

Breakthrough in measurements of critical heat flux at very low mass flux in smooth tubes

Benson boiler technology

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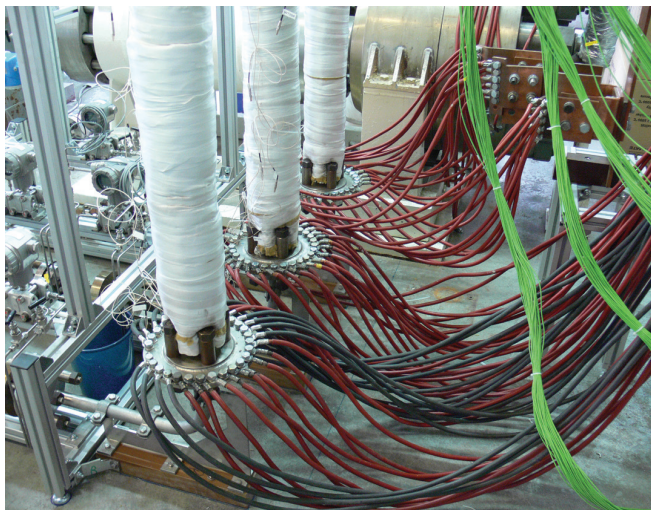
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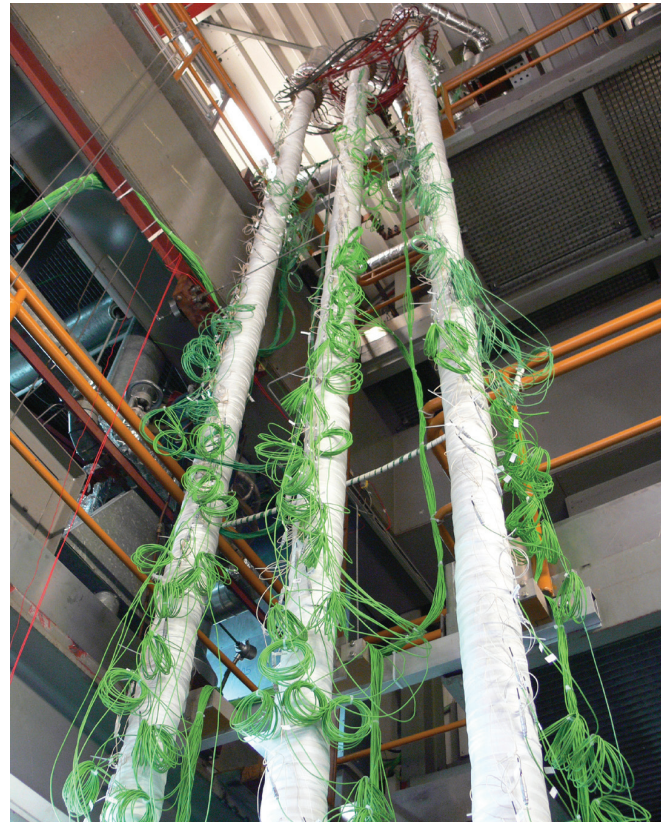
Breakthrough in measurements of critical heat flux at very low mass flux in smooth tubes

Recent measurements recorded at the Benson laboratory in Erlangen are believed to represent the first successful determination of critical heat flux (CHF) in Benson evaporator tubes over a wide pressure range at mass flux levels below $100 \text{ kg}/(\text{m}^2\text{s})$ and as low as $30 \text{ kg}/(\text{m}^2\text{s})$. The research has closed a significant gap in our understanding of CHF and wall temperatures at these low mass fluxes.

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3-tube inlet section and vertical section at the Benson laboratory



Siemens has been granting the so-called Benson licence since the 1930s to leading global manufacturers of once-through boilers. This licence has been modified and further developed as a matter of course over the decades. For example, while specific support was provided on questions of design in the early years, efforts since the mid-1970s have focused on correct thermohydraulic design of the evaporator and the startup system.

Since the mid 1970s, countless test series have been conducted at the world's largest test facility for measurements of pressure drop and heat transfer in the two-phase regime, located in the Benson laboratory in Erlangen.¹ The results of these tests were integrated in calculation programs that enabled the licensees and the Siemens engineers to design these critical components of a boiler for operating reliability.

Motivation for tests

In addition to the correct calculation of heat transfer and wall temperatures, taking

into account the flow distribution in the evaporator heat exchange surfaces, flow stability must also be checked and ensured. A distinction is drawn here between what is known as static stability and dynamic stability. In the static stability analysis, a check is done as to whether individual tubes or groups of tubes can have more than one operating point. In a series of pressure drop calculations, it is determined whether more than one mass flow rate is possible at an identical pressure drop defined by the inlet and outlet headers, which can then result in widely different outlet temperatures.

The physical phenomena associated with and the theoretical basis for the dynamic stability of two-phase flows have been investigated, understood and documented in the context of the Benson licence. Fluctuations measured in a power plant had already by the mid 1980s been correctly calculated quantitatively using non-linear simulation.^{2,3}

A test stand with tubes configured in parallel was installed in the Benson laboratory in Erlangen in 2014 for further

investigation of the phenomenon. For the first time in the world, this setup enabled the reproducible generation and observation under laboratory conditions of dynamic instabilities in vertically configured heated tubes with a geometry typical of Benson evaporators. The purpose of the tests was to destabilise an initially stable flow in the tubes by changing a parameter and to generate a sustained mass flow oscillation. This stability threshold was investigated in many measurement periods with variation of the parameters of pressure, mass flux, subcooling at the inlet and superheating at the outlet. Graph 1 shows a measured flow oscillation in the three parallel smooth tubes of the test system at a system pressure of 80 bar and a mean mass flux of $206 \text{ kg}/(\text{m}^2\text{s})$.

Recalculations for stable or unstable operating phases with mass flux levels significantly below $100 \text{ kg}/(\text{m}^2\text{s})$ revealed deviations from the measured tube wall temperatures. In particular, the calculated location of the boiling crisis deviated significantly from that observed in the

experiment. A boiling crisis occurs when the inner wall of the tube is no longer wetted. A distinction is drawn between the departure from nucleate boiling (DNB), dryout of the heat exchange surface and deposition-controlled dryout. The type of boiling crisis occurring in an evaporator tube depends on the degree of thermal loading (heat flux relative to mass flux) and on the system pressure.

The occurrence of the boiling crisis is always associated with an increase in tube wall temperature. Knowledge of the location of occurrence of the boiling crisis as well as the associated increase in material temperature is therefore extremely important for the design of the heat exchange surfaces.

The occurrence of the boiling crisis and the resulting wall temperatures are calculated in the Benson programs taking into consideration tube geometry, heat input and the physical properties of the water/steam flow. The database for the Benson test system previously ended at the minimum mass flux of 100 kg/(m²s) indicated above. A series of heat transfer tests with a smooth tube at the lowest possible mass fluxes was therefore necessary to enable conclusive recalculation of the completed dynamic stability tests at still lower mass flux.

Outside the Benson licence, lookup tables with values of critical heat flux (CHF) are used. One of the latest lookup tables is based on roughly 24 000 critical heat flux values and is normalised for a water-cooled tube with an inside diameter of 8 mm. Due to a lack of reliable data the region corresponding to a mass flux of less than 100 kg/(m²s) exhibits large uncertainties in this table.⁴ In the lookup table from 2006⁶, Groeneveld and his colleagues extended the database and improved the predictive accuracy of the values for critical heat flux. However, the authors note even for this most current table that the range of lowest mass flux is not reliably covered.

None of the lookup tables covers the pressure range above 210 bar.

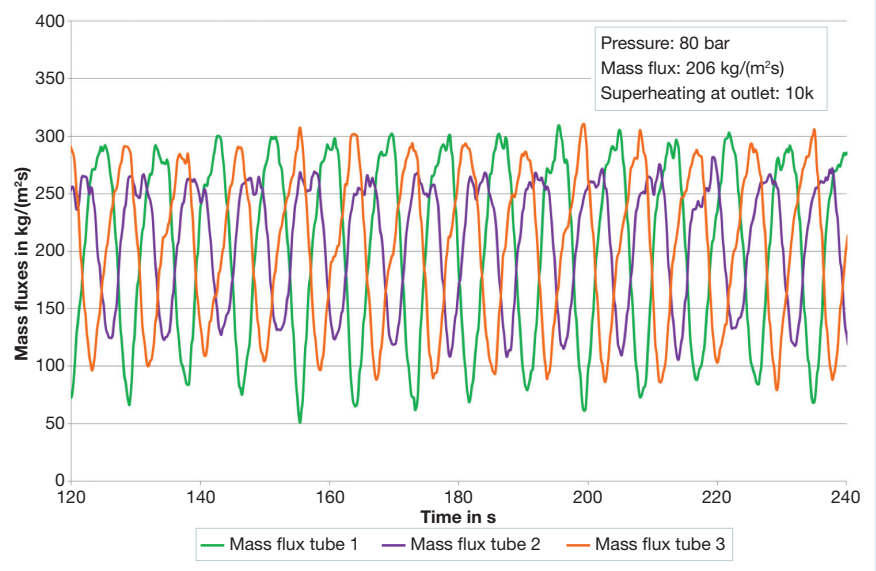
Test setup, test matrix, test procedure

The setup of the Benson test system¹ for the dynamic stability investigation briefly described above was modified for a single-tube test.

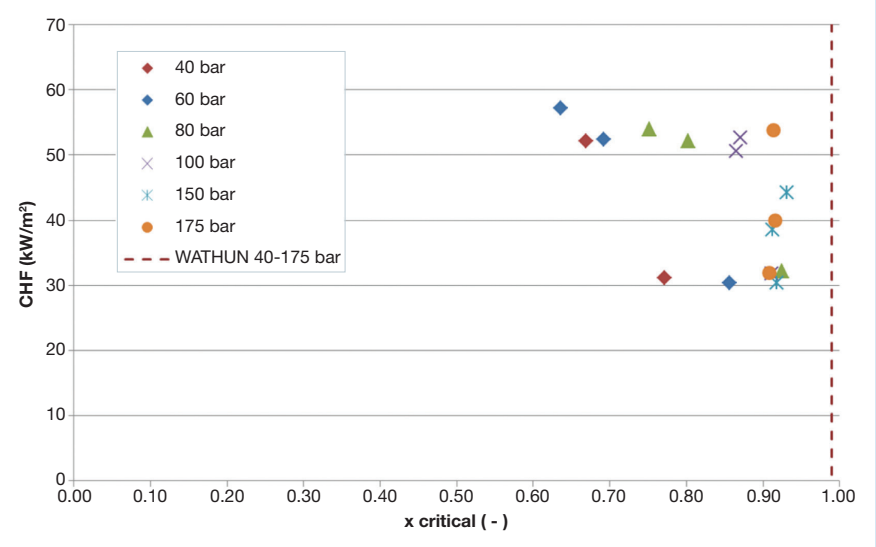
The test matrix focused on the lower mass flux range. Extensive heat transfer tests were performed in the pressure range between 40 bar and 175 bar, at mass flux levels from 30 kg/(m²s) and internal heat fluxes from 20 kW/m². It proved necessary for the operating personnel in the control room to be extraordinarily patient to obtain a settled steady-state condition as the initial basis for each test point. Many test points were retested on different days to check the reproducibility of the test results.

A further parameter range that was investigated focused on the pressure range between 200 bar and 220 bar, in

Graph 1. Measured flow oscillation



Graph 2. Critical heat flux values for various pressures, and values predicted by Wathun (Benson program)



order to validate the existing correlations in the Benson programs in the near-critical pressure range (cf. also ref⁹).

A total of 24 500 data points was recorded in the course of the extensive test series. These are now available for analysis and checking or improvement of the existing correlations for internal heat transfer.

Selected results and their evaluation

Graph 2 shows a small selection of measured critical heat fluxes for various pressures at a constant mass flux lying significantly below 100 kg/(m²s). The critical steam quality calculated using the Benson program Wathun is also shown along with the measured data.

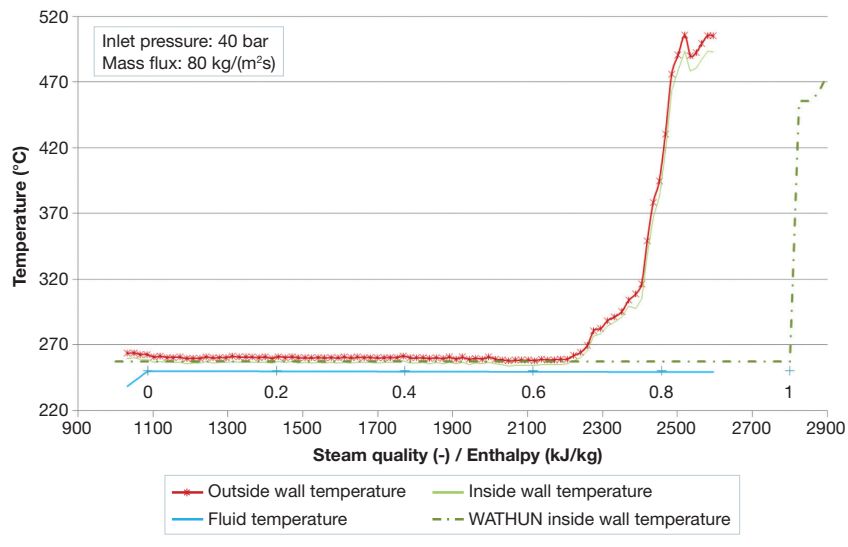
A point entered in the diagram for a pressure level indicates the combination of heat flux and steam quality up to which the inside of the tube is wetted.

While Wathun calculates the occurrence of the boiling crisis at the mass flux from the tests independently from heat input close to steam quality 1, the measurements exhibit highly deviating results that are strongly dependent on pressure.

Graph 3 shows the temperature profile measured along the outside of the tube for one of the tests, the inner wall temperature calculated based on the measured values and the inner wall temperature calculated by Wathun. These values are plotted against enthalpy or steam quality. It can be seen in this plot that Wathun does not correctly calculate the location of the boiling crisis and that the tube wall temperature measured in the post-CHF region is higher than that calculated by Wathun.

There is thus a clear potential for improvement in the calculation of wall temperatures by Wathun at mass flux levels

Graph 3. Measured wall temperatures and those predicted by Wathun (Benson program)



below 100 kg/(m²s). In contrast, Wathun exhibits nearly perfect agreement of the calculated location of the boiling crisis as well as in the increase in tube wall temperature in the post-CHF region within the validated area.

Practical relevance, summary, outlook

We believe that the measurements reported above represent the first successful determination of values for critical heat flux over a broad pressure range at mass flux levels between 30 kg/(m²s) and 100 kg/(m²s).

The new knowledge obtained from the tests and initial analysis are not only of scientific interest. They are of practical relevance, even though the lowest steady-state evaporator mass flux in pulverised coal fired boilers with spiral winding is roughly 800 kg/(m²s) and even circulating fluidised bed systems are not operated at mean mass flux levels in the evaporator significantly

below 200 kg/(m²s). The mean evaporator mass flux in Benson heat recovery steam generators with vertical exhaust flow and horizontal heat exchange tubes is also roughly 200 kg/(m²s) at the lowest part load level. Only in the coldest tube row in heat recovery steam generators with a horizontal gas path can the mass flux drop down to values of 20 kg/(m²s) at steady-state.

However, fluctuations in the mass flux can be so large on the occurrence of a dynamic instability in any of the above evaporators that even flow reversal of the fluid into the inlet header can occur. Dynamic calculation programs in particular must therefore correctly represent all mass fluxes up to the point of stagnation of the fluid. If the location of the boiling crisis and the wall temperature are incorrectly calculated by the programs, the energy term input to and output from the tube wall is also incorrectly calculated by the dynamic tools. Furthermore, representation of the mass

References

- ¹ Test facility flyer; download available on the Benson technology homepage
- ² J. Franke, *Investigation of the hydrodynamic stability of evaporator heat exchange surfaces by nonlinear simulation*, dissertation, Darmstadt University of Technology, 1986
- ³ J. Franke, Flow oscillations in the evaporator section of steam generators, *VGB PowerTech* 67, January 1987
- ⁴ D.C. Groeneveld, et al, The 1995 look-up table for critical heat flux in tubes, *Nuclear Engineering and Design* 163 (1996), 1-23
- ⁵ D.C. Groeneveld, et al, The 2005 CHF look-up table, NURETH-11, Avignon, France, paper 166 (2005)
- ⁶ M. Efert and J. Brückner, Benson low mass flux vertically-tubed evaporators in the power market – a status update, *Modern Power Systems*, April 2017

flow distribution in the evaporator network can also be insufficiently accurate under these circumstances, which in turn has an unfavourable effect on the determination of stability limits.

It is therefore anticipated that the stability limit in the dynamic tools will shift on implementation of the new heat transfer equations.

The test results are currently being analysed in detail and the equations and functions for heat transfer in the steady-state and dynamic programs are being adjusted based on these results.

The described measurements have succeeded in closing an important knowledge gap regarding the critical heat flux and wall temperatures in the post-CHF regime at mass fluxes below 100 kg/(m²s). These data will be available to Benson licensees and Siemens boiler engineers in the form of revised design programs in the near future.



Control room at the Benson laboratory, Erlangen

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