Detailed investigations on flow boiling of water up to the critical heat flux

Stephan Gabriel, Giancarlo Albrecht, Wilson Heiler, Felix Heineken

Introduction

The prediction of two-phase flows with heat transfer using system codes and CFD methods is essential in various power-engineering applications. The current projects of the working group Multiphase Flow (MPF) deal with topics from the field of In Vessel Retention (IVR) by External Reactor Vessel Cooling (ERVC) as an emergency procedure as well as safety-related evaluation of different designs of small modular reactors (SMR) with respect to the boiling processes under full-scale conditions.

The research group concentrates on experimental investigations, in particular on boiling under forced convection up to the critical heat flux. The activities in 2020 focused on the measurement of the critical heat flux at fluctuating mass flows, which can occur under ERVC conditions at the low-pressure COSMOS-L facility. At COSMOS-H , work was continued on completion and commissioning of the loops and, in addition, an initial project relating to small modular reactors (SMR) was started. Within the scope of both projects, the measurement technology was further developed in order to be able to record the relevant measured variables in as much as detailed as possible.

COSMOS-L

Within the scope of the BMWi - project KEKSIMA the critical heat flow under periodically fluctuating mass flows is being investigated in comparison to steady state conditions. The aim is a better understanding of the physical processes in IVR/EVRC scenarios as they are for example conceivable in Gen III+ reactors (e.g. AP1000).

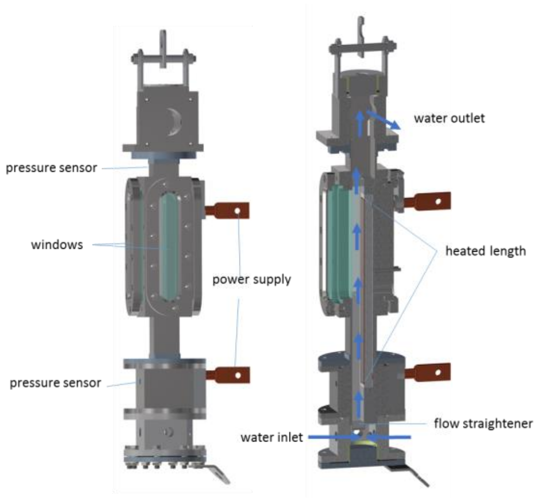


Figure 1 CAD-model of the new test section with planar heater

In cooperation with our project partner KIT/IATF, a new test section with a flat heater (heated length 300 mm, width 20 mm) was developed (Figure 1) for the low pressure loop. The heater is made of stainless steel and extensively instrumented for the measurement of temperature distribution, heating power, pressure gradient and mass flow. In addition, sight glasses from three sides allow the use of optical measurement technology. This test section uses temperature-resistant 3D-printed plastic parts for the first time in COSMOS-L. A flow straightener and several supports for thermocouples at the heater were manufactured. The components can be used permanently at temperatures significantly above 200°C and have already proven themselves in the first experiments.

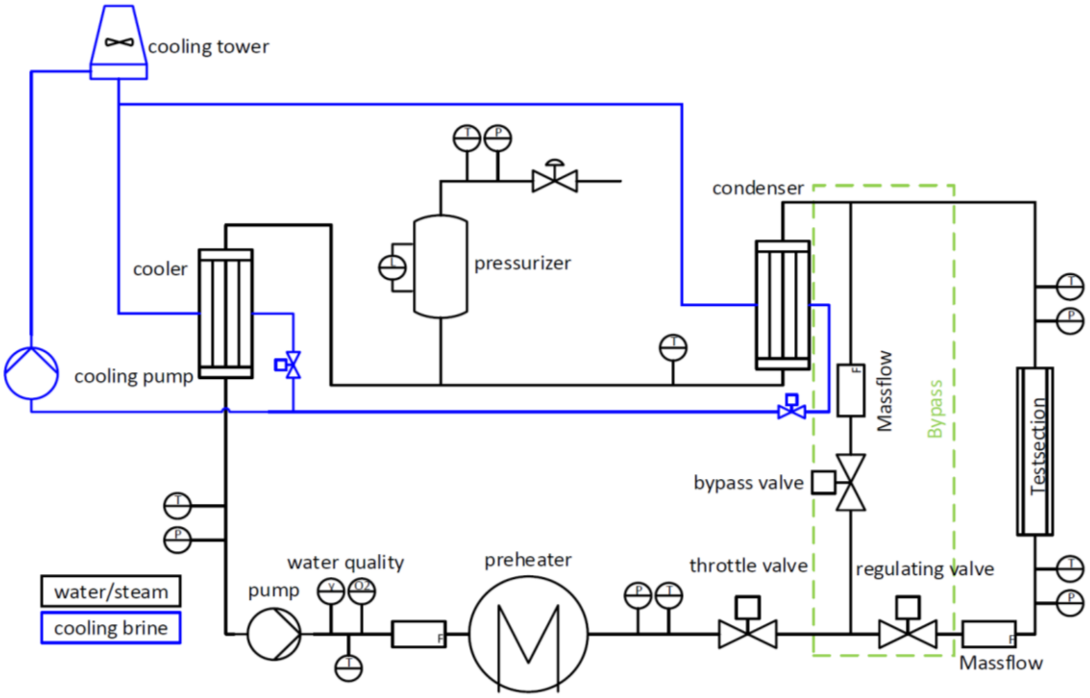
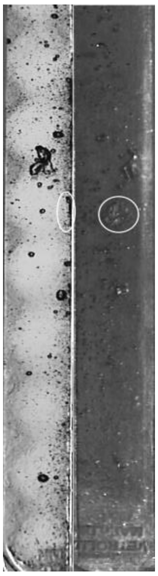


Figure 2 Simplified P&ID of COSMOS-L with new test section bypass

In addition, COSMOS-L was extended with a bypass parallel to the test section (Figure 2). It is controlled by fast-switching proportional valves and has an additional flow meter in order to measure the mass flow through the test section accurately. The mass flow can now be varied via the valves without having to change the total mass flow of the pump. The profile of the variation is thereby programmable. Test track and water loop were put into operation and a first series of tests was carried out. Figure 3 shows two snapshots of the overflowed

Parameter	Value
Pressure	1200 mbar
T_{Inlet}	60°C
Subcooling	45 K
Mass flow density	185 kg/m²s
Heating power	9,3 kW



Parameter	Value
Pressure	1200 mbar
T_{Inlet}	60°C
Subcooling	45 K
Mass flow density	185 kg/m²s
Heating power	0 kW

Figure 3 Instant image of the heated section shortly before the boiling crisis (l) and immediately after the power discharge (r).

heater from these tests. Both images show the side view on the left and the front view on the right of the test track respectively.

First, a number of tests were carried out to determine the measurement uncertainty of the critical heat flux. Subsequently, the first parameter variations were conducted. As the main parameter of the investigation, both the period and amplitude of the oscillation were varied. Experiments were started in which the mass flow oscillates periodically (Figure 4).

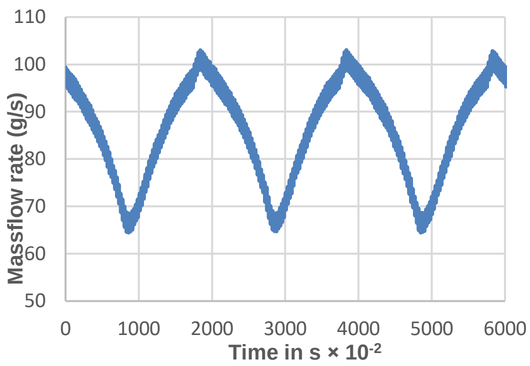


Figure 4 Oscillating mass flow during the first experiments

During the tests, the temperature distribution was observed through thermocouples attached to the back of the heater. The boiling crisis was detected by the associated temperature excursion at the heater and the heating power was dropped to protect the test section (Figure 5).

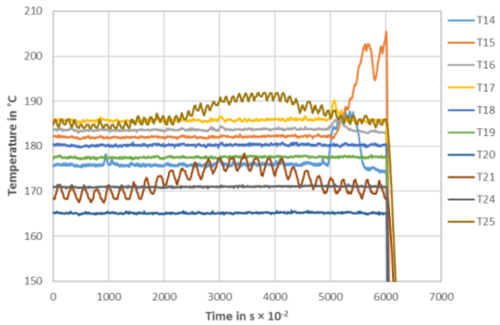


Figure 5 Temperature distribution at the heater

The values obtained this way already show a measurable influence of the fluctuations in the first tests. In Table 1 the example of two selected measuring points shows a reduction of the critical power with fluctuating mass flows of approx. 2.7% with a measurement uncertainty of approx. 1%. This already occurs with a mass flow amplitude of 30% of the nominal value; in the postulated scenario of an IVR, much larger amplitude values can also occur.

Several test series with additional optical instrumentation and parameter variations will be conducted with this test setup over the next few months. In order to investigate larger mass flows with constant inlet subcooling, the thermal power of COSMOS-L facility will be increased in the near future by an additional heat exchanger in order to be able to investigate larger mass flows with constant inlet subcooling.

Exp.	Pressure mbar	Temperature inlet °C	Subcooling K	Massflow-rate kg/m²s	Periode s	Amplitude %	Critical Power kW
1.1	1200	75	45	400	-	-	8.93
1.3	1200	75	45	400	50	30	8.69

Figure 6 Extract from the test evaluation of the first test series. Comparison of a measurement with stationary mass flow and a measurement with fluctuating mass flow

COSMOS-H

Complementary to the activities on the low-pressure facility COSMOS-L, the completion and commissioning of the high-pressure facility COSMOS-H is currently in progress. In 2020, further subsystems of the plant were finalized. Figure 7 shows the simplified flow diagram of the plant, which has two cooling circuits in addition to the high-pressure circuit. With an installed thermal power of approx. 2 MW and a working pressure of up to 17 MPa at approx. 360°C, the water/steam circuit will reach power plant conditions in test operation.

In the EU project McSafer, which started in 2020, investigations into the safety of various SMRs [1] are planned together with the project partner KIT/INR and other partners from research and industry. In COSMOS-H, experiments on heat transfer from nucleate boiling up to the critical heat flow will be carried out on two different test setups, a single tube in the annular gap and a rod bundle consisting of five zircalloy-4 tubes. Comparable experiments have already been performed with a smaller heated length under low pressure conditions at COSMOS-L [2, 3].

Figure 8 shows the first test arrangement. The heated section was constructed and the first components have already been manufactured. The assembly will be fully built up in the following months. In addition to thermocouples and pressure sensors, laser-based glass fibre sensors [4] will also be used in these experiments to measure the phase distribution.

To create a well-defined inflow condition, a flow straightener will be positioned at the inlet of the annular gap. Caused by the electrical, thermal and hydraulic requirements, this part was realized as a ceramic 3D print [Figure 9].

Furthermore, the test track has several sight glasses so that optical methods such as high-speed videometry can also be used in future experiments. As the test track has an increased risk of leaks due to the glass windows, a multi-stage safety concept was created for the plant. For this reason, a fragment shield was constructed around the test section to catch glass splinters and the steam jet in the case of a window failure [Figure 10].

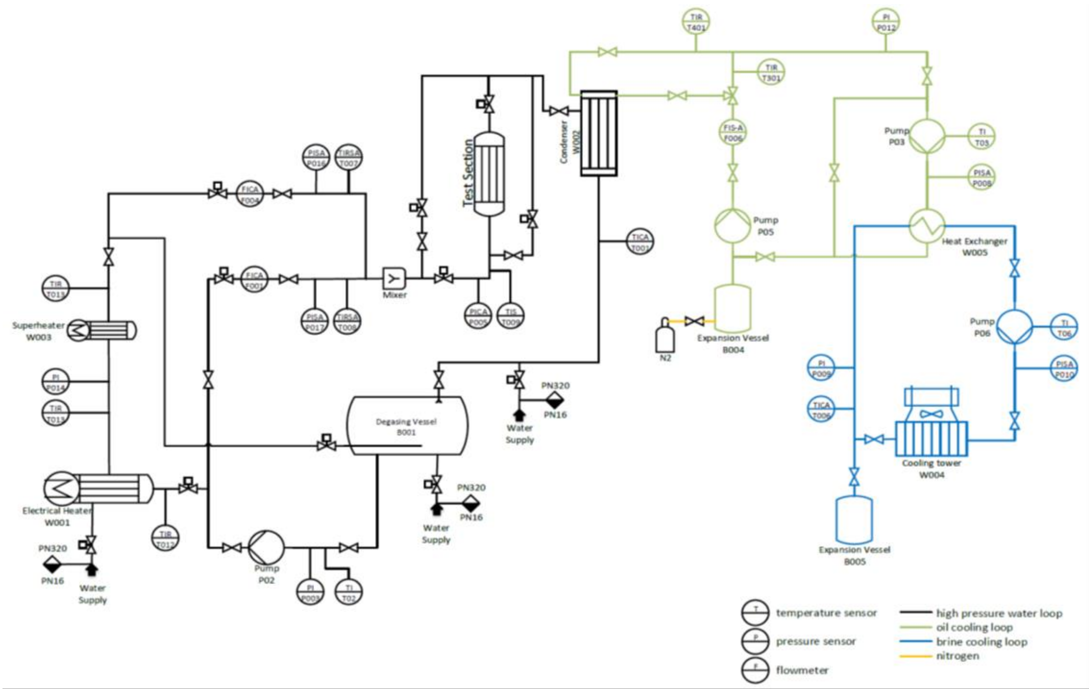


Figure 7 Simplified P&ID of COSMOS-H

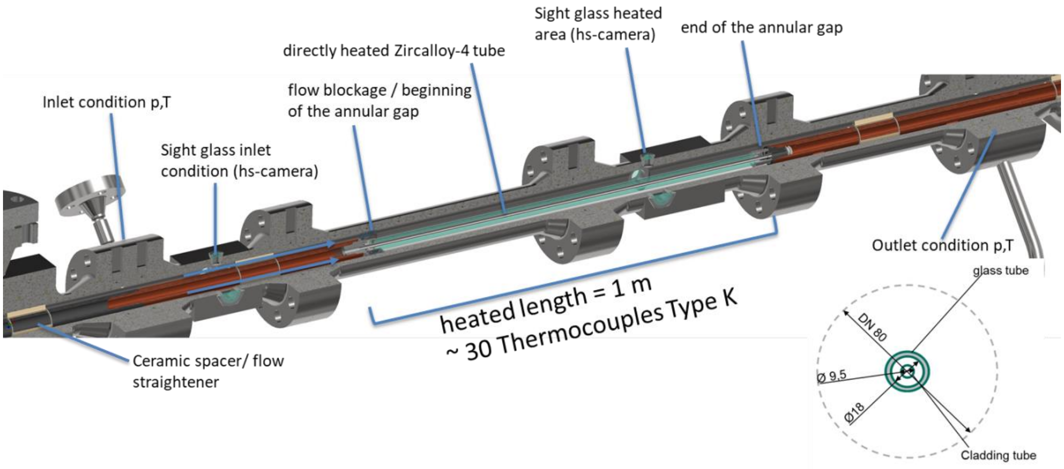


Figure 8 Test arrangement with a single tube in an annular gap

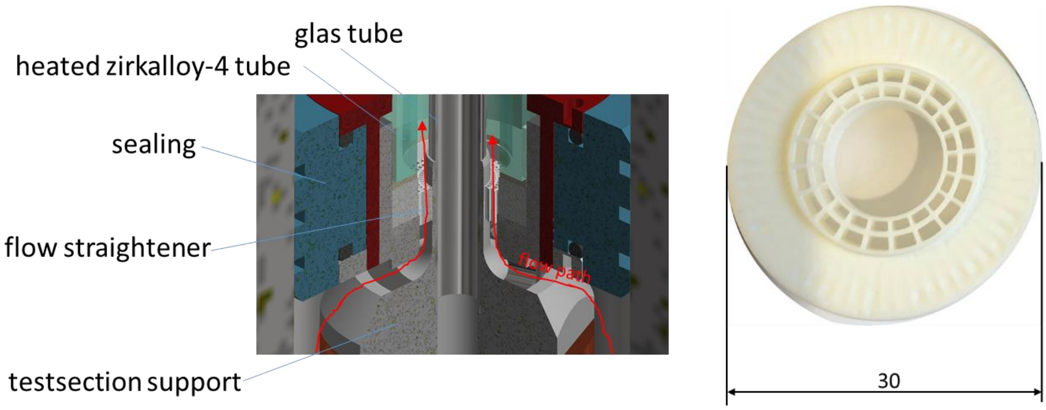


Figure 9 Flow straightener in CAD model and as 3D printed part made of AL_2O_3 ceramics

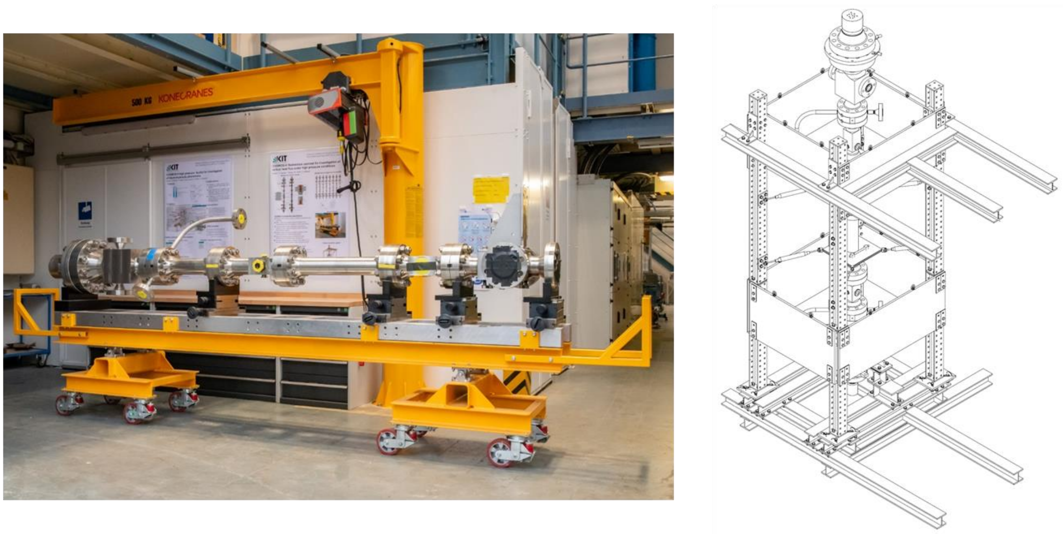


Figure 10 Pressure hull of the test section including high-pressure windows (l) and fragment shields (r)

Acknowledgements

We would like to thank Prof. Xu Cheng and Stelios Michaelides for the fruitful cooperation in the project KEK-SIMA (FKZ1501577). Furthermore, we would like to thank Victor Sanchez for his support and the good cooperation in Project McSafer (GA No 945063).

References

1. Reitsma, F.; Subki, M.H.; Luque-Gutierrez, J.C.; Bouchet; S.; Advances in Small Modular Reactor Technology Developments, A Supplement to: IAEA Advanced Reactors Information System (ARIS) 2020 Edition; http://aris.iaea.org.

2. Kaiser, F.; Gabriel, S.; Albrecht, G.; (2017); Investigation of the Critical Heat Flux in an Annular Gap and a Rod Bundle Configuration under low Pressure Conditions. ProcessNet-Fachgruppe Wärme- und Stoffübertragung, Bruchsal, 16.-17. Februar 2017

3. Kaiser. F.; Dietrich, B.; Gabriel, S.; Wetzel, T.; Experimentelle Ermittlung von kritischen Wärmestromdichten bei reaktortypischen Bedingungen als Validierungsdaten, Final Report Project NUBEKS (BMWi 1501473B, 27.02.2019)

4. Heineken, F.; Weiterentwicklung von lasergestützten Glasfasersonden zur Messung der Phasenanteile in Zweiphasenströmungen, Bachelorthesis KIT, ITES, 2020