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EXPERIMENTAL INVESTIGATION INTO THE EFFECTS OF COOLANT ADDITIVES ON BOILING PHENOMENA IN PRESSURIZED WATER REACTORS

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Abstract

This study investigates the effects of coolant additives like boric acid on boiling phenomena in pressurized water reactors under conditions as realistic as possible. The effects covered range from subcooled boiling to critical boiling conditions (CHF). The focus of this project lies on flow boiling with up to 40 bar and 250 °C in order to generate a data basis for a possible extrapolation to reactor conditions. The results of the experiments are used to implement and validate new models into CFD-Codes in context to a nationwide German joint research project with the specific aim of improving CFD boiling-models.

Introduction

In light water reactors, boiling phenomena can occur in a variety of different forms. For pressurized water reactors (PWR), they can range from subcooled boiling under normal operating conditions to even critical boiling conditions during accidents. A reliable theoretical prediction of the behaviour of the reactor coolant under such conditions is of utmost importance for the safety of a nuclear plant. While previous investigations concentrated mostly on deionised water, this study focuses on the effects of typical reactor coolant additives on boiling phenomena. Earlier experiments have shown that especially surface-active agents can have an enormous impact on bubble growth and heat transfer on walls in pool boiling or two-phase flow patterns in tubes under atmospheric pressure. But all these investigations were carried out under untypical conditions for nuclear reactors.

Therefore, the goal of this study is to investigate the effects of the PWR coolant additives on bubble formation, two-phase flow and critical heat flux (CHF) under conditions as realistic as possible (i.e. flow conditions, geometry and chemistry) so that safety-relevant information can be derived from it. The main focus lies on boric acid as it occurs in the largest concentration in the coolant, but other additives like lithium-hydroxide are considered as well.

This will be achieved by a newly designed research facility that has been constructed at TUD, capable of operating at up to 40 bar and 250 °C. The facility has two test section configurations, equipped with a rod bundle and a single high duty rod respectively.

1. Theory

There have been numerous publications about the effects of surfactants on nucleate boiling heat transfer. The bulk of the research however concentrates on nucleate pool boiling under atmospheric pressure and not flow boiling. In addition, all used additives were surface active agents, so called surfactants, and not reactor-typical coolant additives like boric acid or lithium-hydroxide.

Nevertheless, Lee et al. [1] found out that boric acid has the same effects on bubble formation and CHF as the surfactant tri-sodium phosphate (TSP), although smaller. Figure 1 shows the bubble formation in pure water and boric acid solution on a heated Teflon surface.

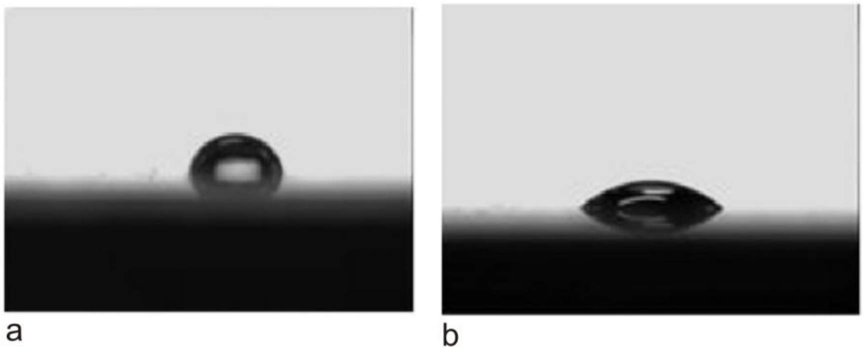

Figure 1. Wettability in pure water (a) and a with boric acid quenched surface (b), Source [1]

The pictures show a clear effect on the surface wettability of the during nucleate boiling and it has been shown that surface wettability has a strong effect on heat transfer [2]. Even though hydrophilic surfaces were used in these tests, they show that the effect of chemical additives in nuclear reactors cannot be neglected.

Surfactants greatly reduce the surface tension of solvents therefore reducing bubble size and increasing wettability during nucleate boiling. Hetsroni et al. [3] observed an increase in heat transfer when adding Habon G to deionised water. In their research he determined an optimum concentration for the heat transfer enhancement. The heat transfer enhancement increases up to a certain point and when passing it, decreases again. They explain this with the change in physical properties of the solution depending on its concentration. Up to the point of maximum heat transfer enhancement, the surface tension decreases asymptotically and with it increases the heat transfer. After that the dynamic viscosity begins to increase and reduces the heat transfer again.

This behaviour is typical for surfactant solutions and can be explained by their molecular properties. Surfactants are amphiphilic, i.e. they have a hydrophilic and a hydrophobic component. The polar (hydrophilic) part seeks to interact with water while the non-polar (hydrophobic) part shuns interaction with water. There are two ways in which a surfactant can achieve both these states. An amphiphilic surfactant molecule can arrange itself at the interface of the water such that the polar part interacts with the water and the non-polar part is held in the other phase. The presence of these molecules on the surface disrupts the cohesive energy at the interface and thus lowers the surface tension. Another arrangement of these molecules can allow each component to interact with its favored environment. Molecules can form aggregates in which the hydrophobic portions are oriented within the cluster and the hydrophilic portions are exposed to the solvent. Such aggregates are called micelles. Once the interface is saturated with the surfactant a further increase in surfactant concentration only lends to a build-up in micelles and does not further influence surface tension. This point is called critical micelle concentration (cmc) [4,5].

Dhir et al. [6] observed an influence of boric acid on heat transfer in a nine-rod bundle. Figure 2 shows the boiling curve for a specific location in the bundle for pure water and boric acid solution. One observes that the heat transfer coefficient for boric acid solution in single-phase flow is lower and for nucleate boiling is higher than for pure water. He explains this not solely by the influence of surface tension on heat transfer – rather by the crud (no or less crud for pure water) on the rods surface. For single-phase flow, the crud inhibits heat conduction and therefore heat transfer to the solution, but for two-phase flow the porous crud presents more nucleation sites than a clean surface.

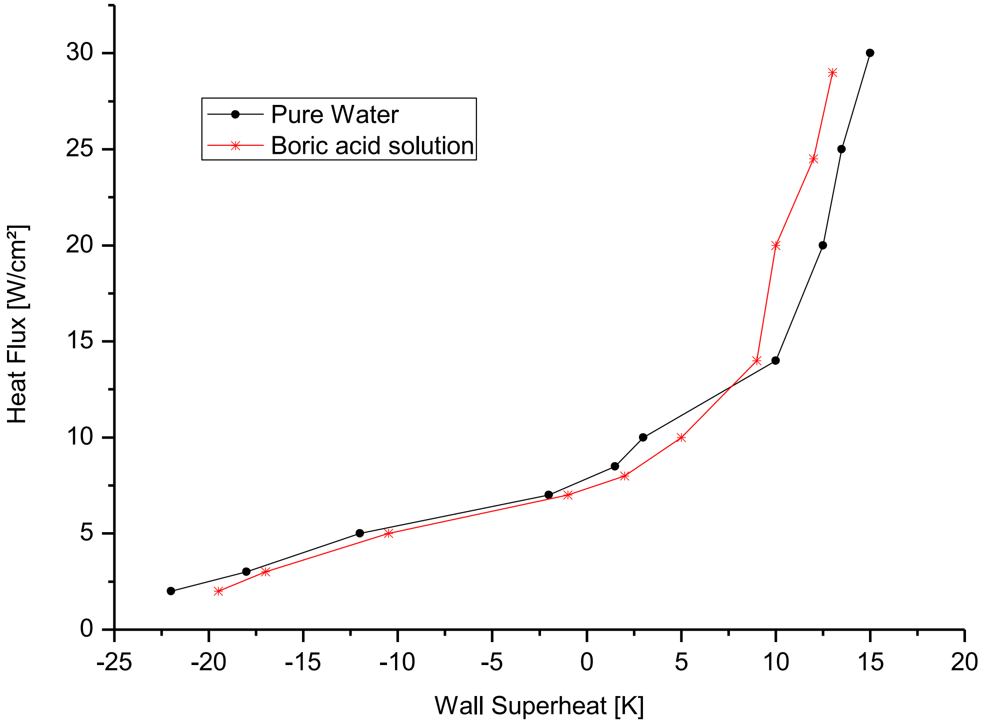

Figure 2. Boiling Curve for pure water and boric acid solution, Source [6]

2. Physical properties of boric acid solutions

The physical properties of boric acid solutions were measured in this project. The measured properties are surface tension (Wilhelmy plate method), thermal conductivity (transient plane source method), kinematic viscosity (DIN 51562-1), density (oscillating U-tube) and thermal capacity (microcalorimeter). Boric acid solutions ranging from 0 to 2500 ppm boron (equals about 14300 ppm of boric acid) were used as well as a 2500 ppm boron solution of highly enriched boric acid 97,75 At-% B-10) to determine if there is any influence of the enrichment.

The measurements confirmed the expectation, that because of the low concentrations, the boric acid has no mentionable influence on properties other than surface tension and perhaps kinematic viscosity as reported by Hetsroni [3]. Heat capacity for different temperatures and concentrations varied less than 1%, kinematic viscosity did not seem to be influenced at all. Furthermore, there was no noticeable effect of the enrichment as well. The only property affected was surface tension, but these measurements turned out to be delicate, as explained in the following.

In order to change the surface tension of the solution, the molecules of the additive have to move to the interfacial boundary. This means, that one has to distinguish between dynamic and equilibrium surface tension. Generally, the dynamic surface tension with additive is lower than without, and the equilibrium surface tension is lower than the dynamic [7]. The movement of the molecules to the interface takes a finite amount of time, depending on the molecular mass [8,9]. Heavy molecules diffuse more slowly than lighter ones. In theory, after a certain amount of time, equilibrium is reached. In reality however, the surface tension experiences constant change for this measuring method.

This is mirrored in the results of the measurements of this project, where the surface tension of the boric acid solution was constant in the beginning but then dropped abruptly from about 70 to 50 mN/m and never reached equilibrium, i.e. it kept increasing and decreasing. This is possibly an effect of the Wilhelmi plate method with which, as of yet, no cohesive results could be obtained.

That a direct dependence of surface tension on boric acid concentration exists, was proven by Arias [10] with the capillary rise method. The results of his measurements as well as a best fit of the Szyszkowski equation are presented in Figure 3 with the parameters $\Psi = 9.76$ and $b = 0.13$ in

$$\sigma = \sigma_0 - R\,T\,\Psi \ln\left(1 + \frac{c}{b}\right),$$

Where σ is the surface tension of the solvent, σ_0 the surface tension of pure solvent, T the temperature (K), R the universal gas constant ($J \cdot mol^{-1} \cdot K^{-1}$) and c the molar concentration.

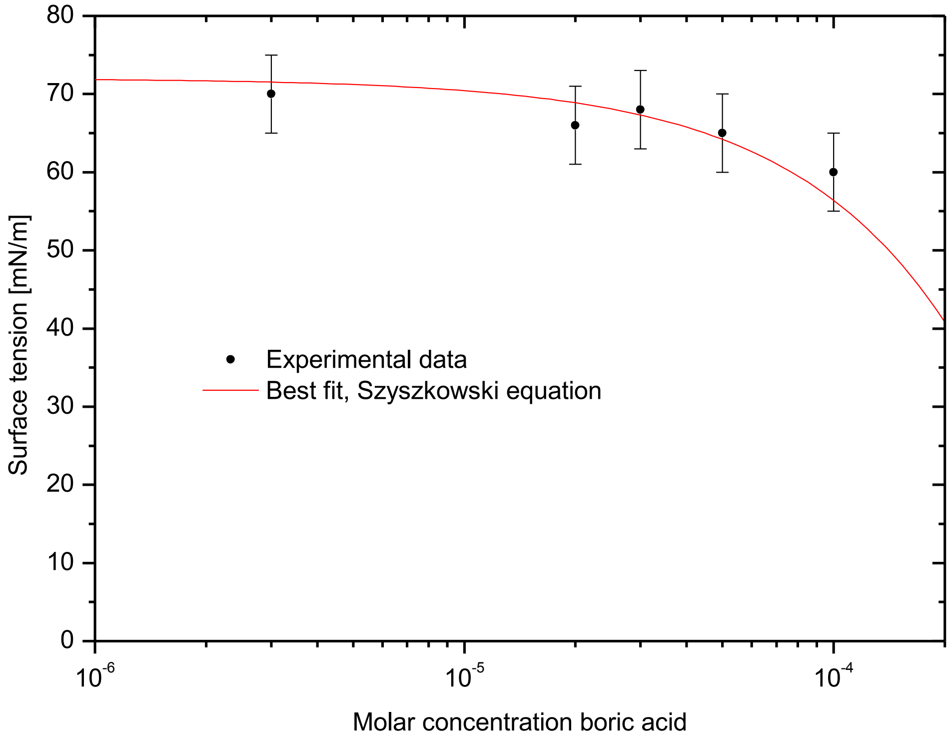

Figure 3. Surface tension as function of boric acid concentration, Source [10]

3. Experimental facility

In order to determine the effects of reactor-typical coolant additives on mentioned phenomena, a new test facility has been built which is capable of operating at up to 40 bar and 250 °C (Figure 4). The fluid is driven by a radial pump with an optimum flow rate of 6 m^3/h. The mass flow rate is measured by a coriolis flow meter before entering the heated test section. The test section itself has two different configurations, each for its special purpose: The first configuration consists of a heated hexagonal rod bundle with an accumulated power of 70 kW (heat flux density approximately 10 W/cm^2), enough to generate a void fraction of up to 0.75 at the exit. To be able to visually analyse the flow inside the test section and the heater surface via high speed camera, a window is installed in the upper part. Figure 5 shows the cross section of one of the viewing windows. Inside the window is the hexagonal rod bundle surrounded by a glass tube so that the flow is not perturbed by the dead volume of the viewing channel. The rod bundle is followed by a riser section which is equipped with another window for the purpose of enabling the examination of the evolution of the two-phase flow (e.g. bubble coalescence). A 16x16 wire-mesh sensor is used to determine the void fraction distribution in the channel with 10 kHz. It can be installed either between rod bundle and riser or above the riser.

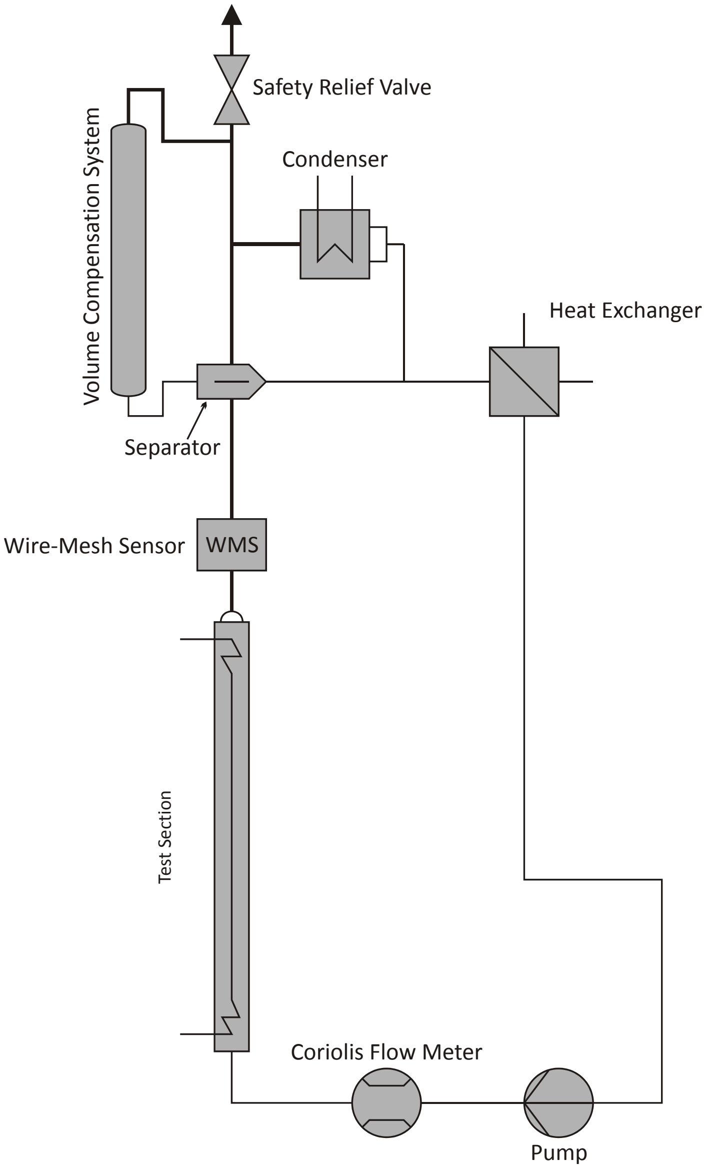

Figure 4. Experimental setup

In the second configuration, the riser is replaced by another heated channel containing a single high duty rod followed by a pressurizer. The single high duty rod serves as a means to generate the whole spectrum of boiling, from single bubble formation to film boiling while the pressurizer regulates the pressure in combination with the condenser. The rod bundles function in this configuration is to preheat the fluid to the desired temperature. Hence, it is possible to regulate the fluids entrance state to the single rod channel from undercooled up to two-phase flow at a specified pressure and void fraction. The rod itself has a power of 20 kW on a short heated length along a viewing window, generating a heat flux density of up to 300 W/cm².

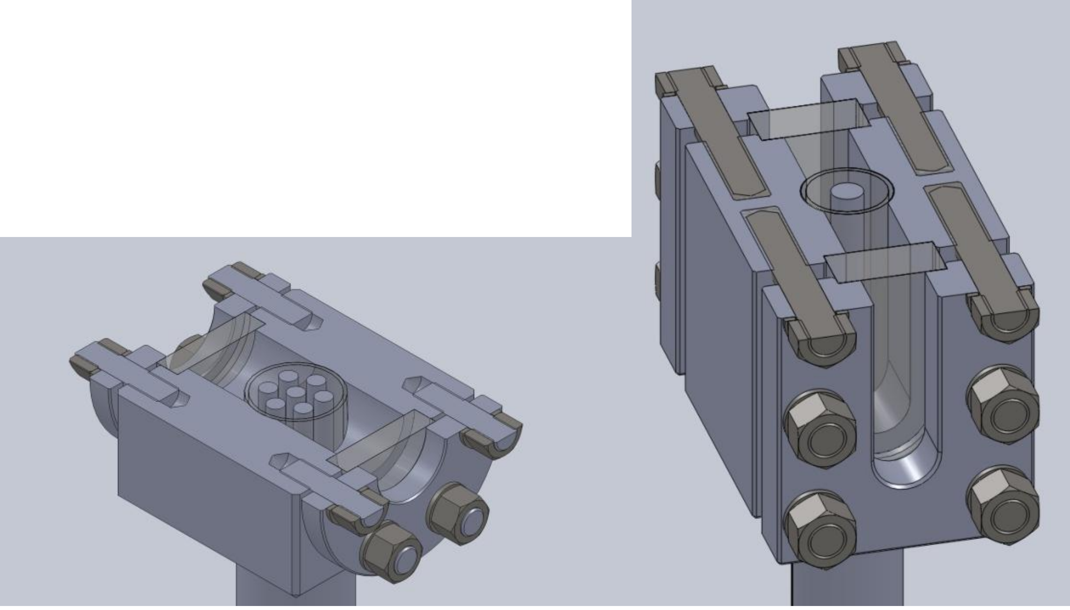

Figure 5. Cross Sections of viewing windows: Rod bundle test section (left), single rod test section (right)

4. Conclusion

Many studies have shown that surfactants have immense influence on bubble formation, growth rate and subsequently heat transfer in nucleate pool boiling under atmospheric pressure and that boric acid has similar effects. This study aims at the investigation of boiling phenomena from nucleate flow boiling to CHF under conditions as close to those in a PWR as possible including geometry, flow parameters, chemistry and pressure/temperature.

Therefore, a newly designed research facility has been built, which is capable of simulating these conditions. The main measuring systems include high-speed videography and a wire-mesh sensor with which it is possible to determine the void fraction distribution over the test channel.

The results of the experiments are used to implement and validate new models into CFD-Codes in context to a nationwide German joint research project with the specific aim of improving CFD boiling-models.

Acknowledgements

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5. References

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SECA Test Facility

(Volume Compensation System and secondary cooling system not displayed)