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Subcooled Boiling Models in CTF: Analysis and Separate Effects Validation

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INTRODUCTION

In light water reactors (LWRs), the steam generator and structural materials are gradually corroded over time. These corrosion products—mostly oxides of iron, nickel, and chromium—are transported by the reactor coolant and preferentially deposit on the outer surface of nuclear fuel rods. These deposits were identified in LWRs as early as 1944 and were colloquially called “crud”. In 1959, this colloquial term was formed into the backronym Chalk River Unidentified Deposits (CRUD) by Commander E. E. Kinter, who oversaw the analysis of crud deposits at the Chalk River site [1].

Crud deposition has important effects on reactor operation that motivate the development of high-fidelity and high-resolution modeling and simulation (M&S) tools. As a result, the Consortium for Advanced Simulation of LWRs (CASL) has focused development on two crud-specific challenge problems: Crud-Induced Localized Corrosion (CILC) and Crud Induced Power Shift (CIPS). Both of these processes are detrimental to reactor margins and safety and are largely determined by the buildup of crud on the surface of fuel cladding.

The deposition of crud is a complex multi-physics phenomena. Accurate modeling activities require a thorough understanding of corrosion, corrosion product transport and deposition, coolant boiling and chemistry, neutronics, and heat transfer characteristics of the crud. In addition, it is important to model the nonlinear coupling between each of these physics, which are shown in Figure 1. Each separate physical process impacts the others in complex nonlinear ways. Therefore, the modeling of crud has been a common research topic in the M&S community [2, 3].

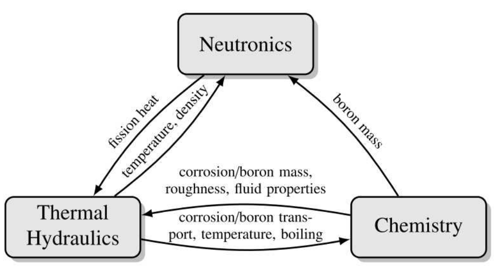

Fig. 1: Nonlinear Feedback

Crud buildup is sensitive to boiling [4]. As steam is formed, solid particles are left behind; therefore, corrosion products preferentially deposit during the boiling process. The flow boiling curve before dryout is shown in Figure 2. After the onset of boiling but before saturated boiling, there is a region called *subcooled boiling*. In this regime, there is boiling at the surface of the clad, even when the bulk fluid temperature has not yet reached the saturation temperature. These subgrid physics cannot be modeled in subchannel codes; therefore, this regime is traditionally treated using an empirical model that is some combination of the surrounding regimes [5].

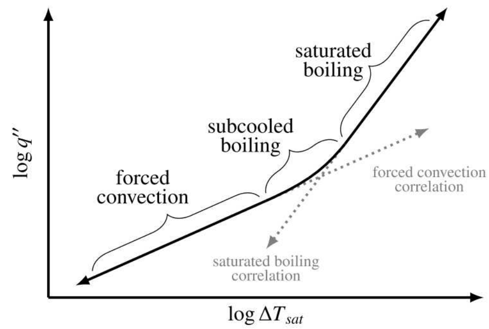

Fig. 2: Pre-dryout flow boiling curve

In pressurized water reactors (PWRs), the only boiling that takes place at normal operating conditions is subcooled boiling. In fact, CASL Phenomena Identification Ranking Tables (PIRTs) have consistently ranked subcooled boiling as one of the most important phenomena determining crud buildup [6, 7]. Therefore, this work focuses on analysis and validation of subcooled boiling models in the CASL version of Coolant Boiling in Rod Arrays–Three Field (COBRA-TF), which is called CTF. CTF is the thermal hydraulic simulator in Virtual Environment for Reactor Applications (VERA).

This work has two parts: a comparison of subcooled boiling models to existing data, and a separate effects validation study for subcooled boiling. More detailed information can be found in the corresponding technical report [8].

DATA ANALYSIS

Four models for boiling heat transfer are analyzed in this section: Chen [9], Thom [10], Gorenflo [11], and Gungor & Winterton [12]. For some models, there are CTF-specific modifications that will be indicated where appropriate. There is more information about these correlations in the technical report corresponding to this work [8].

Four data sources were harvested from the literature and used to compare the correlations:

- The Sani (1960) data [13] was used in the construction of the Chen correlation.
- The Rohsenow (1951) data, which is also used for separate effects validation in the next section.
- Data from two figures in Rohsenow’s textbook [14, 5].
- The NASA data by Stone [15], which includes low pressure data.

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Figures 3 and 4 show the measured heat flux versus the calculated heat flux for each correlation. In Fig. 3, the colors indicate which dataset the point belongs to and the marker type indicates the correlation (see figure legend). Figure 4 shows the same data points, however, the colors correspond to correlation type. Some models are implemented in CTF differently than the original correlations. Where this is the case, the CTF model is indicated by "(CTF)" in the legend.

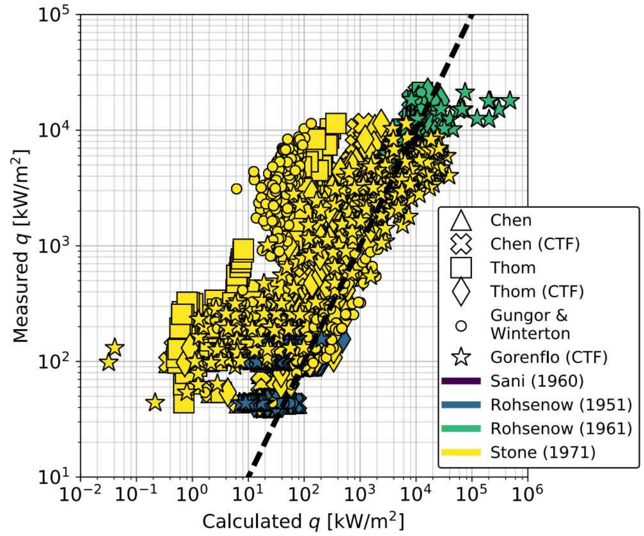

Fig. 3: Experimental vs computed heat flux for each correlation and dataset

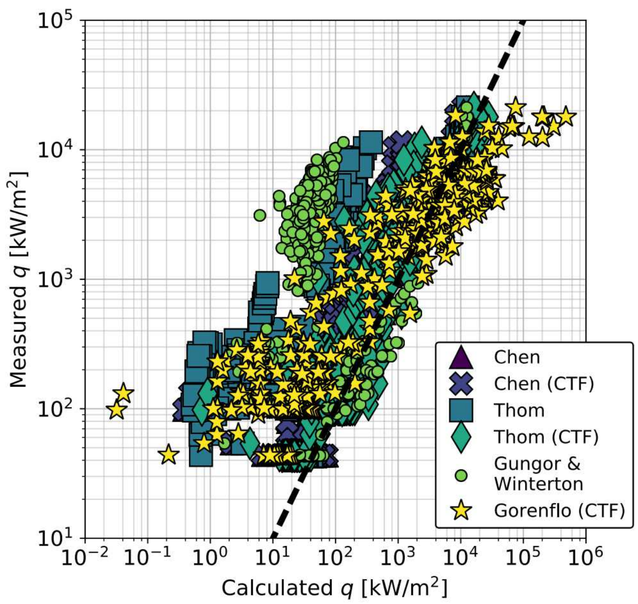

Fig. 4: Experimental vs computed heat flux for each correlation

In general, most correlations tended to underpredict the heat flux, which is shown in the plot of measured heat flux versus calculated heat flux. The relative error in heat flux is generally lower for high heat flux datasets, specifically all Rohsenow data. However, the Stone data includes higher heat flux experiments and do not follow the same trend. Therefore, the observed accuracy at higher heat fluxes might be related to the experimental uncertainty or some other bias rather than an inherent characteristic of the correlations themselves. The notable exception to this is the Gorenflo correlation, which overpredicted some of the higher heat flux datapoints, sometimes by an entire order of magnitude.

The results are summarized in Table I. The Chen correlation, as implemented by Chen, has lower root mean square error (RMSE) values than the Chen correlation implemented in CTF. However, the modifications made in CTF to the Thom correlation do significantly improve the correlation accuracy over the original Thom correlation; it overall has the lowest RMSE value. The Gungor & Winterton correlation has nearly the same accuracy as the unmodified Thom correlation. The Gorenflo correlation performs the worst overall. The very high RMSE value for the Rohsenow book (1961) data is attributed to a few data points with large superheat quantities. The Gorenflo correlation raises superheat to an exponential power, which led to extremely large residuals for large values of superheat. The Sani data has low RMSE values for all correlations as the data was collected at low heat flux values.

All the correlations poorly predict much of the experimental data, sometimes by orders of magnitude. This calls the accuracy and predictability of these models into question. In the next section, we examine how these large biases impact CTF simulations.

SEPARATE EFFECTS VALIDATION

CTF already has integral effects tests in its automated test suite that include subcooled boiling effects [16]; therefore, this work focuses on separate effects validation. Separate effects validation is an important part of the validation process because it ensures that compensating errors between physics models are minimized [17].

Two facilities are examined in this validation study: the Rohsenow experiments [18] and the Westinghouse Advanced Loop Tester (WALT) clean rod experiments [19]. Both facilities consist of steady state flow through a short tube. Therefore, the validation process is straight forward. Convective heat transfer is essentially governed by the equation $q'' = hA(T_f - T_w)$. Assuming that the tube is insulated and therefore external losses are negligible, an energy balance is used to compute the fluid temperature rise. Therefore, the heat flux q'', surface area A, and fluid temperature T_f are essentially fixed. So the interaction between the wall temperature T_w and the heat transfer coefficient h is of primary interest. Since the heat transfer coefficient cannot be directly measured, the wall temperature becomes the quantity of interest for the validation process.

For both facilities, standard CTF boundary condition and geometry options are used to simulate a single channel. Validation results for the Rohsenow experiment are shown in Figure 5 and summarized in Table II. Results for the WALT tests are shown in Figure 6 and summarized in Table III. For both figures, colors indicate the run number modeled and the marker shape indicates the CTF subcooled boiling model being employed (Chen, Thom, or Gorenflo).

TABLE I: RMSE of $q_{model} - q_{exp}$ summary [kW/m^2]

Year	Author	Chen [9]	Chen CTF	Thom [10]	Thom CTF	Gungor & Winterton	Gorenflo CTF
1951	Rohsenow	1652.6	1647.8	1617.6	1159.5	1716.5	1496.4
1960	Sani	12.5	12.5	59.1	47.7	14.2	75
1961	Rohsenow	3385.8	3920.0	2939.4	2978.0	2646.3	90893.1
1971	Stone	2405.1	2636.7	3671.6	2113.5	3730.6	7001.1
ALL DATA		1952.6	2146.5	2689.5	1688.1	2713	23129.1

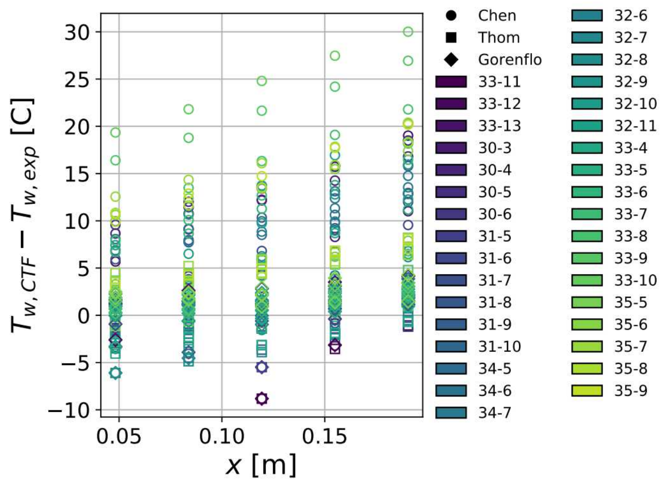

Fig. 5: Validation results for Rohsenow data

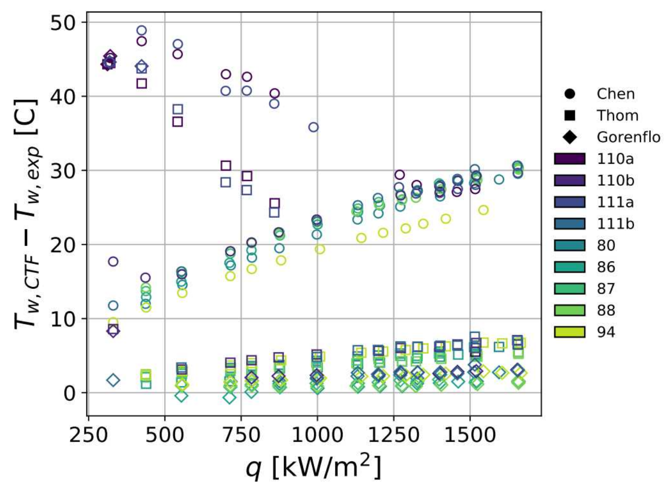

Fig. 6: Validation results for WALT data

TABLE II: Rohsenow validation metrics for each correlation

	Chen	Thom	Gorenflo
mean [°C]	9.5	0.9	1.1
stdev [°C]	7.1	3.0	2.0
RMSE [°C]	11.9	3.1	2.3

TABLE III: WALT validation metrics for each correlation

	Chen	Thom	Gorenflo
mean [°C]	25.7	8.4	3.8
stdev [°C]	8.3	10.4	9.0
RMSE [°C]	27.1	13.3	9.7

Some CTF simulations do not reach steady state according to the CTF steady state indicators. This phenomenon will require future investigation, as it is unclear if this is caused by some physical oscillation or numerical issues inside the code. These cases require additional investigation, though they are currently excluded from reported results.

For both data sets, the correlations can be ranked from most to least accurate: Gorenflo, Thom, and then Chen. In the Rohsenow data, it can be seen that all correlations are more accurate for lower fluid bulk temperatures. In the WALT data, it is generally observed that lower heat fluxes result in better predictions.

A few WALT cases have very large over-predictions of wall temperature, even when using the Thom or Gorenflo correlations. These cases correspond to case 110a and 111b, which have significantly lower inlet temperatures than other cases (by about 40 °C). Therefore, lower inlet temperatures introduce some bias, though the cause of this phenomenon is not known.

CONCLUSION

In this work, subcooled boiling heat transfer was examined as a first step towards qualifying VERA crud modeling. Since crud formation is very sensitive to boiling, a correct understanding of boiling is an important step towards understanding crud deposition. To achieve this, two separate studies were performed: a comparison of various subcooled boiling models to a variety of experimental data, and a separate effects validation of the subcooled boiling models available in CTF. For both parts, more detail can be found in the corresponding technical report [8].

The comparison of subcooled boiling models to experimental data sets showed that all correlations generally underpredict the boiling heat flux. In the nuclear industry, the underprediction of surface heat flux will result in an overprediction of fuel temperatures, which is conservative for clean rods. Differences between the predicted and measured heat fluxes are relatively large, ranging up to an order of magnitude. This is likely due to the large uncertainties in the boiling process, experimental uncertainties, and relatively small ranges of applicability for each model.

A separate effects validation study was completed using the Rohsenow [18] and WALT [19] data. For these two datasets, the correlations ranked from most to least accurate are: Gorenflo, Thom, and Chen. Chen was anticipated to be the least accurate, as it was originally formulated using low pressure experiments. Therefore, conventional wisdom dictates that the Chen correlation should be used for low pressure cases and Thom correlation for high pressure cases [20]. In general, CTF overpredicted wall temperatures in the subcooled region. Additionally, the CTF wall temperatures were less accurate as heat flux increased and fluid temperature increased.

For both datasets, some CTF simulations failed to converge to steady state as determined by CTF steady state indicators. For the Rohsenow data, the Gorenflo correlation failed to converge for several of the cases. For the WALT data, all three correlations failed to converge for different cases. It is unclear if these convergence failures are due to numerical issues in the code, or represent some physical oscillation that is not represented in the steady state experimental data.

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