Error Analysis of Supercritical Water Correlations Using ATHLET System Code For Low and Moderate Mass Flux Cases

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Summary

The thermal-hydraulic computer code ATHLET (Analysis of THermal-hydraulics of LEaks and Transients) is used for analysis of anticipated and abnormal plant transients, including safety analysis of Light Water Reactors (LWRs), Russian Graphite-Moderated High Power Channel-type Reactors (RBMKs) and SuperCritical Water-cooled Reactors (SCWRs). Efforts are being made to study the supercritical phenomena both analytically and experimentally. In this work, a numerical model was created in ATHLET to represent a supercritical water experimental test section and the ability of the code to predict the inside-wall temperature of the test section for low and moderate mass flux ranges was assessed.

1. Introduction

SuperCritical Water-cooled Reactors (SCWRs) are one of six Generation-IV nuclear-reactor concepts and are expected to have high thermal efficiencies (1.2 to 1.4 times higher than that of current water cooled reactors) [1]. SCWRs use light water as a coolant and operate at temperatures and pressures above the critical point of water. Several efforts have been made to study the supercritical phenomena and the flow parameters that govern the heat transfer both analytically and experimentally. While SCWRs typically operate at high mass flux ranges (1000 to 1500 kg/m^2s), analysis of low and moderate mass flux cases are also important from a safety perspective, where natural circulation, for example, becomes significant. In this work, experimental investigations of the local convection heat transfer of supercritical water in a 10 mm diameter bare tube are conducted for upward flow for low and moderate mass flux ranges (200 kg/m^2s and 500 kg/m^2s, respectively).

As satisfactory analytical methods have not yet been developed due to the difficulty in dealing with steep property variations in the pseudocritical region, empirical generalized correlations based on experimental data are used for heat transfer calculations at supercritical pressures. The thermalhydraulic system code ATHLET (Analysis of THermal-hydraulics of LEaks and Transients) is being used for analysis of various accident scenarios of Light Water Reactors (LWRs), Russian Graphite-Moderated High Power Channel-type Reactors (RBMKs) and SCWRs [2]. In this work, a numerical model is created in ATHLET to represent the experimental test section and the numerical results for the inside-wall temperature are compared with the experimental data and the ability of the code to predict supercritical water behavior for low to moderate mass flux cases is assessed.

2. Methodology

By verifying the numerical simulation results against the experimental data, ATHLET can then be evaluated for accurately predicting the inside-wall temperature. The correlations used in the ATHLET analysis are best estimate correlations and ATHLET is a best estimate computer code.

A dataset provided by Kirillov et al. at the Institute for Physics and Power Engineering (Obninsk, Russia) was used for the study [3]. The experiments were performed using the Supercritical-Pressure Test Facility SKD-1 loop. The Kirillov tube consists of a 4-m long vertically-oriented pipe of inner and outer diameters of 10 mm and 14 mm, respectively. Subcritical water was pumped upwards through the test section at four different mass fluxes of 200, 500, 1,000, and 1,500 kg/m^{2}s approximately. In this work, only the former two cases are assessed. The test section was heated by passing an electrical current through the tube. The effective surface heat flux was varied within the ranges of 73-1,256 kW/m^2. All simulations were run with an inlet pressure of 24 ± 0.1 MPa [3].

81 thermocouples were used to measure the outer-wall temperature of the tube at intervals of 5 cm spaced axially and the inner-wall temperature was calculated using basic heat-conduction equations. The dataset includes 89 experimental runs, with 81 data points for outside wall temperature per run. The dataset was classified into two cases: Normal Heat Transfer (NHT) (i.e. runs which did not experience deteriorated heat transfer), and runs which experienced Deteriorated Heat Transfer (DHT).

The vertical bare tube tested by Kirillov et al. was modeled in ATHLET (Mod 3.0, Cycle A). There are two existing heat transfer correlations for supercritical pressures in ATHLET, namely, the Watts-Chou correlation [4], and the Mokry et al. correlation [5]. As part of a previous analysis, the Yang correlations for Normal Heat Transfer (NHT) and Deteriorated Heat Transfer (DHT) were added to ATHLET [6,7]. The Yang correlation was developed for supercritical carbon dioxide, which is considered a modeling fluid for supercritical water. It is used in this analysis to see if similar trends in heat transfer regimes occur.

3. Analysis and Discussion

The ATHLET model of the vertical bare tube tested by Kirillov et al. is shown in Figure 1. The model consists of two Thermo-Fluid-dynamic Objects (TFOs), PIPE and PHBOUND. A Heat Conduction Object (HCO), HROD, is used to heat the PIPE TFO. The PIPE TFO is divided into 80 Control Volumes (CVs) and the Heat Transfer Coefficient (HTC) is calculated in each CV (for details, see [7]).

As previously mentioned, both low and moderate mass flux cases were analysed in this work. The heat flux was varied and four different cases were assessed. The first two heat flux cases for each mass flux case experienced NHT while the latter two experienced DHT:

- Low Mass Flux: 203 kg/m^{2}s (q_{avg} = 72.4, 90.8, 146.9, and 202.8 kW/m^2)
- Moderate Mass Flux:~ 500 kg/m^{2}s (q_{avg} = 109.2, 239.6, 361.5, and 430.0 kW/m^2)

The test matrix used for this analysis is shown in Table 1. The errors associated with the correlations predicting the inside-wall temperature are shown in Figures 2 and 3.

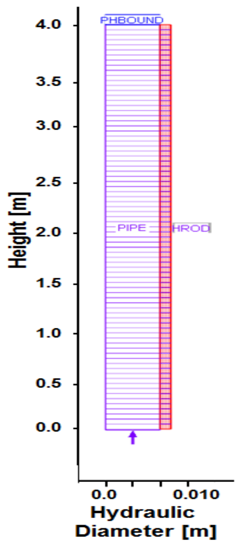


Figure 1: ATHLET Input Graphic for the Kirillov Test Section

	Boundary Conditions				Calculated Parameters
№	P_{in} [MPa]	T_{in} [°C]	G [kg/m²s]	q_{ave}'' [kW/m²]	q_{dht}'' [kW/m²]
Low Mass Flux					
1	24.1	341	203	72.4	92.3
2	24.1	340	203	90.8	92.3
3	24.1	341	203	146.9	92.3
4	24.1	341	203	202.8	92.3
Moderate Mass Flux					
1	24.1	342	498	190.2	312.0
2	24.0	341	495	239.6	309.8
3	24.1	342	496	361.5	310.6
4	24.0	341	503	430.0	315.8

Table 1: Test Matrix used for this Analysis

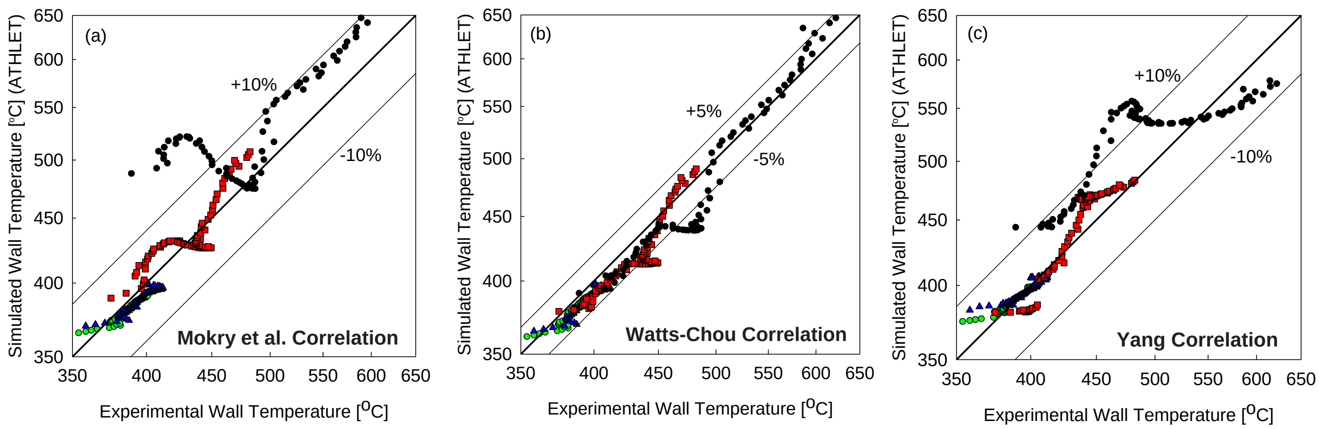
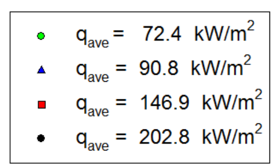


Figure 2: Error in Inside-wall Temperature for Low Mass Flux Cases (200 kg/m²s) using (a) Mokry et al. Correlation, (b) Watts-Chou Correlation, and (c) Yang Correlation



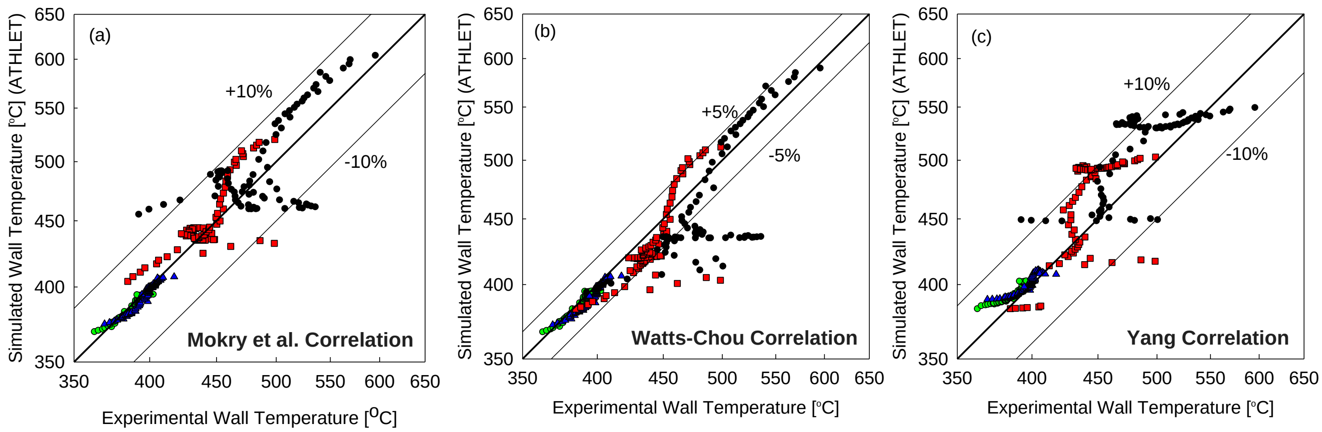
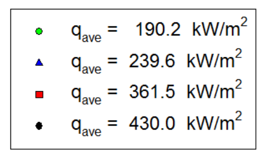


Figure 3: Error in Inside-wall Temperature for Moderate Mass Flux Cases (~500 kg/m^{2}s) using (a) Mokry et al. Correlation, (b) Watts-Chou Correlation, and (c) Yang Correlation



For the low mass flux case (G = 205 kg/m^{2}s), all three correlations seem to accurately capture the trends for the data shown for the heat flux cases were NHT is observed (q_{avg} = 72.4, and 90.8 kW/m^2) within 2.5 %. For the cases were DHT is observed (q_{avg} = 146.9, and 202.8 kW/m^2), the Mokry et al. correlation does not capture the trend as it appears to be perpendicular to the 0% reference line. The Watts-Chou correlation predicts reasonably well (within 5%) with the exception of the onset of DHT where the trend is horizontal. The Yang correlation over predicts the inside-wall temperature; however, the trend is captured with a bias.

Like the low mass flux cases, all three correlation accurately capture the trends for the data shown for the moderate heat flux case (G = ~500 kg/m^{2}s) where NHT is observed (q_{avg} = 190.2, and 239.6 kW/m^2). None of the correlations accurately capture the trends where DHT is observed (q_{avg} = 361.5, and 460.0 kW/m^2) as observed by the horizontal points. These results are analogous to high mass flux cases [8].

In terms of overall error for the correlations, the Watts-Chou correlation is most promising for both mass flux cases as the experimental data is predicted within ±5%, with the exception of the onset of DHT. The Yang correlation captures some trends, albeit with a bias. This could be attributed to the correlation being developed for carbon dioxide and not water. It appears that the numerical results are predicted well up to a certain ratio of heat flux to mass flux. Incorporating this ratio in the correlations may prove useful.

4. Concluding Remarks

The tested 1-D heat transfer correlations are able to accurately predict the heat transfer for the low and moderate mass flux cases for a normal heat transfer regime. For the low mass flux case, the Yang correlation captures the trends for the deteriorated heat transfer regime with a bias. The Watts-Chou and the Yang correlation appear to capture some trends for the moderate mass flux cases where DHT occurs. The Watts-Chou correlation is most promising for both low and moderate heat flux. Incorporating a ratio of heat flux to mass flux term in the correlations and into ATHLET may improve results.

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6. References

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