published on the 29th International Meeting on Reactor Noise, Budapest, 17-19 May 2004

INVESTIGATION OF FLASHING-INDUCED INSTABILITIES AT THE CIRCUS TEST FACILITY USING THE CODE ATHLET

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Introduction

The CIRCUS test facility (Circulation during startup) has been built to study the start-up phase of a natural-circulation BWR. During the start-up so called flashing-induced instabilities can arise. These instabilities are induced by flashing, due to steam production in the long adiabatic riser section, which is placed above the core to enhance the flow rate. Flashing occurring in the riser causes an unbalance between driving force and pressure losses in the natural-circulation loop, giving rise to flow oscillations.

The thermohydraulic code ATHLET, which has been developed by GRS (Gesellschaft für Anlagen- und Reaktorsicherheit mbH), is used for the calculation of natural circulation experiments at the CIRCUS test facility. In this paper calculations of selected experiments at low pressure conditions are presented. For the calculations the code version ATHLET Mod 1.2 CYCLE B was used [3].

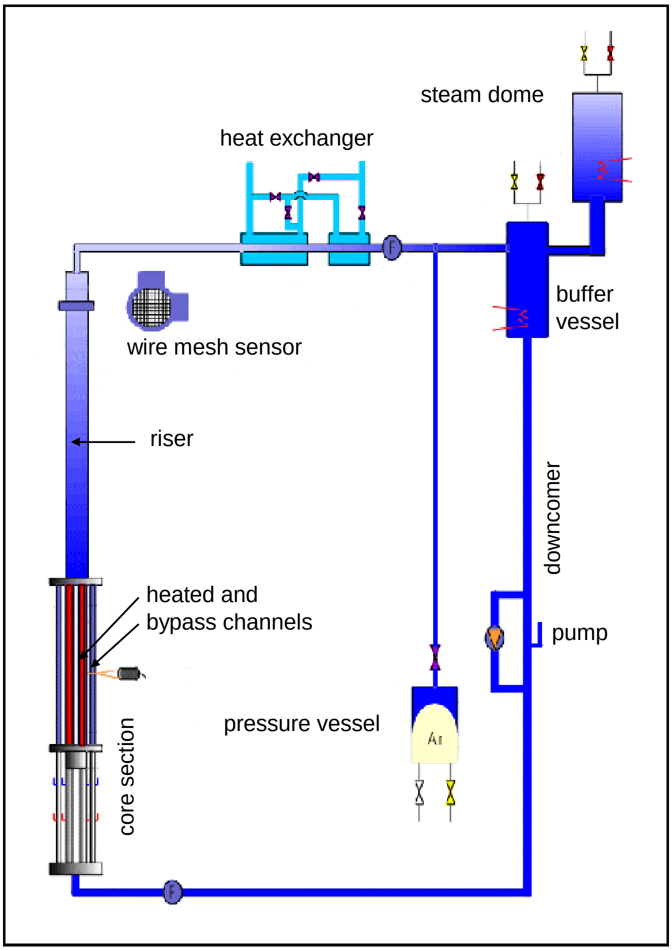

Fig. 1: Overview about the CIRCUS test facility, [1]

The CIRCUS test facility

The CIRCUS test facility (Fig. 1) consists of a single loop with a core section, riser and downcomer, the upper and lower horizontal parts, a buffer vessel and a steam dome. The core section consists of four electrically heated rods and four bypass channels. In the riser above the core the natural circulation is enhanced. In the heat exchanger the two-phase mixture is condensed. With help of the buffer vessel temperature and flow oscillations can be suppressed. A pump is installed in a downcomer bypass (not used during the experiments). The test facilitiy operates at low pressure (typically at 1 or 2 bar) with different core powers (up to 3 kW per heated channel).

Thermohydraulic model

The presented calculations were performed with ATHLET Mod 1.2 Cycle B, [3]. The input dataset models all main parts of the CIRCUS test facility (see Fig. 2). The core section is modelled by 4 parallel channels. The core bypass channels are not modelled. Each core channel is simulated as a pipe with an electrical heater. For the nodalization of 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 modelled as an adiabatic section. At the top of the facility the buffer vessel and steam dome are connected to a pressure dependent volume to maintain the pressure during a steady state calculation.

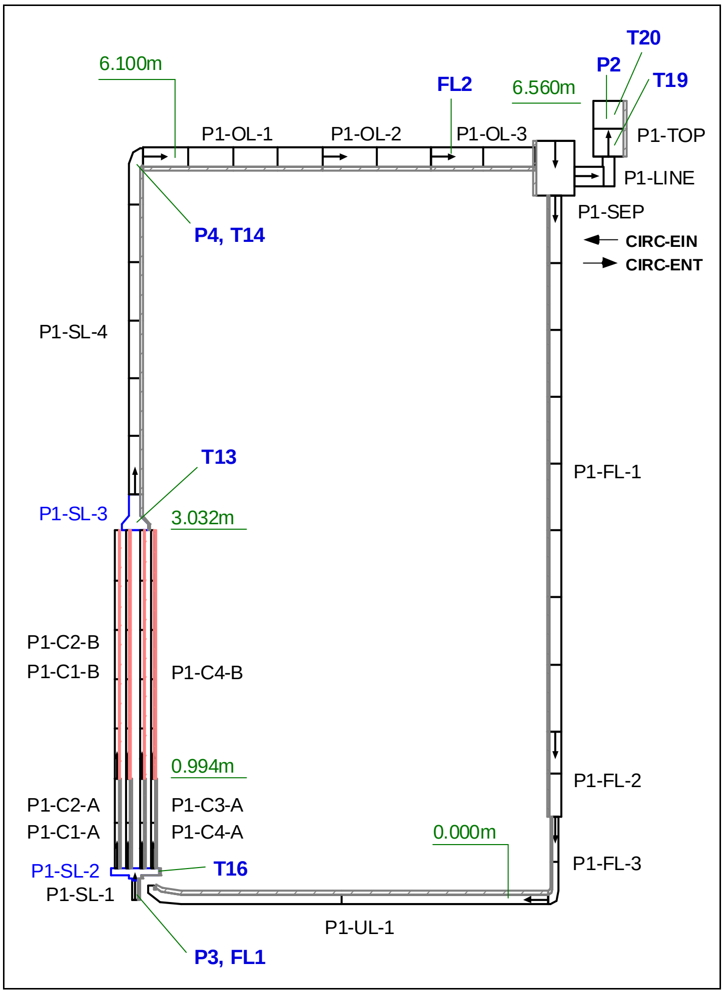

Fig. 2: Nodalization scheme for CIRCUS

Experiments

Different experiments were carried out at the CIRCUS test 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, Ref. [4]. The experiments were performed at pressures of 1 and 2 bar, with different core powers, core inlet temperatures and for different heights of the steam cushion in the steam dome. During each experiment the core power and the temperature at the inlet of the heated section were kept constant. Within a series of experiments the core inlet temperature was stepwise increased, while the systeme pressure and core power were kept constant. Fig. 3 shows typical results from such a series of experiments (pressure 1 bar, core power 8 kW). At a certain core inlet temperature the flashing-induced instabilities arise and with increasing inlet temperatures the period of the instabilities decreases.

Five experiments from a test series with 8 kW power and a system pressure of 1 bar were selected for a comparison with ATHLET calculations, see Table 1. The whole test series consists of 17 experiments with different core inlet temperatures.

Test No.	T_{inlet}	Test No.	T_{inlet}	Test No.	T_{inlet}
010913_M01	72.7 °C	010912_M03	78.25 °C	010912_M05	83.0 °C
010912_M07	87.3 °C	010912_M09	93.5 °C		

Table 1: Selected experiments from a test series at a pressure of 1 bar and a core power of 8 kW (2kW per channel)

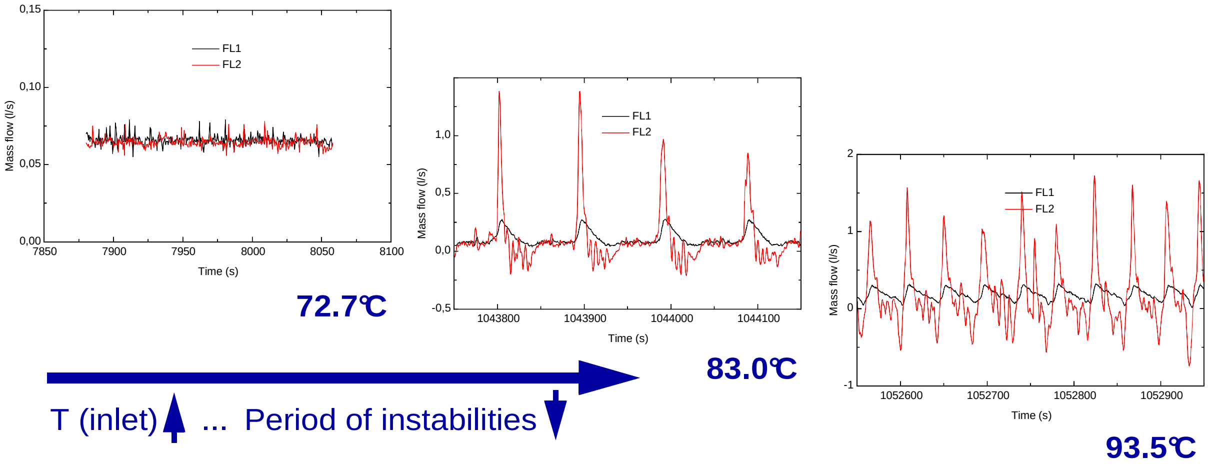

Fig. 3: Loop mass flow for different core inlet temperatures (experiment)

Steady state calculation

At first steady state calculations with constant boundary conditions were performed. With help of these calculations the pressure losses, heat losses and the temperature distribution along the loop were adjusted according to the boundary conditions described in [2]. For each test scenario (different pressures, core inlet temperatures and loop mass flows) a steady state calculation was performed. The steady state calculation starts with zero power. After a few seconds the core power is switched on and the power is increased stepwise with time. The steady steate calculation is stopped if the loop mass flow is nearly stable (see Fig. 4). At this point the reactor power is a bit lower than the nominal value. The temperature in the riser and also in the upper part of the facility is below the saturation temperature and in this way no flashing can occur.

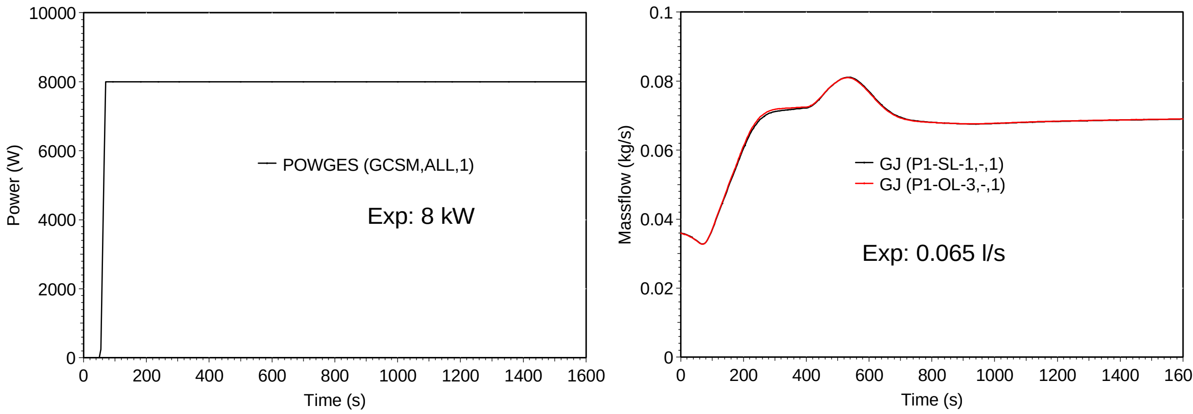

Fig. 4: Core power and loop mass flow - steady state calculation

Transient calculations

The transient calculations start if the mass flow in the loop is nearly stable and the reactor power has reached the nominal level, as described in the experimental scenario [2]. During the transient calculation the temperature in the adiabatic section increases with time. If the temperature in the upper part of the riser reaches saturation conditions, the flashing induced instabilities occur. Due to the void production in the riser, the natural circulation mass flow is increased. The increase of flow rate leads to a decrease of the coolant temperature at the inlet of the adiabatic section, so that the process of flashing will stop and the flow rate will be low again. After a few seconds delay the coolant temperature entering the adiabatic section increases again, leading to a new flashing cycle. This behaviour in case of the calculated void fraction and mass flow can be seen in Figure 5. In this calculation a dataset with finer nodalization was used to visualize the void fraction distribution. The blue color in the nodalization corresponds to a void fraction of 0 % and the red color is equivalent to a void fraction of 100 %.

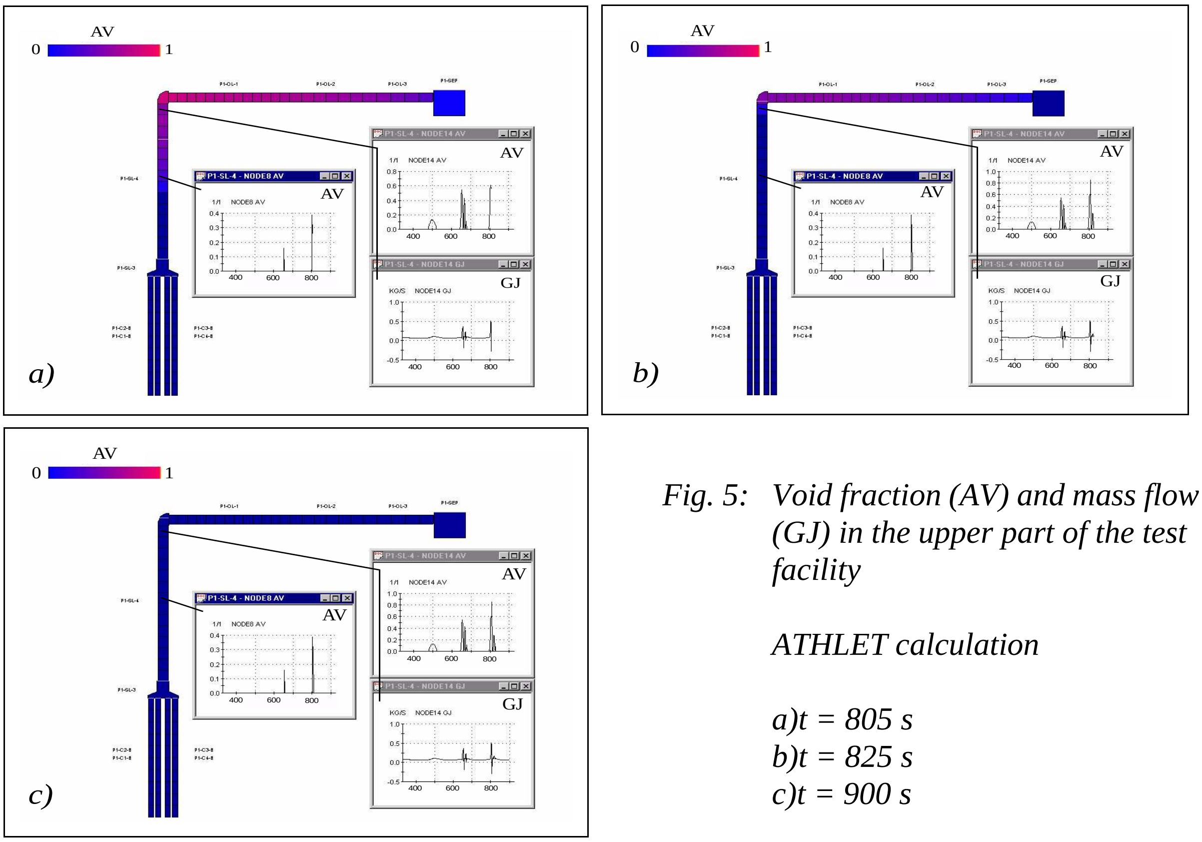

Fig. 5: Void fraction (AV) and mass flow (GJ) in the upper part of the test facility

ATHLET calculation

a)t = 805 s
b)t = 825 s
c)t = 900 s

Fig. 6 and Fig. 7 show a comparison between calculated and experimental results in case of experiment 010912_M05 and 010912_M09. These two experiments were performed with 8 kW core power, a system pressure of 1 bar and core inlet temperatures of 83 °C and 93 °C. The ATHLET calculations show, that the period of the instabilities is shorter for higher core inlet temperatures. This corresponds to the experimental results. In general the calculated mass flows show a good agreement with the experimental data. How described further above, the flashing induced instabilities start when the temperature in the riser reaches saturation conditions.

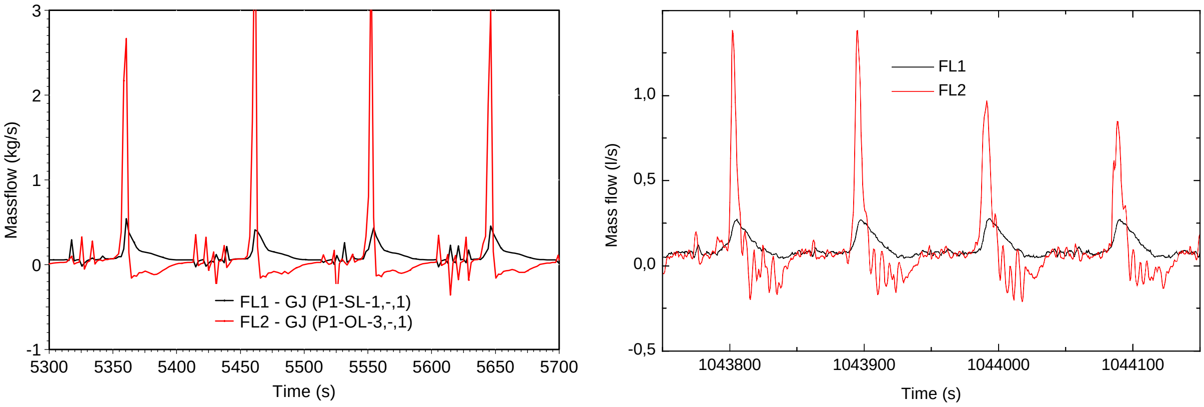

Fig. 6: Mass flow at core inlet (FL1) and heat exchanger outlet (FL2)
ATHLET calculation (left) and experiment 010912_M05 *(right) -* T_{inlet} *= 83 °C*

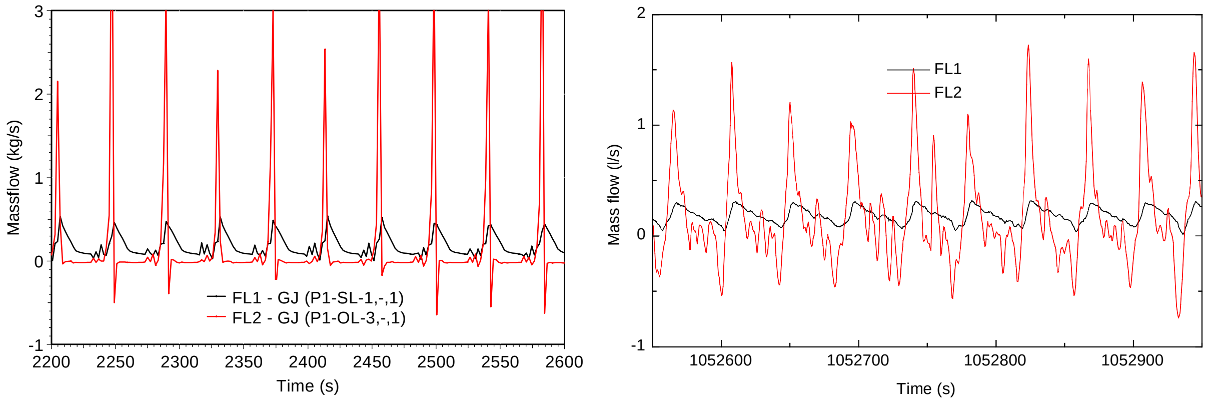

Fig. 7: Mass flow at core inlet (FL1) and heat exchanger outlet (FL2)
ATHLET calculation (left) and experiment 010912_M09 *(right) -* T_{inlet} = *93 °C*

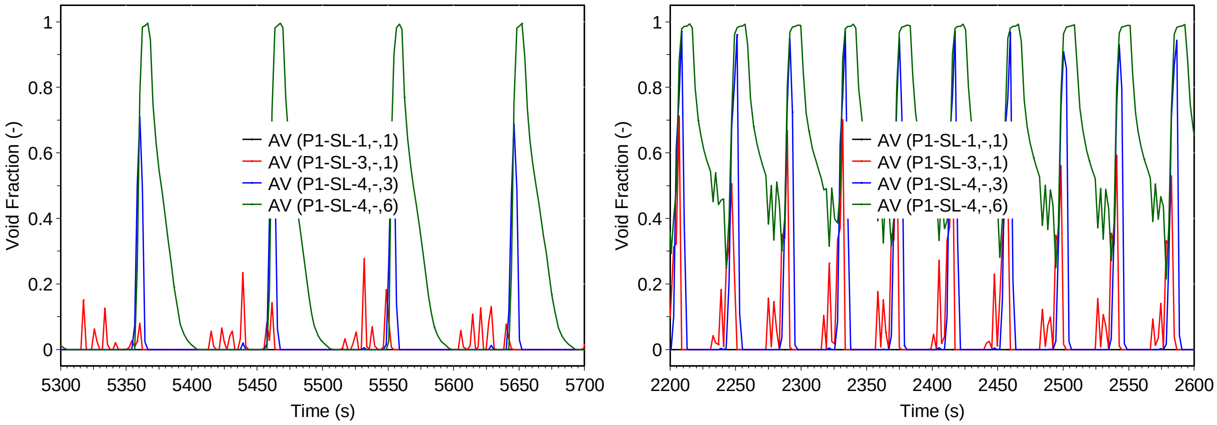

Fig. 8: Calculated void fraction at core inlet (P1-SL-1,-,1), core outlet (P1-SL-3,-,1), middle (P1-SL-4,-,3) and top of the riser (P1-SL-4,-,6)

Calculation of experiment 010912_M05 *(*T_{inlet} *= 83 °C): left*
Calculation of experiment 010912_M09 *(*T_{inlet} *= 93 °C): right*

Already at the core outlet flashing can occur. Above the core the void fraction increases with the height of the riser. The time dependent behavior of the void fraction ist illustrated in Fig. 8 for the ATHLET calculations. The void production in the riser leads to an increased mass flow in the loop and afterwards to a decrease of the core inlet temperature, so the flashing will stop. After a few seconds delay the core inlet temperature increases again and a new flashing cycle can start. As in the experiments in all ATHLET calculations the period of the flashing induced instabilities depends on the core inlet temperature. In case of the mass flow rate Fig. 9 show a comparison of all 5 ATHLET calculations with the experimental data. The calculated periods show a very good agreement with the experiments.

Further ATHLET calculations show, that the heat capacities and heat losses of the CIRCUS loop have also an influence on the calculated period. The results of different calculations with and without heat structures show, that the period of the instabilities can fluctuate by a factor of about 20 or 30%. Without consideration of heat losses and heat capacities the period is shorter, see Fig. 10. In addition calculations with a more detailed nodalization has been performed to investigate the influence of the nodalization. These calculations show, that the calculated period did not depend on the number of nodes used in the ATHLET model. In a calculation with a finer nodalization the flashing induced instabilities starts later in time, but the period of the instabilities is the same as in the previous calculation, see Fig. 11.

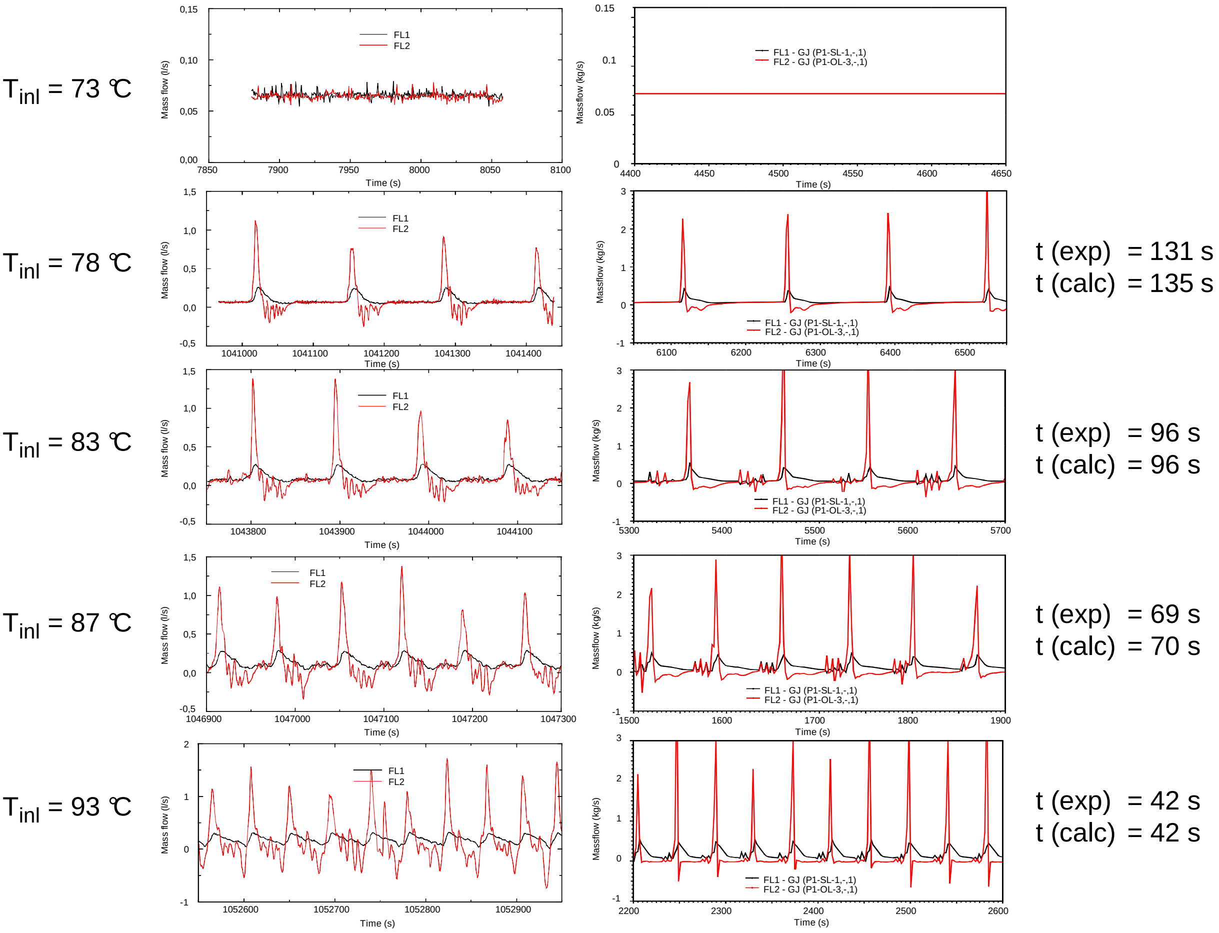

Fig. 9: Measured and calculated loop mass flows and periods of the instabilities for different core inlet temperatures - experiment (left) and calculation (right)

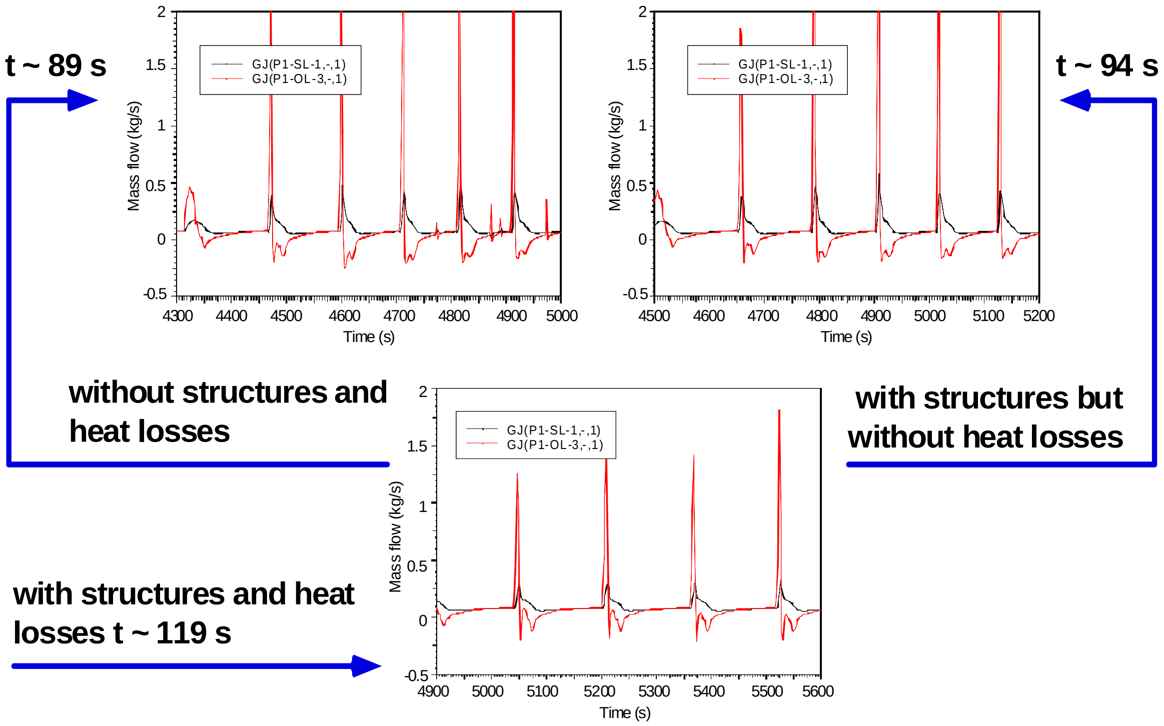

Fig. 10: Calculated loop mass flows and periods of the instabilities with and without structures and heat losses

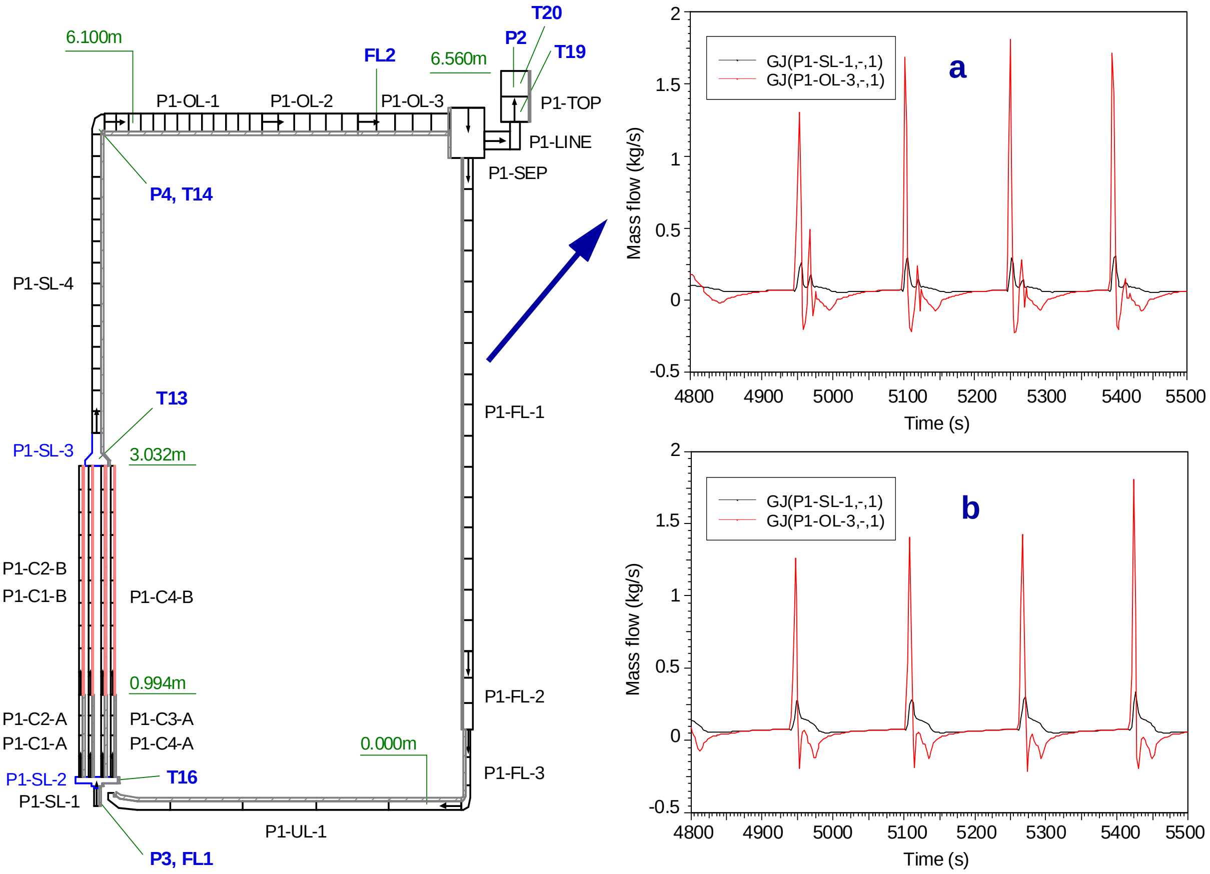

Fig. 11: Calculated loop mass flows with a more detailed nodalization (a) compared to the nodalization used in the other calculations in this paper (b) - see also Fig. 2.

Summary

The presented calculations show, that the flashing induced instabilities can be modelled with the code ATHLET. The period of the instabilities depends mainly on the core inlet temperature. The ATHLET calculations reproduce this behaviour very well in a qualitative and also quantitative way. Additional calculations show, that the period depends on the heat capacities and also on the heat losses of the CIRCUS test facility. Without consideration of heat losses and / or heat capacities the period is shorter. To predict the period of the instabilities, the heat capacities and heat losses must be modelled as exactly as possible.

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