

Analysis of Wall Heat Transfer in the Pre-CHF Region of Becker Post-Dryout Tests Using the SPACE Code

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1. Introduction

Best estimate plus uncertainty analysis of an intermediate break loss of coolant accident (IBLOCA) requires quantified input uncertainty for the reactor core wall heat transfer models. Following the SAPIUM guidance [1], this study performs an inverse uncertainty quantification (IUQ) of these models in the SPACE code [2] against the Becker heated tube post-dryout experiments [3], from which quantification and validation subsets were drawn by systematic screening.

Prior to the sensitivity analysis on the quantification subset, a baseline calculation with all wall heat transfer multipliers at unity was performed. Contrary to expectation, this nominal case overpredicted the inner wall temperature in the pre-CHF region (before the critical heat flux) by about +9 K for TS1 and +3 K for TS2. The deviation is governed primarily by tube diameter, being large and positive for the wider tubes TS1 and TS3 and small for TS2, and it grows with heat flux and mass flux while remaining largely insensitive to pressure (Fig. 1). Because this temperature is not measured directly but inferred from an outer wall thermocouple through the wall conductivity, the deviation admits two interpretations, a code heat transfer coefficient (HTC) inadequacy or a data reduction (conductivity) artifact.

Table I. Becker post-dryout test sections and conditions.

Parameter	TS1	TS2	TS3
Inner diameter (mm)	14.9	10.0	24.69
Heated length (m)	7.0	7.0	7.1
Pressure (bar)	30–200	30–200	180–200
Mass flux (kg/m ² ·s)	500–3000	500–3000	≈2300
Heat flux (W/cm ²)	40–80	35–80	≈88
Number of runs	334	138	38

Resolving this ambiguity is a precondition for IUQ. The study therefore identifies the origin of the deviation and quantifies the experimental uncertainty required for it.

2. Methods and Results

The three Becker test sections are vertical, uniformly heated round tubes with upward water flow. Their geometry and operating envelope are summarized in Table I.

2.1. Deviation characteristics

For matched TS1/TS2 pairs at 30 and 70 bar, the calculated wall HTC is nearly independent of diameter (ratio 0.91) and the calculated superheat stays near 12–13 K for both, whereas the measured superheat differs markedly, at 4.5 K for TS1 and 9 K for TS2. The diameter dependence of the deviation therefore originates in the measurements, not in the calculated HTC.

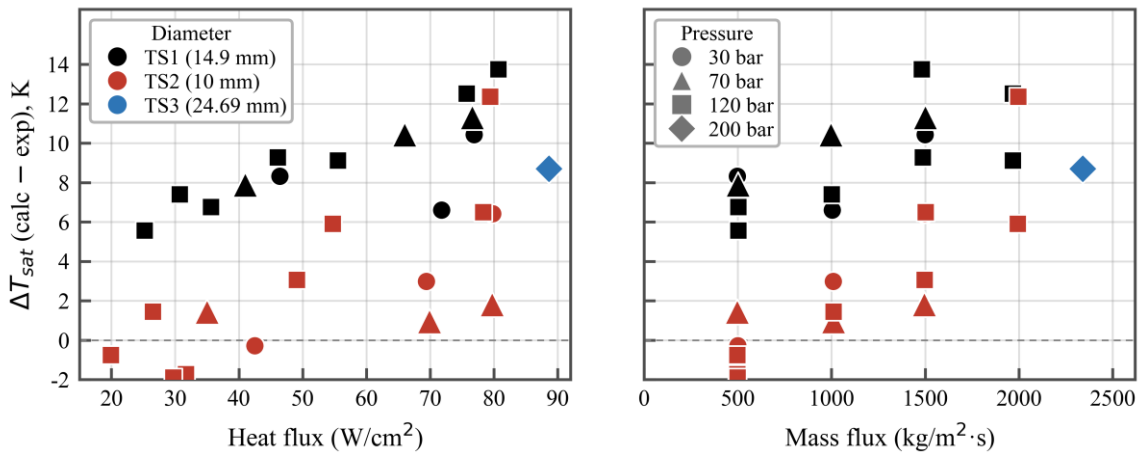


Fig. 1. Pre-CHF wall superheat deviation (calc – exp) versus heat flux (left) and mass flux (right). Color denotes tube diameter (TS1, TS2, TS3) and marker shape denotes pressure (circle 30 bar, triangle 70 bar, square 120 bar, diamond about 200 bar).

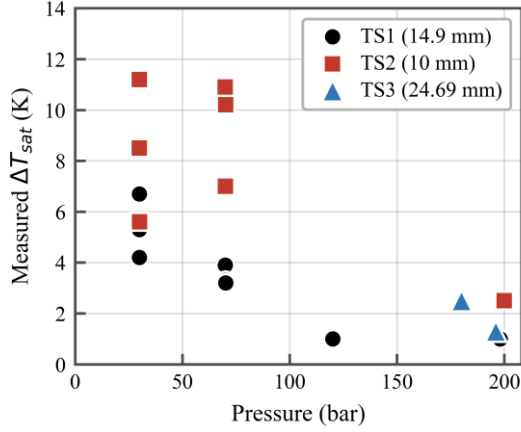


Fig. 2. Measured pre-CHF wall superheat versus pressure.

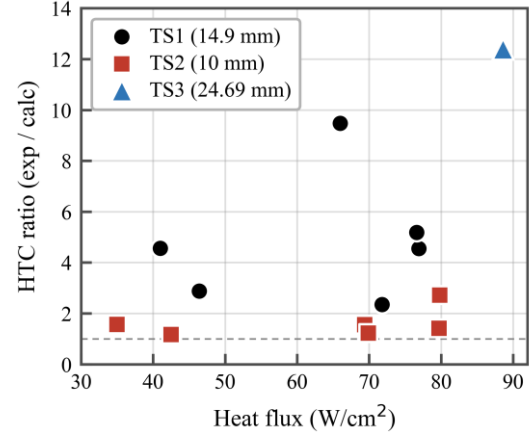


Fig. 3. Wall HTC ratio versus heat flux.

2.2. Experimental parameter effects

Seventeen tabulated runs (three test sections, 30–200 bar) were digitized. The measured pre-CHF superheat falls monotonically with tube diameter and pressure (Fig. 2), taking values of 8.0, 3.6, and 1.9 K for TS2, TS1, and TS3. The measured HTC instead rises up to twentyfold with heat flux and mass flux, a dependence the code correlation does not reproduce.

2.3. Cause of the overprediction

Across every matched run the code underpredicts the wall HTC, more so with tube diameter (Fig. 3). The ratio of measured to calculated HTC rises from about 1.2–1.6 for TS2 to 2.4–9.5 for TS1, the proximate cause of the overprediction.

The competing explanation, an error in the conductivity used to infer the inner wall temperature, is excluded by two checks. First, TS3 has a conductivity from a dedicated high Reynolds number measurement rather than a manufacturer correlation, so its inferred temperature is free of manufacturer bias, yet SPACE still overpredicts its pre-CHF superheat (about 10 K against 1.3 K measured, HTC ratio near 12). Second, the measured and manufacturer resistivities agree to about 1.5 %, which through the Wiedemann–Franz relation implies a bias far too small to account for the roughly 8 K deviation. The two checks jointly exclude a data reduction artifact and establish a code HTC inadequacy in large diameter, high flux flow boiling.

2.4. Experimental uncertainty for IUQ

The inner wall temperature $T_{w,in}$ is obtained from the outer wall temperature $T_{w,out}$ as

$$T_{w,in} = T_{w,out} - q \cdot C_{geo} / \lambda \quad (1)$$

where q is the heat flux, C_{geo} a geometry factor, and λ the wall conductivity, the dominant term, correlated by

material (rank one). The absolute conductivity is assigned a conservative 10 to 15 % uncertainty, wider than the 1.5 % resistivity agreement because the resistivity to conductivity conversion is less certain. Propagating the measurement uncertainties gives an experimental standard deviation of 6.45 K for TS1 and 3.61 K for TS2 (mean off-diagonal correlation 0.87), which serves as the measurement error covariance for the Bayesian data assimilation module of PAPIRUS [4].

3. Conclusions

A measured conductivity test section and an empirical bound on the conductivity uncertainty show the nominal SPACE overprediction of the pre-CHF wall temperature for the Becker quantification subset to be a code HTC inadequacy rather than a data reduction artifact. The IUQ will proceed within PAPIRUS, using the quantified experimental covariance as the measurement error covariance and a model discrepancy term for the residual deviation. Reducing the deviation will require a code wall heat transfer model that captures the observed diameter and heat flux dependence.

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