditions, the core inlet temperature and the pressure at the riser outlet are kept constant. The boundary condition on the temperature is exact, since the inlet temperature is kept constant also during the experiments. This is not the case for the outlet pressure. At CIRCUS, the loop is connected to a steam dome, where a steam/water mixture 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 leads to 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 the analysis, one should expect higher amplitude of the flow oscillation in the simulations.

A series of experiments was carried out at the CIRCUS facility to study the characteristics of flashing-induced flow instabilities and to provide a data base 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 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 oscillates at which flashing starts (flashing boundary), 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. The 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 an unstable region has to be crossed. The code FLOCAL slightly over-estimates the maximum flow rate achieved during the flow oscillations. As mentioned previously, this is due to the fact that the feedback due to the presence of a steam dome has been neglected. Despite this approximation, the general phenomenology and trends seem to be reproduced very well.

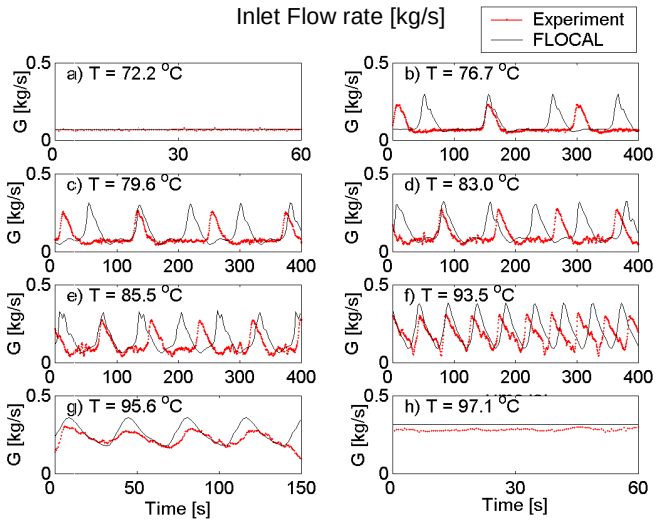

Fig. 3: Typical flow-rate time traces

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 (right picture) and experimental (left 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 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).

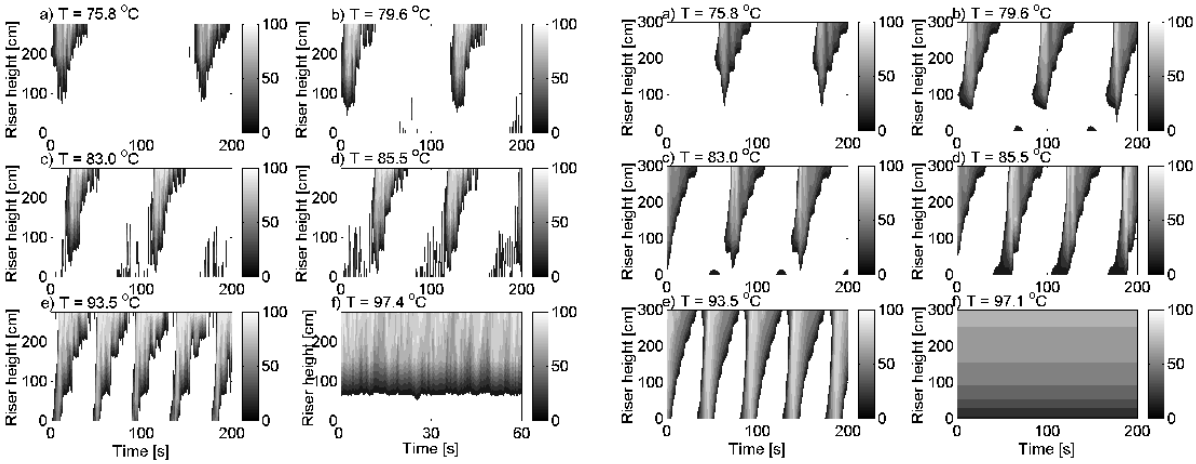

Fig. 4: Void-fraction evolution as measured with needle-probes at the CIRCUS facility (left) and from FLOCAL simulations (right). Vertical bars give the grey-scale coding for the void fraction (in percent)

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 <G>, 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. 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.

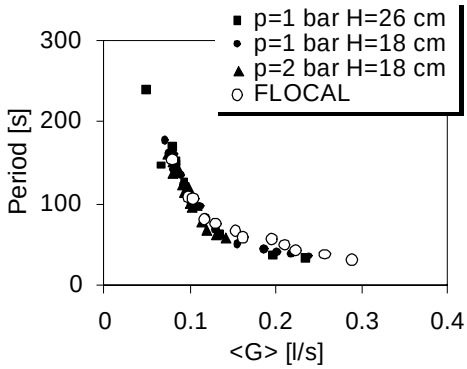

Fig. 5: Oscillations period as function of the average flow rate (H indicates the height of the steam cushion in the steam dome)

The relation between oscillation period and inlet subcooling is presented in Fig. 7 (8 kW, 1 bar), both for experiments and simulations. In many cases the FLOCAL model under-estimates the oscillation period (from Fig. 3 it can be seen that mainly the incubation period is under-estimated rather than the duration of the flow peak caused by the flashing transient). The oscillation period is well predicted at low subcoolings (i.e. high flow rates and absence of

single-phase circulation) and under-estimated 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, neglected in the calculation, and on the smearing of the temperature front during single-phase circulation. Calculations including heat losses have been performed 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. Thus this effect explains the trends observed in Fig. 7. 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).

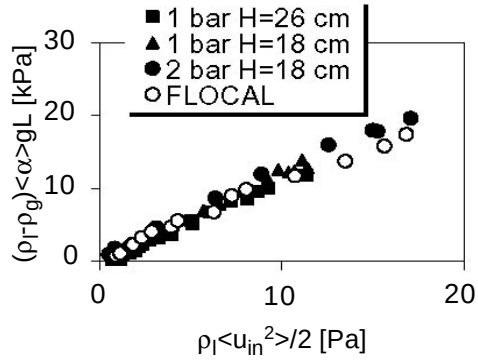

Fig. 6: Driving vs kinetic pressure

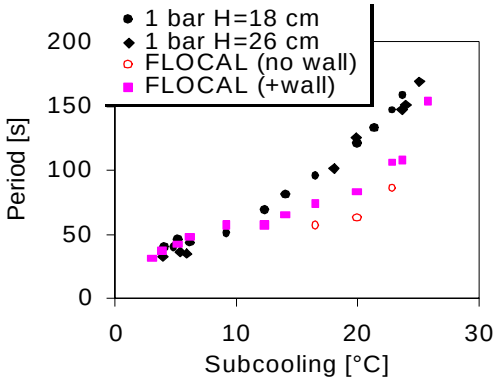

Fig. 7: Oscillation period as function of the inlet subcooling.

Several experiments have been carried out to derive so-called stability maps. These maps are represented in the power-subcooling plane since power and subcooling are the variables directly controlled during the measurements. Examples of stability maps are shown in Fig. 8 at a pressure of 1 bar and two different steam cushion heights in the steam dome. The stability boundaries predicted by FLOCAL are reported in the same figure. In agreement with other experimental results the range of inlet subcoolings for which instabilities occur increases with power. 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 will lead to vapor collapse and to an increase of saturation temperature. This feedback limits the amplitude of the flow oscillation. However, the effect on the extension of the unstable two-phase region is not significant, see Fig. 8.

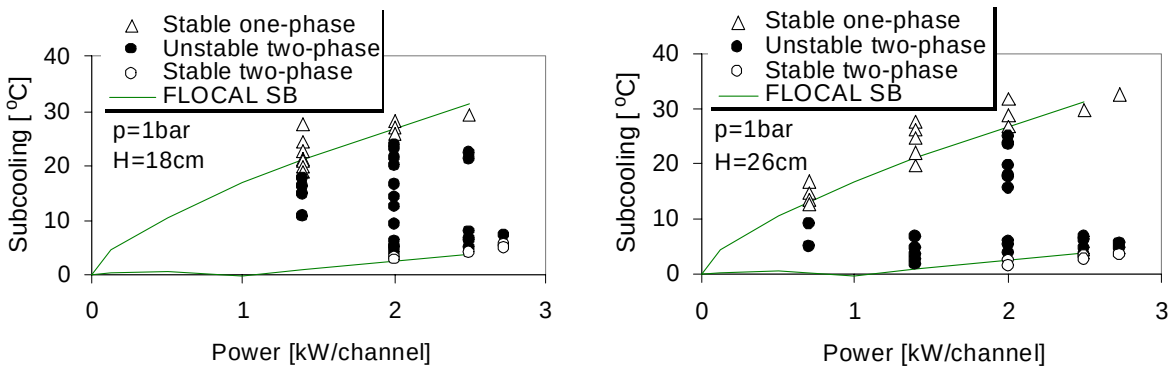

Fig. 8: Comparison between experimental and FLOCAL stability boundaries (H = steam cushion height in the steam dome)

5. Results of the ATHLET calculations

The FLOCAL code described in section 4 has been developed especially to model natural circulation instabilities. The aim of the investigations reported below was to demonstrate whether general thermo-hydraulic system codes like ATHLET are capable of reproducing the relevant phenomena too. For the presented calculations the code version ATHLET Mod 1.2 Cycle B [5] was used. The core section is modeled by 4 parallel channels. Each core channel is simulated as a pipe with an electrical heater. For the riser, downcomer, upper and lower horizontal parts the exact dimensions, heat capacities of glass and copper, heat losses and pressure drops are considered. The riser is modeled as an adiabatic section. The steam dome is connected to a pressure dependent volume to maintain the pressure during a steady state calculation. In the calculations the heat exchanger is not modeled. Therefore a bypass is connected to the downcomer section to keep the core inlet temperature constant. A special amount of water from the loop circulates through the bypass and can be injected with a lower temperature. In all control volumes the 5-equation model (separate conservation equations for liquid and vapour mass and energy, mixture momentum equation) and the full-range drift-flux model were used. With help of a steady state calculation the pressure losses, heat losses and the temperature distribution along the loop were adjusted according to the boundary conditions.

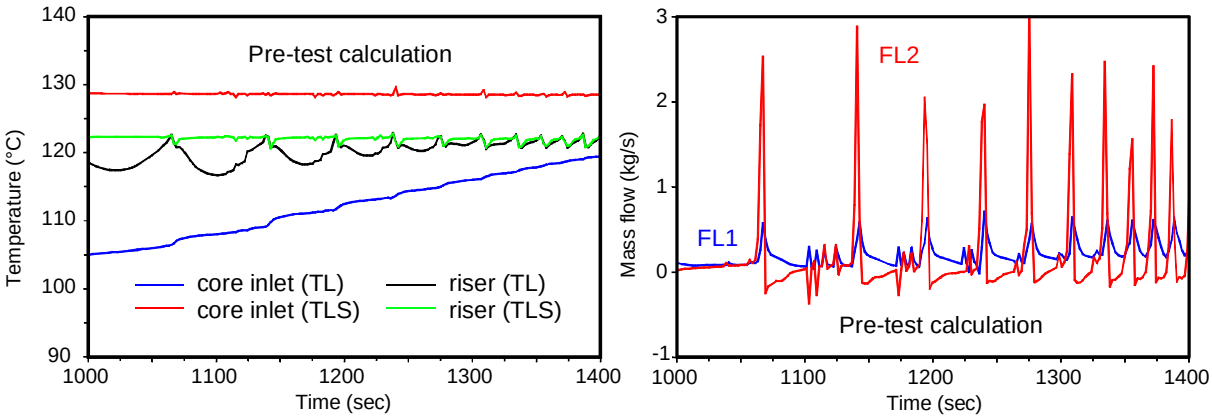

Fig. 9: Liquid (TL) and saturation (TLS) temperature at the core inlet and in the middle of the riser, core inlet mass flow (FL1) and mass flow in the upper horizontal part (FL2)

Within the NACUSP project pre-test calculations for different initial conditions (pressure, mass flow, core inlet temperature and core power) were performed. The pre-test calculations should answer the question, whether the program is able to calculate the flashing induced instabilities or not. The results of one pre-test calculation (pressure 2 bar, 8 kW power) are presented in Fig. 9. In this calculation the heat exchanger was not modelled. Due to the missing heat sink the temperature at the core inlet is rising from appr. 105 °C up to 120 °C. If the temperature in the upper part of the riser reaches saturation conditions, the flashing induced instabilities start. The phenomenology of these instabilities described in the previous section of that paper is well modeled by ATHLET. According to experiments with different core inlet temperatures, the period of the instabilities is shorter for higher temperatures. This effect can be seen in the calculated mass flows.

To consider the behaviour of the heat exchanger, a simplified bypass was modelled for the post-test calculations. The bypass is connected to the top of the downcomer to keep the core inlet temperature nearly constant during the transient calculation. The results for two transient calculations (different core inlet temperatures, pressure of 1 bar, 8 kW reactor power) are pre-

sented in Fig. 10 and 11. The results show, that the period of the instabilities is shorter for higher core inlet temperatures. This corresponds to the experimental findings. In general the calculated mass flows and temperatures show a very good agreement with the experimental data. Especially the period of the flashing induced instabilities can be reproduced very well. However, the magnitude of the mass flow oscillations is slightly overestimated.

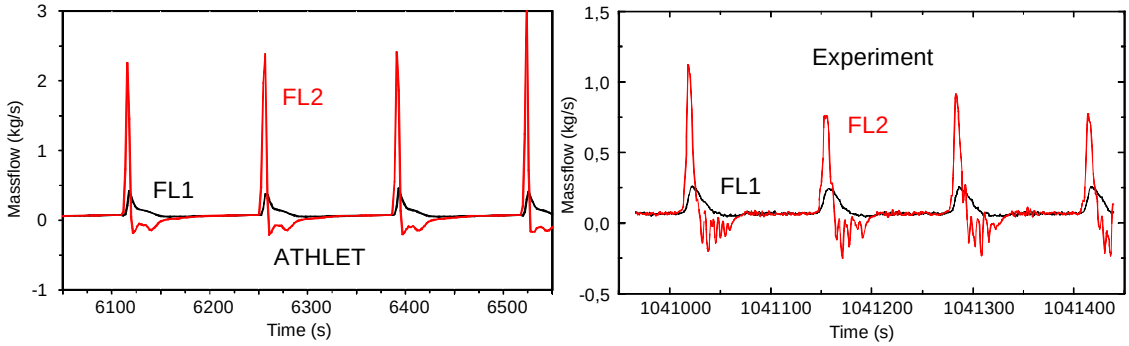

Fig. 10: Core inlet mass flow (FL1) and mass flow in the upper horizontal part (FL2) post-test calculation for 1 bar, 8 kW and T_{inl} = 78 °C

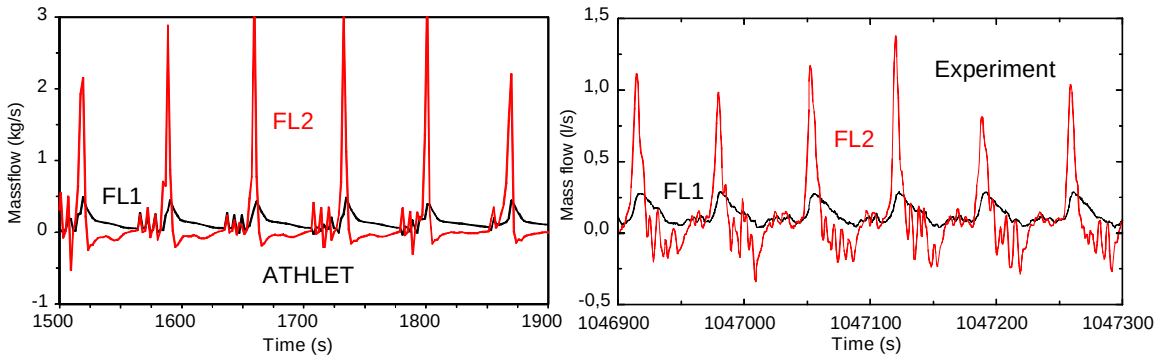

Fig. 11: Core inlet mass flow (FL1) and mass flow in the upper horizontal part (FL2) post-test calculation for 1 bar, 8 kW and T_{inl} = 86 °C

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