Int. J. Multiphase Flow Vol. 14, No. 5, pp. 575–586, 1988
Printed in Great Britain. All rights reserved

0301-9322/88 $3.00 + 0.00

HEAT TRANSFER IN AN EVAPORATOR TUBE WITH CIRCUMFERENTIALLY NON-UNIFORM HEATING

K. M. Becker, A. Enerholm and L. Sardh
Royal Institute of Technology, 100 44 Stockholm, Sweden

W. Köhler, W. Kastner and W. Krätzer
Kraftwerk Union AG, Erlangen, F.R.G.

(*Received* 12 *October* 1987; *in revised form* 26 *May* 1988)

Abstract—Heat transfer tests were performed for flow of water in a high-pressure test loop using a tube 7 m long with 24.69 mm i.d. that was heated on one side. For the simulation of one-sided heating the tube was silver-plated over one-half of its circumference. The measurements were carried out for pressures between 50 and 200 b, mass velocities between 500 and 2500 kg/m^2 s and hot-side heat fluxes up to 1157 kW/m^2.

On the basis of the temperatures measured at the outer wall of the tube, the temperatures and the heat fluxes on the inside of the tube were determined by means of one- and two-dimensional analysis. The two-dimensional analysis, which was carried out with a relaxation method, showed that the circumferential heat conduction in the tube wall from the hot to the cold side should be taken into consideration for the evaluation of the post-dryout heat transfer results.

The location of the boiling crisis was determined by means of the measured wall temperature distributions. It was shown that the location of the boiling crisis of tubes that are heated from one side can be calculated using the equations developed for uniformly heated tubes.

The heat transfer in the post-CHF region was predicted using the WATHUN computer program which was developed for uniformly heated tubes. It appears that the maximum inner wall temperatures can be calculated fairly well when the tangential heat conduction in the tube wall is taken into account.

Key Words: dryout, critical heat flux, post-dryout heat transfer, post-CHF heat transfer, one-sided heat flux

INTRODUCTION AND LITERATURE REVIEW

In fossil-fired steam generators the heat is often supplied to only one side of the boiler tubes. By contrast with the conditions in a tube heated uniformly over its circumference, there is a non-symmetrical heat input. This may influence the occurrence of the boiling crisis and the heat transfer in the post-CHF region.

Figure 1 illustrates the approximate heat flux distribution on the inside wall of a boiler tube, which is heated from one side. The heat transfer coefficient was assumed to be constant over the tube circumference.

From investigations performed to date it may be inferred that, due to the non-uniform heat flux distribution, the circumferential mean heat flux when dryout occurs is smaller than with uniform tube heating. On the other hand, the circumferential peak heat flux at dryout is greater than with uniform heating.

For a cosine-shaped distribution of the heat flux Butterworth (1971) developed a model taking into account the influence of the degree of non-uniformity on the mean critical heat flux measured over the tube circumference. Using this model, the test results obtained by Alekseev *et al.* (1964) and Miropolskii & Mostinskii (1958) can be predicted. The extensive test results obtained by Chojnowski & Wilson (1972) can also be predicted if the term containing the length-to-diameter ratio and the spreading coefficient is maintained at the same value as used in the tests of Alekseev *et al.* Miropolskii & Mostinskii. This is the form in which the Butterworth model was included in the *VDI-Wärmeatlas* (1984).

In 1970 Becker *et al.* carried out critical heat flux and post-CHF heat transfer measurements in a 7 m long tube with one-sided heating. The simulation of the one-sided heating was achieved by means of silver-plating 180° of the circumference of the outer surface of the tube. This test section was also employed for the present measurements.

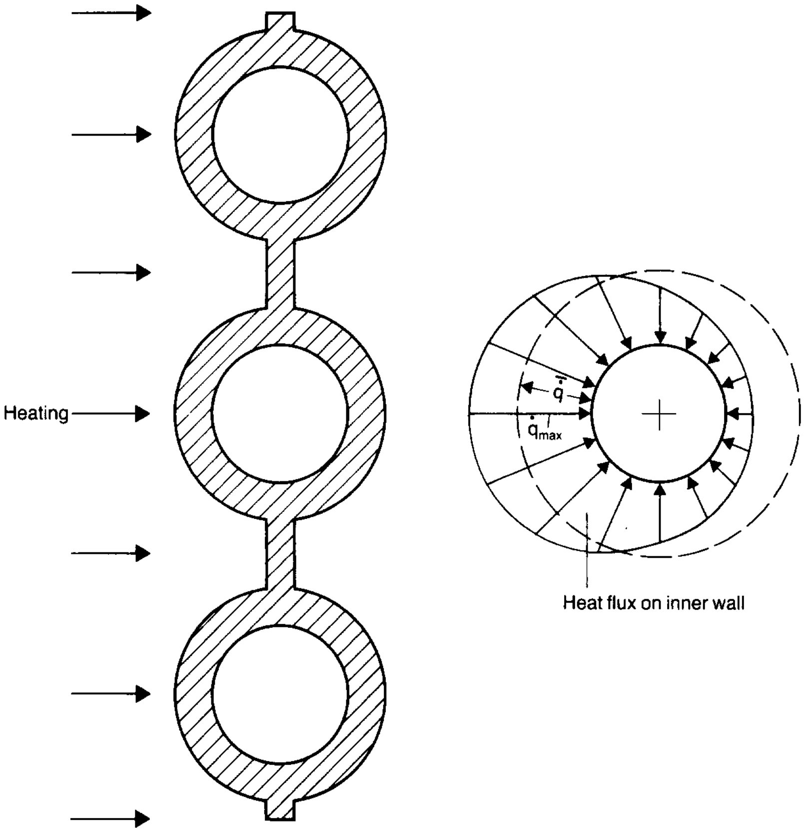


Figure 1. Heat flux distribution on the inner wall with one-sided heating.

Recent investigations made by Kitto & Wiener (1982) and Humphries *et al.* (1984) show that the influence of a non-uniform heat flux distribution is considerably dependent on the local steam quality. With low steam quality the peak heat flux of the non-uniform heating approaches the critical heat flux of the uniform heating. In contrast, with high steam quality and non-uniform heating, the mean heat flux over a tube circumference reaches the value which was measured with uniform heating. This means that with low steam quality the occurrence of the boiling crisis depends on the local variables and with high steam quality it depends on the average variables. Such a relationship between local and integral heat flux effects was postulated also by Lahey & Moody (1977) for a non-uniform axial heat flux distribution.

Since the previously published investigations only set trends, and as a direct application under steam-generating conditions is possible in very few cases only, the need for additional experiments was evident. The purpose of the present investigation is to provide measurements in the parameter range, which is encountered in fossil-fired steam boilers.

EXPERIMENTAL INVESTIGATIONS

The experimental investigations were carried out at the Royal Institute of Technology, Stockhom. They were made in a test loop with 1 MW heating capacity and a maximum pressure of 250 b. Figure 2 shows the flow diagram of the test facility, which is described in detail by Becker *et al.* (1984). The facility is designed such that the water always enters the test section subcooled.

The dimensions and instrumentation of the test tube, which is heated from one side, are shown in figure 3. The flow through the electrically heated tube was vertical from bottom to top. To simulate one-sided heating, the tube was silver-plated with a 0.41 mm layer over half of its circumference. The ratio of the heat flux generated on the silver-plated side (hot side) to the heat flux generated on the unplated side (cold side) was approx. 4.5. The wall temperatures were

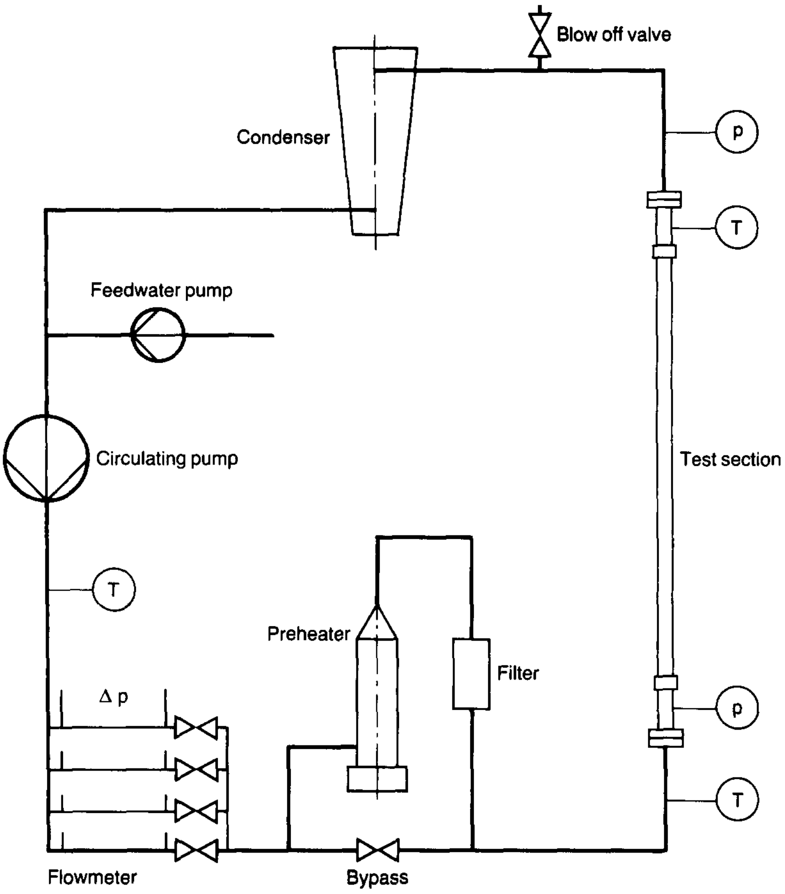
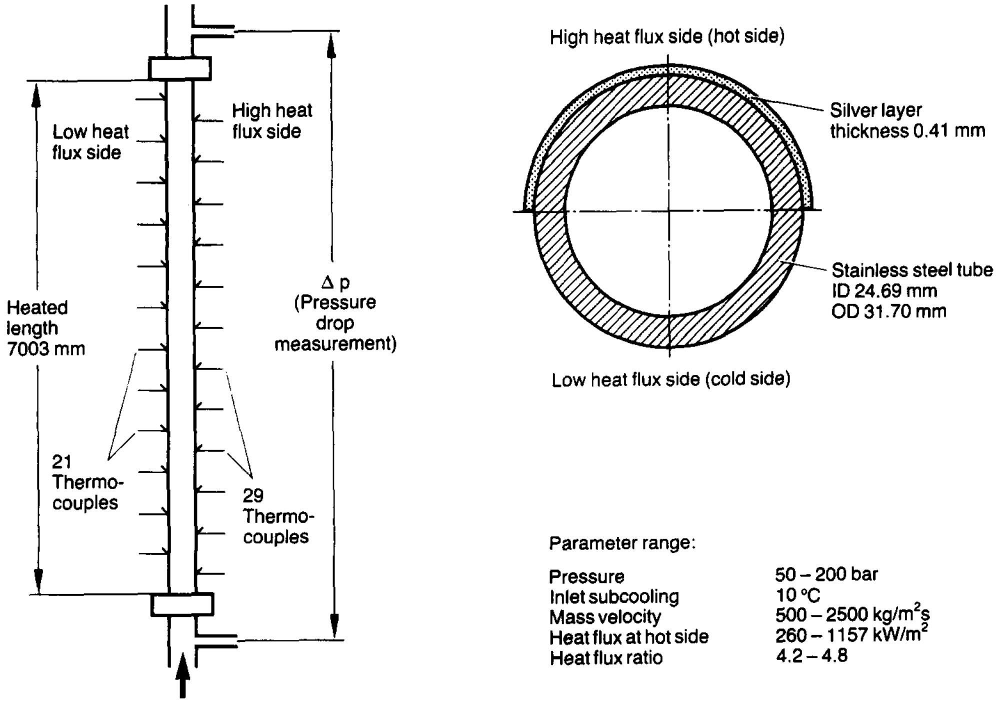


Figure 2. Flow diagram of the test loop.



Parameter range:

Pressure	50 – 200 bar
Inlet subcooling	10 °C
Mass velocity	500 – 2500 kg/m^{2}s
Heat flux at hot side	260 – 1157 kW/m^2
Heat flux ratio	4.2 – 4.8

Figure 3. Test section and parameters.

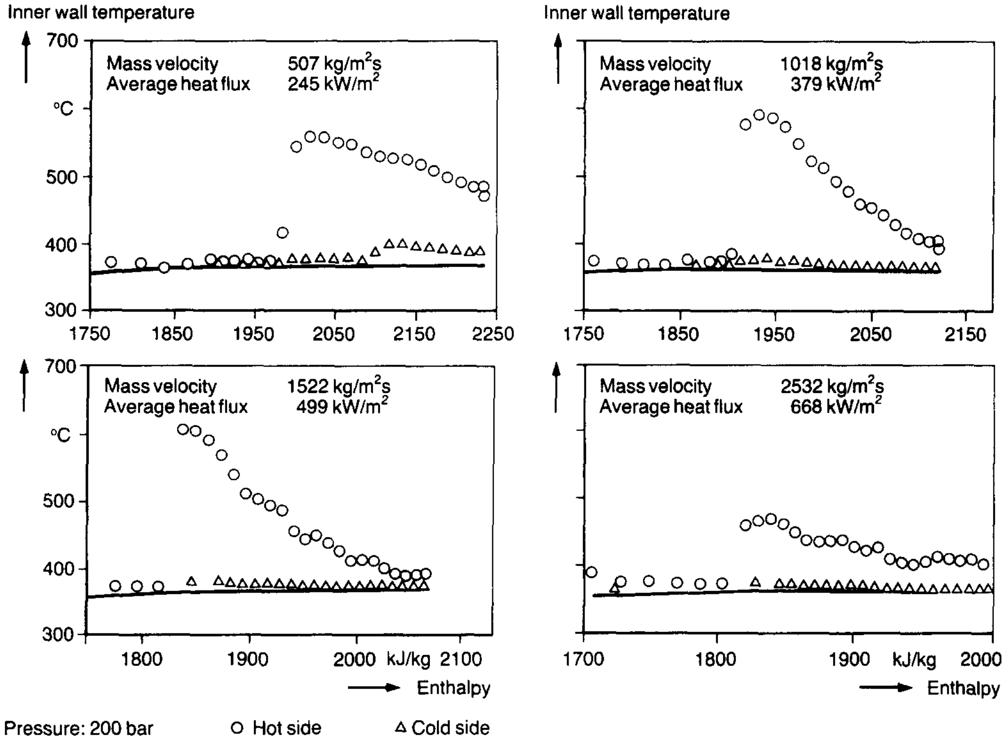


Figure 4. Typical wall temperature distribution of the tube with one-sided heating (one-dimensional analysis).

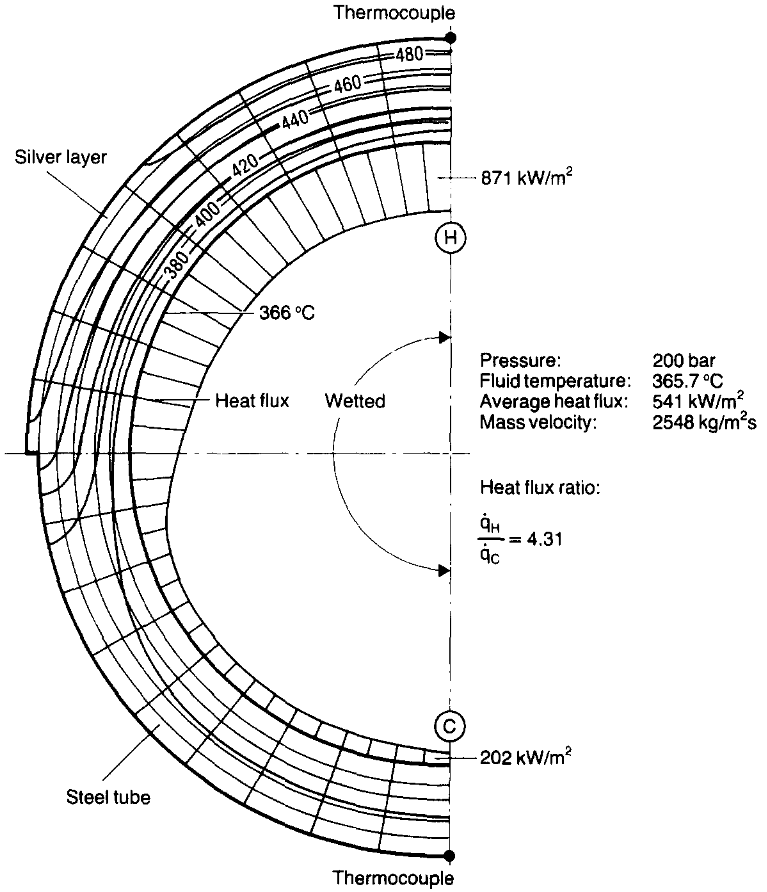


Figure 5. Temperature field in the tube wall and heat flux on the inner wall in the wetted region (relaxation method).

measured on the outside of the tube using thermocouples which were installed along the silver-plated and unplated side of the tube.

The test parameters are also shown in figure 3. On account of the subcooled inlet condition, the boiling crisis was reached for only a few tests in the pressure region between 50 and 100 b. The investigations thus focused on the pressures between 150 and 200 b.

In all, 75 runs were carried out. Complete tables of the data and illustrations of all of the axial temperature distributions are given by Becker *et al.* (1984). In the present paper only a few characteristic examples of the results will be included.

TEST EVALUATION

From the values measured for current and voltage at the test tube and the temperatures measured at the outer wall of the tube, the temperatures and heat fluxes at the inner side of the tube were determined by means of a one-dimensional analysis, which only takes into consideration the heat flux in the radial direction. Figure 4 shows examples of the wall temperature patterns on the hot and cold sides of the tube. The boiling crisis was mostly observed on the hot side only. However, for low mass velocities, dryout occurred on both sides of the tube. The dryout location for the two sides differed significantly: the cold-side dryout occurring farther downstream of the hot-side dryout position.

Whereas one-dimensional analysis is sufficent for the determination of the boiling crisis, the calculation of post-CHF heat transfer necessitates the consideration of heat conduction in the wall material from the hot to the cold side. As a consequence of this heat conduction, the heat flux transferred to the coolant is decreased on the hot side and is increased on the cold side as compared with the one-dimensional approach.

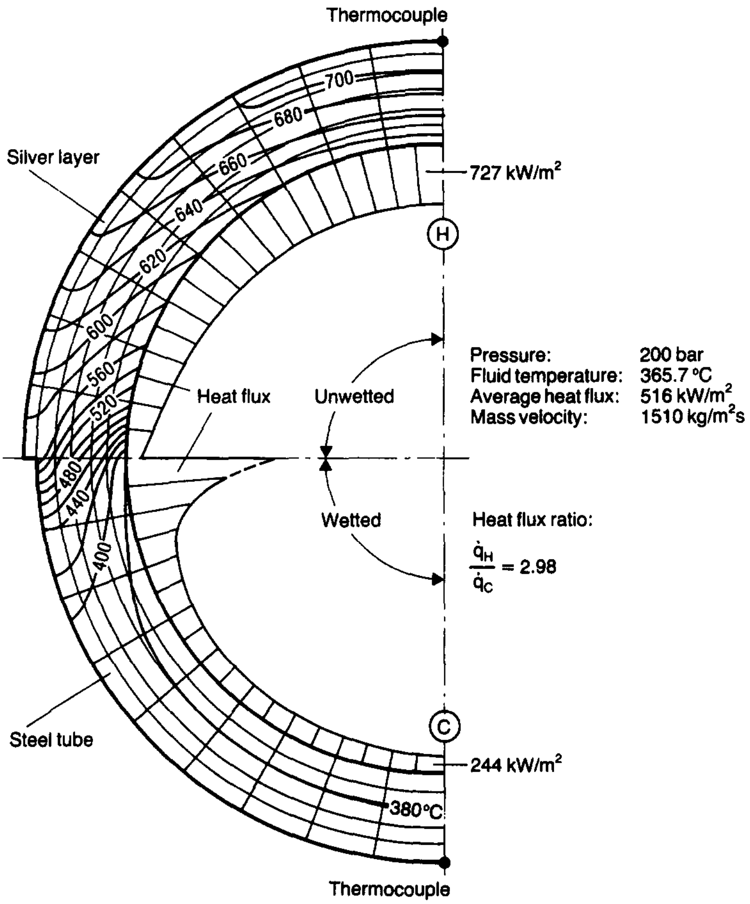


Figure 6. Temperature field in the tube wall and heat flux on the inner wall in the partially wetted region (relaxation method).

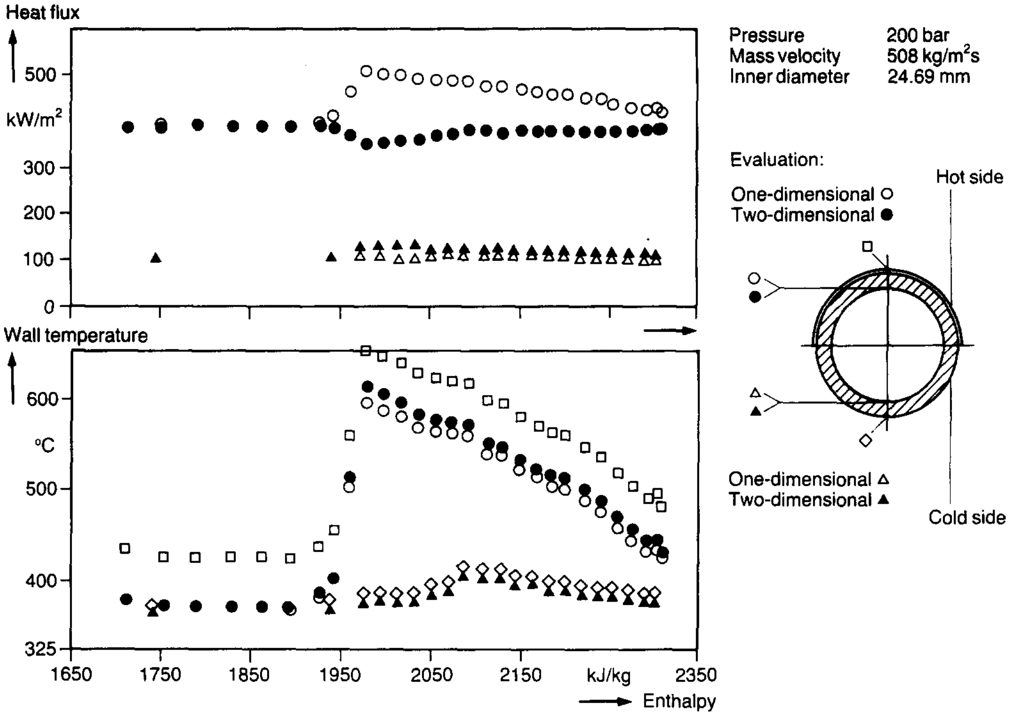


Figure 7. Influence of circumferential heat conduction on the calculated inner wall temperature and heat flux.

For the two-dimensional analysis of the tests a relaxation method was applied. As shown in figure 5, the influence of the heat flux in the circumferential direction is only evident near the borderline between the hot and cold tube wall if the inner side of the tube is entirely wetted. As the isotherms near the instrumented lines H and C are in the shape of concentric circles, the heat fluxes are not affected by two-dimensional effects along these lines. In contrast, with a partially wetted inner side and great temperature differences between the hot and cold side, there is a noticeable redistribution of the heat flux on the inside of the tube. As illustrated in figure 6, the heat flux ratio $\dot{q}_H/\dot{q}_C$ may decrease from 4.5, originally, to approx. 3.

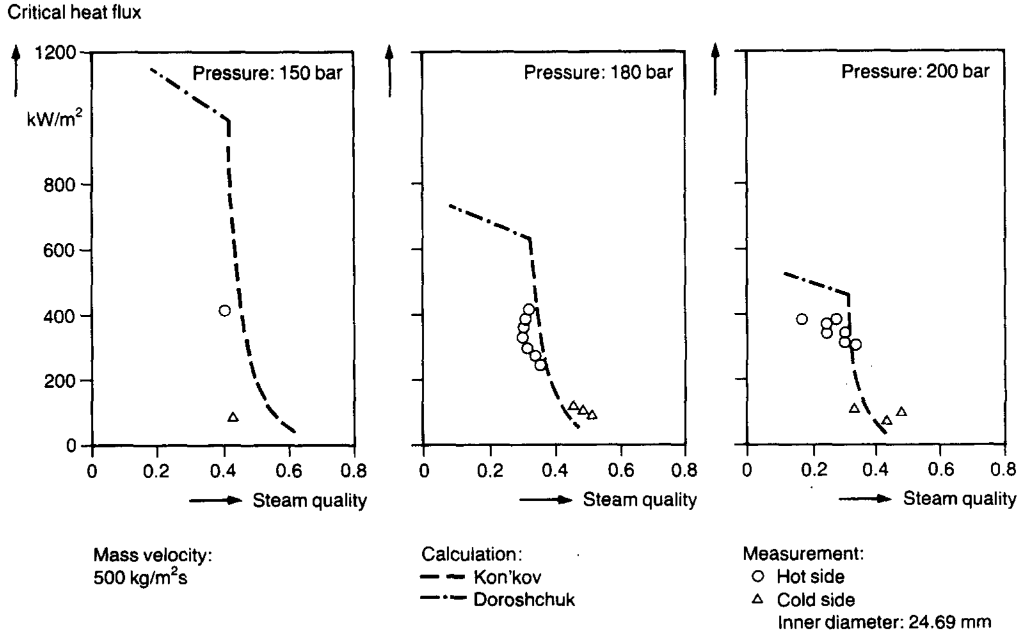


Figure 8. Critical heat flux in a tube with one-sided heating.

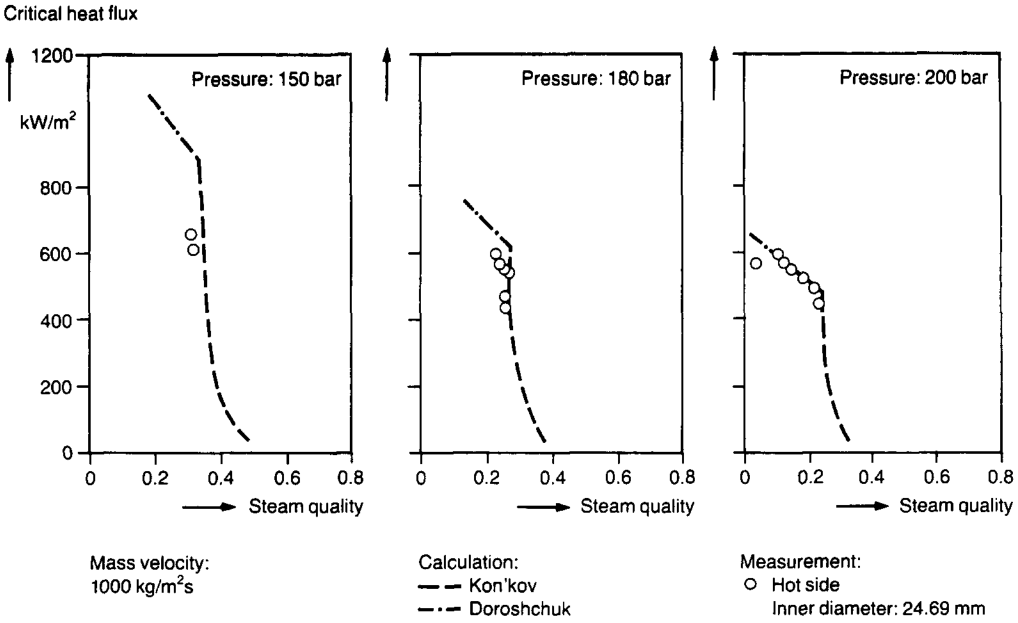


Figure 9. Critical heat flux in a tube with one-sided heating.

At the boundary between the wetted and unwetted inner tube wall, the calculated heat flux pattern is discontinuous. Since the discontinuity in the heat flux distribution is an unrealistic condition resulting from the assumption of an abrupt change in the heat transfer coefficient, the temperature distribution is shown as a broken line in this region. However, this local inaccuracy has only a small effect on the computation of the heat flux on the hot and cold sides.

Figure 7 shows a typical comparison between a one- and a two-dimensional test evaluation. Whereas a one-dimensional analysis suggests that the heat flux on the hot side increases when dryout occurs, as a result of the temperature dependence of the electrical resistance, the two-dimensional analysis shows that this effect is more than offset by the circumferential conduction effect, so that the heat flux is actually reduced following dryout. The lower diagram

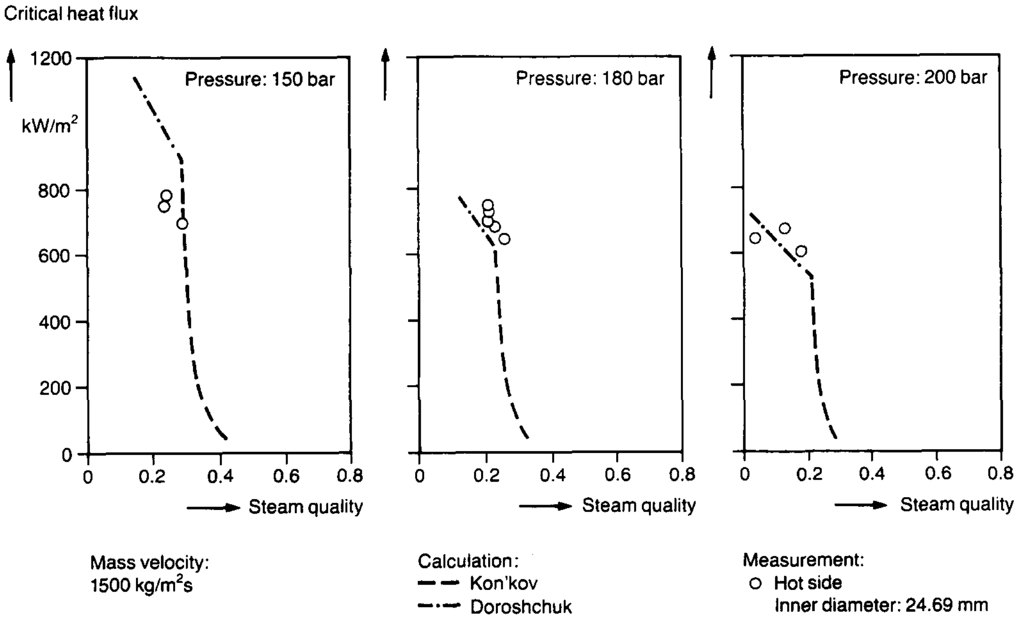


Figure 10. Critical heat flux in a tube with one-sided heating.

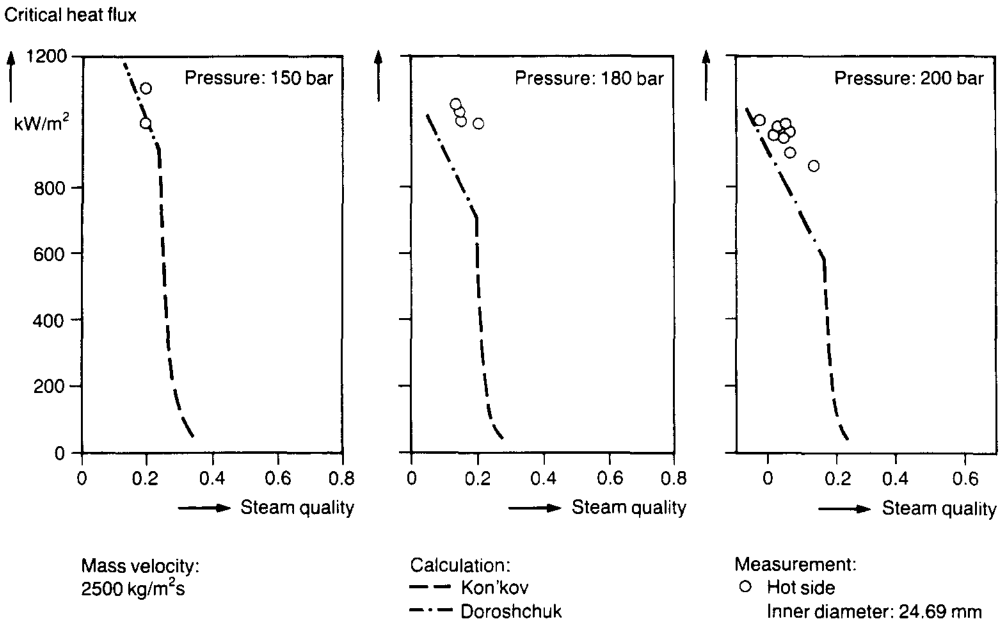


Figure 11. Critical heat flux in a tube with one-sided heating.

in figure 7 also illustrates that, due to the reduced heat flux, the two-dimensional analysis generally yields higher inner wall temperatures in the post-CHF region on the hot side than were obtained with the one-dimensional analysis.

As expected, the redistribution of the heat flux on the inner wall is influenced by the angles of the wetted and unwetted parts of the circumference. A sensitivity study showed that there is a strong spreading of the unwetted part immediately after dryout on the hot side. Therefore, it can be assumed that the unwetted zone covers the hot side entirely.

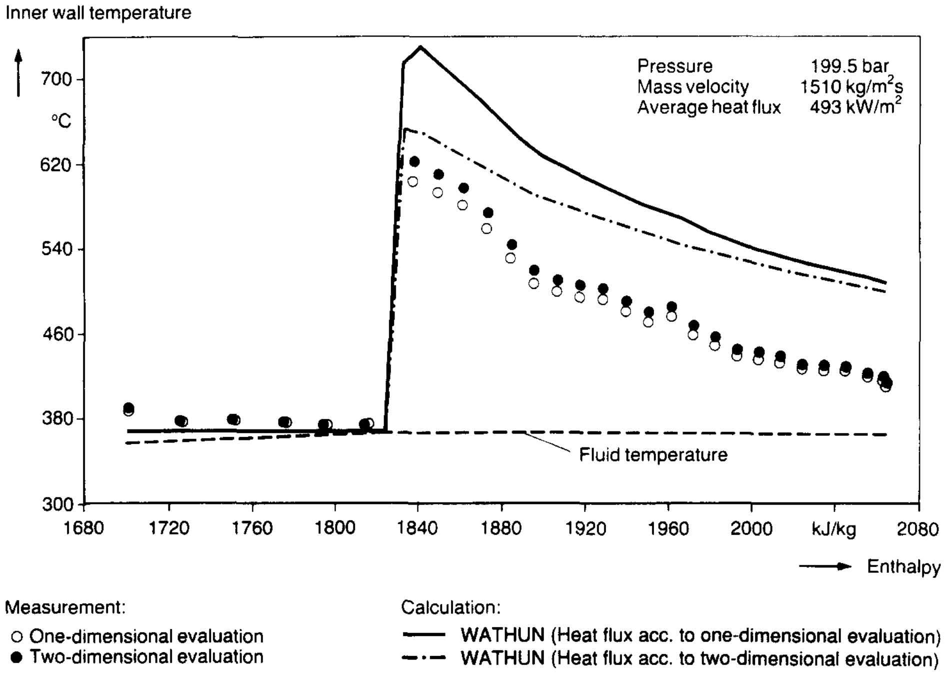


Figure 12. Calculated and measured wall temperature distribution on the hot side.

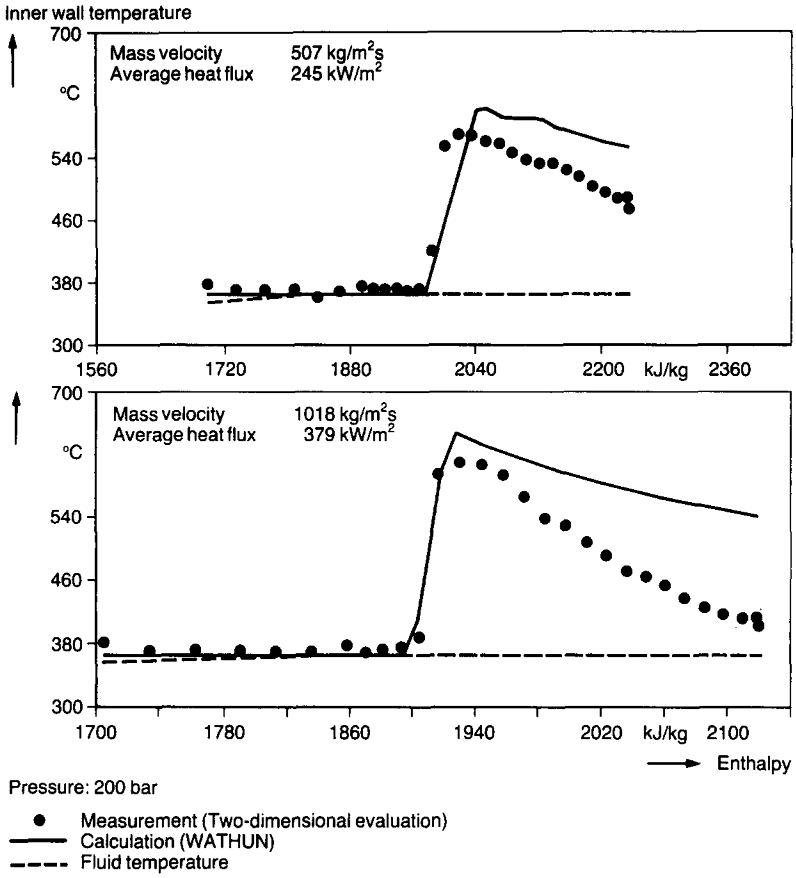


Figure 13. Calculated and measured wall temperature distribution on the hot side.

CRITICAL HEAT FLUX

With the aid of the measured axial wall temperature distributions the location of the boiling crisis was determined on the hot and—where applicable—the cold sides. Figures 8–11 show the measured critical heat fluxes as a function of the local steam quality, as well as the critical heat fluxes calculated by means of the Kon'Kov (1966) and Doroshchuk *et al.* (1975) correlations. For uniform heating, Drescher & Köhler (1981) proposed that a combination of the Kon'Kov and Doroshchuk *et al.* equations yielded satisfactory predictions; the dryout conditions being covered by the former equation and the film boiling conditions by the latter equation. As shown in figures 8–11, this procedure may also be applied for tubes heated from one side. With the critical steam quality measured here, ranging from 0 to 0.4, the occurrence of the boiling crisis is apparently dictated by the local variables.

POST-CHF HEAT TRANSFER

The measured axial wall temperature distributions in the post-CHF region were compared with calculations performed with the WATHUN code, which is explained in detail by Hein & Köhler (1984). This computer program is based on experiments with inside-cooled tubes in the pressure range of 50–250 b. It takes into account a thermal non-equilibrium between steam and water droplets.

The vapour superheat is calculated by means of an energy balance. The unknown quantity in the energy balance—the product of the surface area of the droplets and the heat transfer coefficient between the water droplets and steam—is determined with an empirical equation as a function of

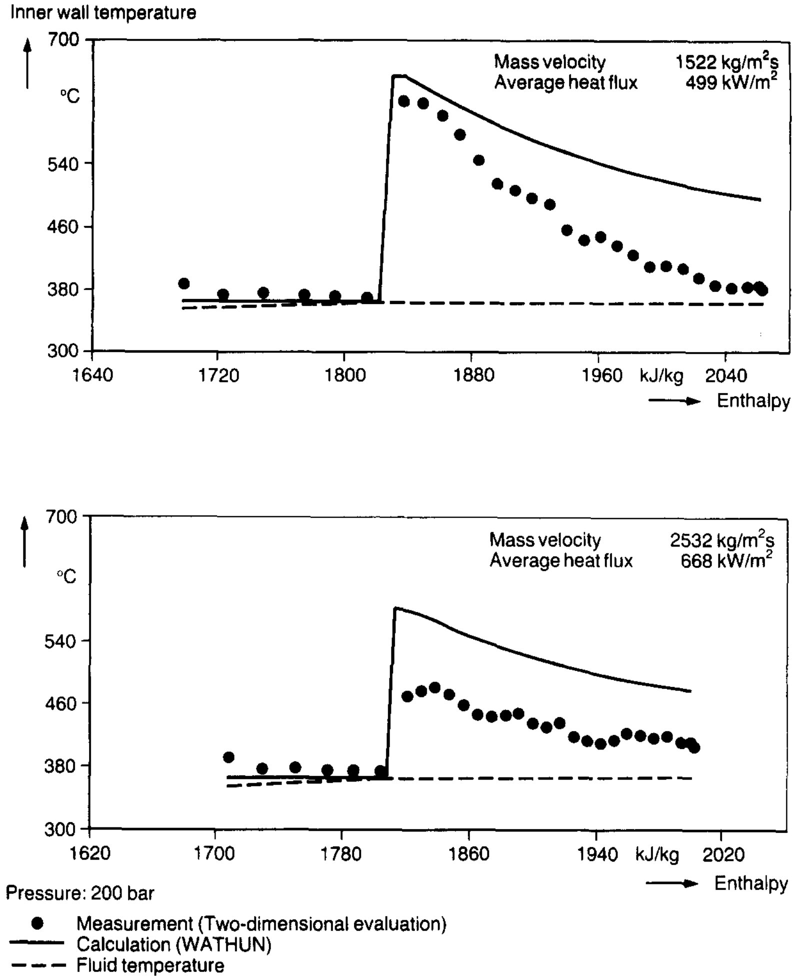


Figure 14. Calculated and measured wall temperature distribution on the hot side.

the mass flow rate and the Laplace constant. This procedure avoids the necessity of knowing the size distribution of the droplets and the phase slip for all the parametric conditions of interest. Calculating the vapour superheat in this manner, one of the well-known single-phase heat transfer correlations is applied for determination of the wall temperatures. In this form WATHUN is recommended in the *VDI-Wärmeatlas* (1984).

The calculations were carried out employing both one- and two-dimensional analyses. For determination of the thermal non-equilibrium or the vapour superheat in the post-CHF region WATHUN used the mean circumferential heat flux. As illustrated in figure 12, the two-dimensional test evaluation provides considerably better agreement between the calculations and the measurements. On account of the heat flux from the hot to the cold side, the calculated wall temperatures are lower than with the one-dimensional analysis. Moreover, the two-dimensional calculations predict the measurements even better, as a result of the higher inferred inner wall temperatures which were obtained by this method. However, there are still significant differences between measurements and calculations, especially in the high enthalpy region. This is also illustrated by figures 13 and 14. While it is generally possible to predict the maximum wall temperatures with a high degree of accuracy—except for cases with high mass velocities—the calculated wall temperatures are mostly too high in the case of higher flow enthalpies. This may be explained by the presence of the liquid film on the cold side of the tube, which causes cooling of the hot side by means of tangential flow of water in the liquid film as well as tangential heat conduction in the tube wall.

CONCLUSIONS

On the basis of the present investigation the following conclusions were obtained:

1. On account of the circumferentially non-uniform heating there are great differences in the post-CHF region with respect to the axial wall temperature distributions on the hot and cold sides. As a consequence, part of the heat flux generated on the hot side in the wall material flows to the cold side. Therefore, a two-dimensional analysis is necessary for the determination of the tube wall temperatures and the heat fluxes on the inner wall of the tube.

2. For the determination of the critical heat flux, one-dimensional analysis may be used. In the parameter ranges covered by the present investigation the measured critical heat fluxes were predicted fairly well by means of the equations developed by Kon'Kov (1966) and Doroshchuk *et al.* (1975) for uniformly heated tubes.

3. The measured heat transfer conditions in the post-CHF region were in fair agreement with the WATHUN computer program, which was developed for tubes with uniform heating. While the maximum wall temperatures can usually be predicted with a high degree of accuracy—except for cases with higher mass velocities (2500 kg/m^2 s)—there are greater differences between the calculations and the measurements in the case of higher enthalpies of the fluid.

REFERENCES

ALEKSEEV, G. V., ZENKEVITCH, B. A., PESKOV, O. L., SERGEEV, N. D. & SUBBOTIN, V. I. 1964 Burn-out heat fluxes under forced water flow. *Proc. 3 U.N. Int. Conf. peaceful Uses atom. Energy* **28,** 237a.

BECKER, K. M., BODE, M. & STRAND, G. 1970 Burnout and post-burnout measurements for flow of water in a round tube with one-sided heating. Report KTH-NEL-14.

BECKER, K. M., ENERHOLM, A. & SARDH, L. 1984 Post-burnout measurements for flow of water in a round tube with one-sided heating. Report KTH-NEL-37.

BUTTERWORTH, D. 1971 A model for predicting dryout in a tube with a circumferential variation in heat flux. Report AERE-M 2436.

CHOJNOWSKI, B. & WILSON, P. W. 1972 Critical heat flux for steam generating tubes when heated by thermal radiation from one side. Presented at *Eur. Two-phase Flow Gp Mtg*, Rome.

DOROSHCHUK, V. E., LEVITAN, L. L. & LANTSMANN, F. P. 1975 Recommendations for calculating burnout in a round tube with uniform heat release. *Teploenergetika* **22,** 66–70.

DRESCHER, G. & KÖHLER, W. 1981 Die Ermittlung kritischer Siedezustände im gesamten Dampfgehaltsbereich für innendurchströmte Rohre. (The determination of critical boiling conditions throughout the entire steam content range for flows in tubes.) *Brennst.—Warme—Kraft* **33,** 416–422.

HEIN, D. & KÖHLER, W. 1984 A simple-to-use post-dryout heat transfer model accounting for thermal non-equilibrium. In *Proc. Int. Wkshp Fundamental Aspects Post-Dryout Heat Transfer*, Salt Lake City, Utah. Report NUREG/CP-0060.

HUMPHRIES, P., DENNETT, G. F. & SCRUTON, B. 1984 Critical heat flux characteristics for vertical steam-generating tubes with circumferentially non-uniform heating. In *Proc. 1st U.K. natn. Conf. Heat Transfer. Univ. of Leeds, W. Yorks. Inst. Chem. Engrs Symp. Ser. No. 86*, Vol. 2, pp. 817–828.

KITTO, J. B. & WIENER, M. 1982 Effects on nonuniform circumferential heating and inclination on critical heat flux in smooth and ribbed bore tubes. *In Proc. 7th Int. Heat Transfer Conf.*, Munich, Paper FB 21.

KON'KOV, A. S. 1966 Experimental study of the conditions under which heat exchange deteriorates when a steam–water mixture flows in heated tubes. *Teploenergetika* **13,** 12.

LAHEY, R. T. & MOODY, F. J. 1977 *The Thermal-hydraulics of a Boiling Water Nuclear Reactor*. American Nuclear Society.

MIROPOLSKII Z. L. & MOSTINSKII, I. L. 1958 Critical heat flux in uniform and nonuniform heating of the circumference of steam-generating tubes. *Teploenergetika* **11,** 64–69.

VDI-Wärmeatlas, Capt. Hbc and Hbd. VDI-Verlag, Düsseldorf, 1984.