Group: Multi Phase Flow

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

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Introduction

The research group Multiphase Flows (MPF) emerges 2018 together with the group Severe Accident Research (SAR) from the Accident Analyses group (UNA) and deals with technically relevant, complex multiphase flows. During the last two years, the activities concentrated on the construction of the high-pressure test facility COSMOS-H and the experiments on the low-pressure test facility COSMOS-L, which were carried out in cooperation with the Institute for Thermal Process Engineering (TVT) at KIT and partners from industry and research.

The subject was flow boiling under forced convection up to critical heat flux (CHF). Boiling media are often used in heat exchangers to enable effective cooling of technical systems. However, when the critical heat flux is reached, the boiling crisis occurs and a sudden rise in temperature will follow, which can lead to a possible damage to system components.

Numerous experiments on COSMOS-L and preliminary tests were carried out for this purpose. Additionally, our special measurement techniques such as fibre optic void sensors or videometric void measurement technique (OVM) have also been enhanced. The experiments were carried out on the one hand in an annular test section and on the other hand in a rod bundle test section. At the same time, a test track was built up for the high-pressure tests and the construction of the high-pressure facility COSMOS-H was continued.

Experiments on Boiling under forced convection up to critical heat flux

At the COSMOS-L test facility, deionised water is used as test medium to investigate boiling crisis for various operating conditions and test section configurations. First experiments were carried out in the annular test section with one heated tube of 32 cm length made from zircalloy-4. Water is pumped through the annular gap with defined pressures and inlet temperatures while the cladding tube is electrically heated. This results in heat transfer between the cladding tube and the surrounding water up to flow boiling and critical heat flux. The system pressure was varied between 0.1 – 0.3 MPa. The maximum heat power of the test section was 17 kW; this corresponds to a heat flux of 1.78 MW/m².

A second test series was carried out in a new rod bundle test section consisting of five tubes. Mass flow and pressure were slightly reduced in these experiments, but the critical power was significantly higher. The test section assembly consists of a central tube surrounded by four additional tubes. All tubes are individually heated and instrumented. The central tube gets a moderately higher heating power, which allows that the instrumentation can be concentrated on the center tube.

Experiments in the annular test section

Extensive experiments were carried out to determine CHF statistics at the annular gap. The first experiment consisted of a CHF statistic.

Criteria for persistence and reproducibility were identified and the measurement uncertainty of the instrumentation was determined. Due to the possibility for a quick load shedding at COSMOS-L, 55 tests could be carried out in series with the same tube without any damage. The results are shown for one parameter set in the diagram in Figure 1. It shows that CHF is not a single value, but appears as a distribution.

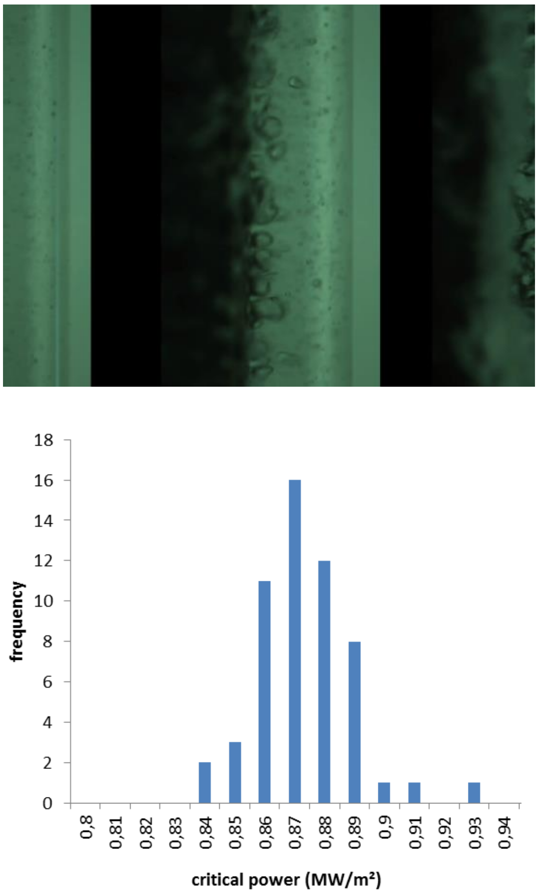

Fig. 1: Flow image and CHF-statistics over 55 single CHF Events

Further measurements were carried out with (laser-) optical fibre sensors at the annular gap to determine the local vapour content. The required optical fibre probes were manufactured, tested and validated. Measurements were performed on four parameter sets. In addition to the transformer power for heat input, the positions of the optical fibre probes were varied radially and axially, resulting in a total of 21 measuring positions. An example of the results is shown in Figure 2. The diagram shows the local vapor content as a function of the radial distance to the tube surface. The evaluation of these measurements showed that at a high power input in the upper area of the annular gap steam clusters flow along at some distance from the heating rod. As the power input decreases, these steam connections become significantly smaller. In the middle and lower area of the annular gap are no steam clusters visible. A reduced subcooling temperature hardly changes the flow conditions in the annular gap. This can be seen from the significant similarity of the content of the local steam content. However, the absolute values are lower at lower subcooling temperatures. An increase of the mass flow leads to the fact that a high density of steam bubbles occurs directly at the heating rod only in a higher position of the annular gap. With the exception of the local steam content in the middle area near the heating rod, however, the values remain in comparable ranges with a mass flow increase. If the system pressure is reduced, the steam clusters mentioned already occur with a slightly lower power input.

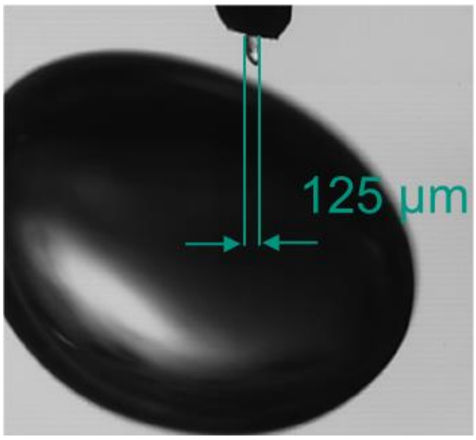

Fig. 2: Image of bubble and probe tip (right) phase distribution near the heater surface.

Furthermore, the decrease of the local steam content with increasing distance to the heating rod is lower from such a power input, which leads to the conclusion that the produced steam bubbles collapse later at lower system pressure and can move further into the radius of the annular gap.

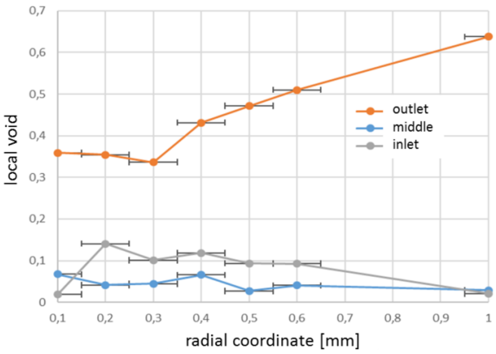

Fig. 3: Image of bubble and probe tip (right) phase distribution near the heater surface

Another important part of the investigations at the annular gap were the laser-based measuring methods PIV and shadowgraphy at the annular gap test section. Measured values were bubble velocity (axially and radially), bubble velocity fluctuation, bubble position and bubble size. An excerpt from the results can be seen in Figure 3.

The velocity profile shows a significant acceleration of the flow from bottom to top through the decreasing fluid density with increasing steam mass fraction. In addition, the measuring positions at the inlet and in the center of the test section are showing a significantly larger boundary layer on the heated tube wall. The bubble size distribution shows the spectrum of gas bubbles in the flow. Both vapor bubbles and bubbles of non-condensable gases are detected if they still exist. In addition to the size distribution, which is an important result for the validation of CFD codes, bubble trajectories, the depth at which the bubbles penetrate into the subcooled flow and further spatially resolved data could be recorded and evaluated in these experiments. The results provided a detailed impression of the processes taking place and permitted our Project partners to validate their advanced CFD-Codes.

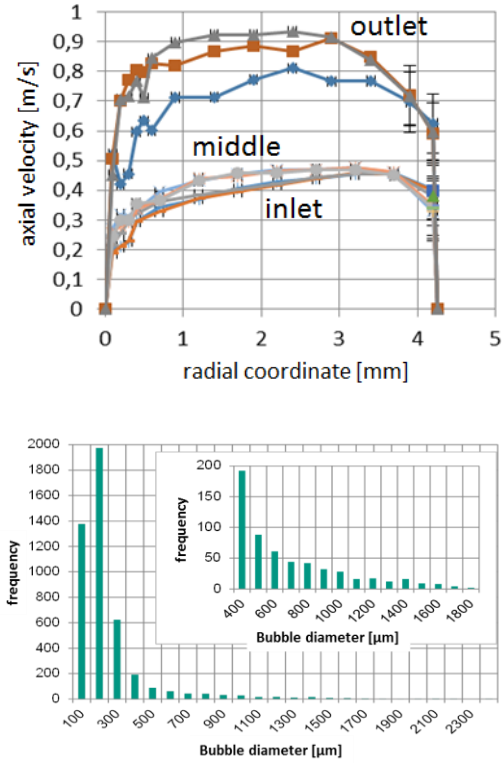

Fig. 4: Velocity distribution and droplet size distribution in the boiling flow

Experiments in the rod bundle test section

The tests on the rod bundle were carried out in an additional test section. Heating rod arrangement, spacing and material were chosen in such a way that they come as close as possible to those in a reactor. Extensive data packages were also created during these tests and made available to the project partners. The experience gained within the project concerning instrumentation, relevant parameter ranges, etc. and the completed high-pressure test section can also be applied in subsequent projects. Figure 4 gives an Impression of different flow conditions. It becomes visible how strongly the two-phase flow mixes in the test track. The flow pulsates violently at high heating powers, so that no single phase interfaces are more recognizable.

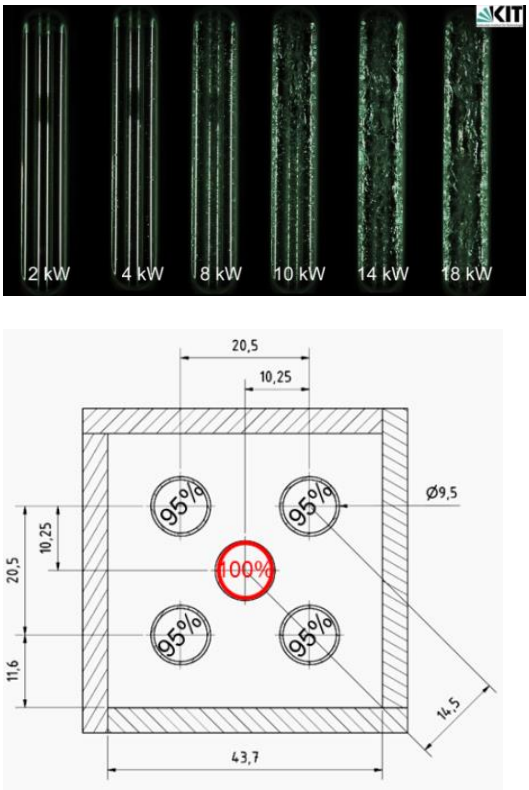

Fig. 5: (top) flow image of a rod bundle image (bottom) cross section of the rod bundle test section

Due to the high grade of instrumentation, detailed data could nevertheless be collected in these flows. An example of this is the temperature distribution of the heated tube wall, which can be seen in Figure 5. Measurements with the above-mentioned fiber probe and laser doppler anemometry (LDA) are currently being carried out.

High Pressure-Loop

The COSMOS-H plant was developed for the investigation of safety-relevant thermohydraulic phenomena under reactor-typical conditions. Both the modular test track (pressure hull) and the required assembly trolley to precisely arrange, assemble and disassemble the test section were completed. The planned test section for high-pressure tests, including the optical access modules, was designed and manufactured. The test section provides all the required characteristics and passed the pressure test according to the Pressure Equipment Directive at 32 Mpa (Fig. 7). The crane traverse required to lift the 1.6 tonne test section without bending and to turn it into the installation position is constructed and is currently in production.

The construction of the high-pressure loop continues, the two cooling loops have been completed and passed the pressure test. The power supply for the test track has already

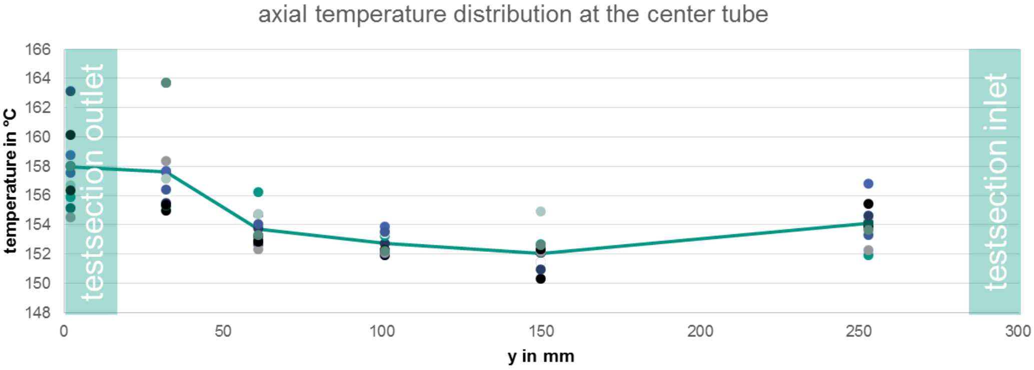

Fig. 6: Axial temperature distribution of the central tube in the rod bundle

been put into operation and has passed the load-loss tests carried out.

Fig. 7: (top) Ground floor at construction Site COSMOS-H, (bottom) modular high pressure test section for COSMOS-H

Conclusions and Outlook

Overall, good progress has been made over the last two years in understanding flow boiling and boiling crises. Experimental facilities and Measurement techniques have been further developed and are now incorporated in new projects. Nevertheless, much work remains to be done.

Recent work is the further adaptation and further development of the measuring technology in relation to the glass fiber probes, optical void measurement as well as the laser measuring technique for disperse and continuous flow components. Furthermore, a method for locating CHF events by triangulation of thermocouple signals is currently being developed.

The construction of the high-pressure facility COSMOS-H will be continued with the completion of the high-pressure circuit within the next year. Furthermore, a new project for the critical heat flux in intermittent flows started in January 2019 at COSMOS-L.

Partners

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List of Acronyms

MPF	Group Multiphase Flows
SAR	Group Severe Accident Research
UNA	Group Accident Analysis
TVT	Institute for Thermal Process Engineering
CHF	Critical Heat Flux
OVM	Optical Void Measurement
WENKA	Water Entrainment Channel Karlsruhe
COSMOS-L	Critical heat flux On Smooth and Modified Surfaces - Low pressure loop
COSMOS-H	Critical heat flux On Smooth and Modified Surfaces - high pressure loop
LDA	Laser Doppler anemometry
PIV	Particle Image velocimetry

References

[1] 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 (Poster)

[2] Gabriel, S.; Albrecht, G.; Kaiser, F.; (2017) “Experimental Investigations of the Critical Heat Flux in a modular Test Section under high Pressure Conditions”. ProcessNet-Fachgruppe Wärme- und Stoffübertragung, Bruchsal, 16.-17. Februar 2017 (Poster)

[3] Kaiser, F.; Gabriel, S.; Albrecht, G.; Huckle, J.; (2016) “Investigation of the Critical Heat Flux in a Rod Bundle Configuration under low Pressure Conditions”. Jahrestagung KIT-Zentrum Energie, Leopoldshafen, 15. Juni 2016 (Poster)

[4] Gabriel, S.; Kaiser, F.; Schulenberg, T.; Albrecht, G.; Heiler, W.; Wetzel, Th.; Miassoedov, A.; “Optical void measurement method for stratified wavy two-phase flows”. 9th World Conference on Experimental Heat Transfer, Fluid Mechanics and Thermodynamics, 12-15 June, 2017, Iguazu Falls, Brazil (Presentation)

[5] Gabriel, S.; Kaiser, F.; Schulenberg, T.; Albrecht, G.; Heiler, W.; Wetzel, Th.; Miassoedov, A.; “Optical Void Measurement Method for stratified wavy two-phase Flows”. Experimental Thermal and Fluid Science 97 (2018) 341–350

[6] Haas, C.; Kaiser, F.; Schulenberg, T.; Wetzel, Th.: “Critical heat flux for flow boiling of water on micro-structured zircaloy tube surfaces”. International Journal of Heat and Mass Transfer, 120 (2018) 793-806

[7] Frank, Th.; Amine Ben Hadj Ali; Lifante, Conxita; Bruder, Moritz; Kaiser, Florian; Eickenbusch, Henning; "Prediction of Convective Boiling up to Critical Heat Flux (CHF) Conditions for Test Facilities with Vertical Heaters". 15th Joint HZDR & ANSYS Conference "Multiphase Flows: Simulation, Experiment and Application". Helmholtz Zentrum Dresden-Rossendorf (HZDR), Germany, 14.-17. Nov. 2017.

[8] Frank, Th.; Amine Ben Hadj Ali; Lifante, Conxita; Kaiser, Florian; Gabriel, Stephan; Eickenbusch, Henning; "Modeling of Wall-boiling Phenomena from Nucleate Subcooled Boiling up to CHF Conditions" .13. ERCOFTAC Technologietag, ERCOFTAC Pilotzentren Deutschland Süd und Nord, Internationales Begegnungszentrum "Eulenhof" der Universität Stuttgart, Germany, 30. November 2017. ERCOFTAC = European Research Community on Flow, Turbulence and Combustion.

[9] Albrecht, G.; Meyer, L.; Miassoedov, A.; Kirstahler, M.; Schwall, M.; Wachter, E.; Gaus-Liu, X.; FCI Experiments in the DISCO-H Facility performed under the COOPERATION AGREEMENT N° 45001082 between IRSN and KIT, (2015)

[10] Höhne, T.; Gabriel, S.; “Simulation of a counter-current horizontal gas/liquid flow experiment at the WENKA channel using a droplet entrainment model”, Annals of Nuclear Energy 121, 414-425, (2018)

[11] Albrecht, G.; Meyer, L.; Meignen, R.; Miassoedov, A.; Ex-vessel fuel-coolant interaction experiment in the DISCO facility in the LACOMECO project, J. Nuclear Science and Technology, Volume 53, (2016)

[12] Albrecht, G.; Meyer, L.; Meignen, R.; Miassoedov, A.; Ex-vessel fuel-coolant interaction experiment in the DISCO facility, NUGENIA TA2 Meeting, Spain (2016)

[13] Albrecht, G.; Meyer, L.; Meignen, R.; Miassoedov, A.; Ex-vessel fuel-coolant interaction experiment in the DISCO facility, NUTHOS-12, Qingdao, China (2018)

[14] Albrecht, G.; Meyer, L.; Meignen, R.; Miassoedov, A.; Ex-vessel fuel-coolant interaction experiment in the DISCO facility, SAFEST final seminar, Cadarache, France (2018)