Investigation of the critical heat flux in a rod bundle configuration under low pressure conditions

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Introduction

Diverse boiling phenomena occur during the operation of light-water reactors. Their understanding is necessary to guarantee a safe service and to avoid unstable operating modes. For example, the comportment of the coolant could either be subcooled boiling during normal operation or even critical boiling during the occurrence of a disturbance. Besides, boiling effects also appear on the secondary loop of the steam generator.

The boiling process allows significantly higher heat transfer rates compared to the single-phase convection. But this heat transport can be suddenly decreased when the limit of the critical heat flux (CHF) is reached. The occurrence of the boiling crisis leads generally to severe damage of the facility components and has to be avoided during reactor operation. Until today, there is no reliable method predicting this phenomenon based on universally valid correlations. A substantial benefit for the reactor safety research would be a prediction method which is based on the solution of the transport equations for the two-phase flow of water and steam.

There exist many correlations based on observations in experiments or theoretical reflections which try to explain the occurrence and the development of the critical heat flux. Unfortunately, they cannot be combined to one complete model as they are counter-predicting effects or are set up on different physical effects. For example, the 'Near Wall Bubble Crowding Model' [Kandlikar, S. G., 2011] postulates the decrease of the liquid flow to the wall due to turbulence with increasing heat flux as bubbles will concentrate near the wall. Whereas the 'Interfacial Lift-Off Model' [Galloway, J., Mudawar, I., 1993] predicts pseudo-periodic 'wetting-fronts' which cause the agglomeration of steam leading to the CHF as these zones lift off from the wall. Using the COSMOS-L test facility, IKET at KIT tries to contribute to analyzing the different existing theories and to examine specific phenomena like flow pattern or void distribution for flow boiling.

Test facility COSMOS-L

The test facility which is used for the measurements is called COSMOS-L which stands for 'Critical Heat Flux On SMOooth and Structured surfaces under Low pressure conditions'. It was built by C. Haas [Haas, C., 2011] who examined the occurrence of the critical heat flux on smooth zirconium alloy tubes as well as on tubes possessing microstructured surfaces.

The facility is a cycle which runs with deionized water under a pressure range from 1 to 4 bar. It provides in its actual configuration a mass flow between 0.01 kg/s and 0.1 kg/s. COSMOS-L possesses – beside the deionized water loop – a secondary loop which is used for cooling. A glycol mixture is used here and it is also cooled via two air fans. The primary loop itself consists of a gear pump providing the mass flow. The water quality is controlled using an O_2-sensor and a sensor to measure the conductivity. To be capable of using different subcooling temperatures to enter the test section, the water loop possesses a pre-heater allowing inlet temperatures between 45 °C and 120 °C. Directly in front of the test section, a throttle valve is positioned to allow a control of the pressure drop. The condenser is directly following the test section. It has to condense the content of vapor achieved through the heat input. Then, the liquid passes a pressurizer used to control the system pressure. Finally, a cooler is installed directly in front of the pump to guarantee subcooled liquid passing the pump and avoiding though cavitation.

The test sections

In previous investigations carried out by C. Haas [Haas, C., 2011] the test section consisted of a vertical internally heated annulus. The water was flowing upwards through the concentric gap. The inner tube of the annular gap was made out of Zircaloy-4 with an outer diameter of Ø9.5 mm and a wall thickness of 0.65 mm. It was directly electrically heated. The outer tube of the annulus was made out of glass to allow an observation of the flow pattern during the experiments. The inner diameter of the outer glass tube was either Ø13 or Ø18 mm. The water is carried to the test section from four different directions. The power was supplied electrically by a controllable transformer with a maximum power of 75 kW. The heated length of the annular gap was about 326 mm. The outlet of the test section was horizontally connected to the condenser allowing the gas and liquid phase to separate from each other. Beside smooth Zircalloy-4 tubes, modified surfaces with micro-channels, porous coatings and cracks have been investigated.

The experiments addressed the relationship between the critical heat flux and the change in gap size, as well as the changes in outlet pressure, pressure drop, void fraction, inlet subcooling and vapor mass quality for the smooth Zircaloy-4 tube. These experimental data points were compared to literature data and calculated values according to different theories. The best agreement was found with the model of Doerffer et al. [Doerffer, S., Groeneveld, D. C., Cheng, S., and Rudzinski, K., 1994]. After characterizing the tubes with structured surfaces regarding their wetting behavior, contact angle, wetting force and topographical structure, there were also investigations carried out concerning the occurrence of the critical heat flux. The comparison between the smooth tube experiments and those of the structured surface showed different values for the appearance of the critical heat flux. In some cases, the CHF performance could be increased up to almost 30 %.

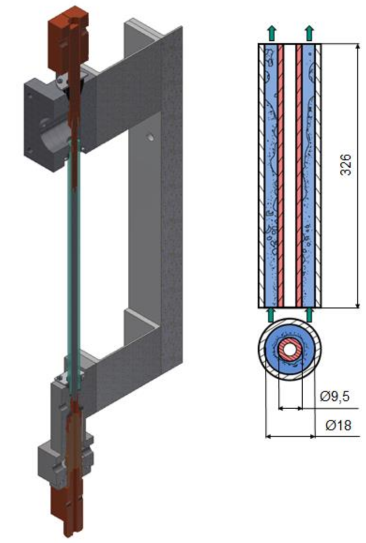

Fig. 1: Test section with annular gap (Haas, C.).

With a new test section design, currently being developed, the influence of the CHF performance will be analyzed in a reactor-typical design using a 3x3 rod-bundle configuration. This means that the inner tube is completely surrounded by other tubes. Despite of the heating of all tubes, the CHF will always appear at the center tube as it will be peaked in power. Therefore, a previous investigation was conducted by J. Eckel [Eckel, J.] to find out how the peaking has to be designed. For several data points, he estimated the deviation of the CHF appearance and introduced an additional safety coefficient for the peaking.

The geometry of the rod-bundle configuration is shown in figure 2. The tubes used are made out of Zircaloy-4 and possess a heated length of about 330 mm. The pitch between the tubes is 14.5 mm and the cross section has a value of 1360 mm². In order to investigate the new test section with similar mass fluxes as for the annular gap, a new pump will be installed delivering a mass flow of 0.8 kg/s. In order to visualize the flow pattern, the new flow channel will have a total number of sight windows of four. In each direction, one of the windows is arranged in order to get full optical access.

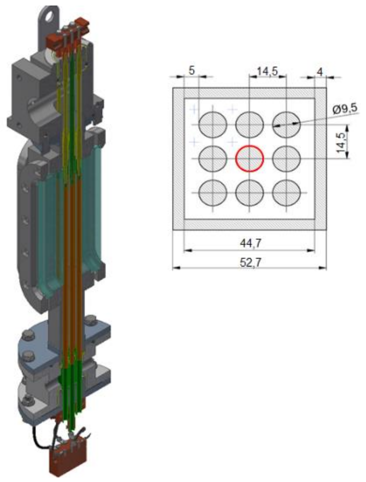

Fig. 2: Test section with 3x3-rod bundle design.

Measurement instrumentation

The instrumentation of the test section has already been applied in the previous work of Christoph Haas, but will be complemented with further sensors in order to get new information. It has a high time and spatial resolution which is completed by an optical access. The measurement data obtained in the test section will be extended by additional sensors of the test facility which give a detailed view on the boundary conditions. In the inlet area to the test section, a volume flow sensor is installed. Directly in front of and behind the test section, the pressure and the temperature of the flow are measured. Through the four sight windows an optical visualization will be possible and the flow pattern can be studied via high-speed cameras. In addition, the electrical power that is introduced into the cladding rods and the surface temperature of the rods in order to detect the CHF are measured. The measurement of the local steam void fraction is planned under use of an optical fiber sensor which has been implemented in cooperation with the Technical University of Munich [Bloch, G, 2013].). The measurements will be completed by laser-optical velocity measurements such as LDA or PIV.

Outlook

Additional investigations of the described annular gap equipped with additional measurement instrumentation such as the optical fiber sensor and laser-optical velocity measurements will be done in order to analyze which of the predicted effects of the different existing mechanistic boiling models can be proven. These measurements will be completed by investigations of a 3x3 rod-bundle configuration. A comparison of these investigations will show if the discoveries made in the annular gap also can be found in the reactor-typical geometry of the rod bundle.

References

[1] Bloch, G. (2013). Setup and Fabrication of cost effective, robust Fiber Optical Needle Probes for Applicationin Multiphase. München.

[2] Doerffer, S., Groeneveld, D. C., Cheng, S., and Rudzinski, K. (1994) *A comparison of critical heat flux in tubes and annuli*. Nuclear Engineering and Design.

[3] Eckel, J. (2015). Konstruktion einer Stabbündelstrecke für Siedeversuche an einem Thermohydraulikversuchsstand. Bachelorarbeit, Institut für Kern- und Energietechnik, Karlsruher Institut für Technologie, Eggenstein-Leopoldshafen.

[4] Galloway, J., Mudawar, I. (1993). *CHF Mechanism in Flow Boiling From A Short Heated Wall* – I. Examination of Near-Wall Conditions With the aid of Photomicrography and High Speed Video Imaging. Int. J Heat Mass Transfer.

[5] Haas, C. (2012*). Critical Heat Flux for Flow Boiling of Water at Low Pressure on Smooth and Micro-Structured Zircaloy Tube Surfaces*. KIT Scientific Reports 7627.

[6] Kandlikar, S. G. (2001). *Critical Heat Flux under Subcooled Boiling*. An Assessment of Current Understanding and Future Directions for Research. Multiphase Science and Technology.