Progress on the Development of a Look-up Table for Trans-critical Heat Transfer in Water-cooled Heated Tubes

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Summary

A skeleton table has been constructed from the best prediction methods. This table describes the convective heat transfer coefficient as a function of pressure, mass flux, wall superheat (i.e., the difference between wall and bulk temperatures) and fluid enthalpy. The table has been updated by including all experimental data available to date in suitably normalized forms. Discontinuities in the variations in heat transfer coefficient with the table parameters have been removed. The parametric trends of the skeleton table, the updated table and the smoothened table have been assessed and compared to experimental data. The results of statistical error analyses are presented in this paper. It was found that the uncertainty in predicting the heat transfer coefficient using the present trans-critical look up table is much lower than that of the assessed correlations for all trans-critical sub-regions.

1. Introduction

Canada has undertaken to design a supercritical water-cooled reactor (SCWR), which is one of the six nuclear reactor concepts recommended by the Generation IV International Forum. Compared to existing reactors, the SCWR is expected to have a higher thermal efficiency and a considerably simplified design. Reliable supercritical (SC) heat transfer prediction methods are required for the thermalhydraulic design and safety of the SCWR.

Thermo-physical properties of fluids at near-critical conditions exhibit large changes within a narrow range of temperature, resulting in significant variations in fluid properties within a cross-section of flow. This strong property change introduces significant prediction errors when using SC heat transfer correlations based on bulk property values. Figures 1 and 2 present the various thermo-dynamic phases and processes of water at subcritical and supercritical conditions. A supercritical fluid is a fluid at a pressure higher than the fluid's critical pressure. The pseudo-critical line as shown on Figure 1 (dashed line) can be viewed as an extension of the saturation line beyond the critical pressure. This line separates supercritical liquid-like water from supercritical vapour-like water. No distinct phases are present beyond the critical point. Water changes its behaviour from being liquid-like (e.g., dissolving soluble substances) to vapour-like (e.g., diffusing into other materials) along the trajectory A-A (Jackson, 2007).

Look-up tables (LUTs) have been used successfully to predict complex heat transfer phenomena such as critical heat flux (Groeneveld et al., 2005) and film boiling heat transfer (Groeneveld et al., 2003) with an accuracy that is much higher than the best available prediction methods. This article describes the derivation process and error analysis of a trans-critical LUT.

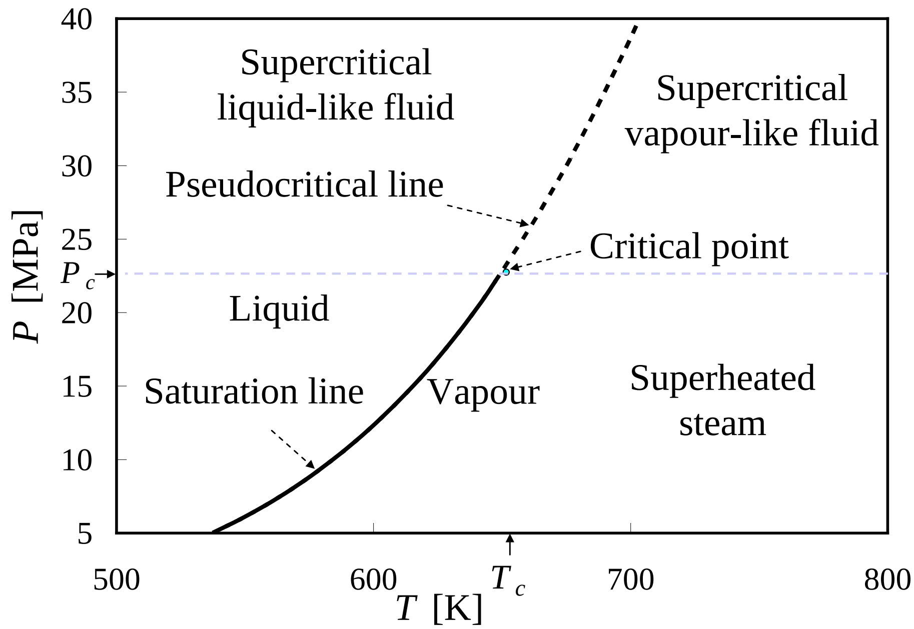

Figure 1 Pressure - temperature diagram. P_c = 22.064 MPa, T_c = 647.1 K.

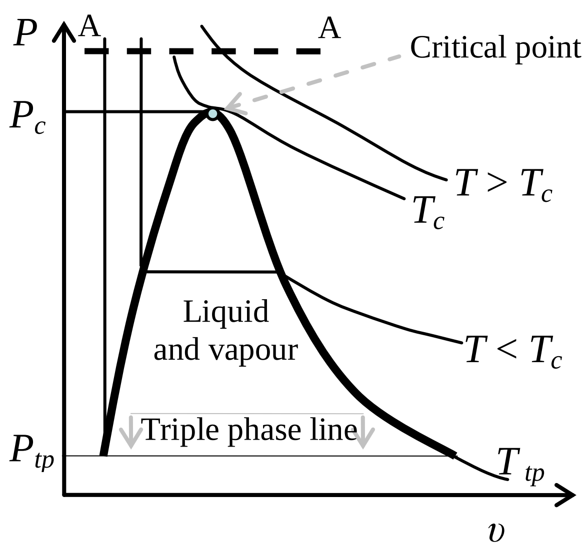

Figure 2 Pressure - specific volume diagram. The triple point pressure and temperature for water are, respectively, P_{tp} = 6.117×10^{-4} MPa, T_{tp} = 273.16 K.

2. Development of the trans-critical LUT

Development of a LUT includes compilation of experimental data and construction of a skeleton table. The University of Ottawa (UO) team compiled a large subcritical and supercritical heat transfer database primarily for water cooled tubes. The database includes additional data for other fluids in different geometries. A skeleton table has been constructed from the best prediction methods. This version of the table tabulates the convective heat transfer coefficient (HTC) as a function of four independent parameters, namely pressure, mass flux, wall superheat and fluid enthalpy. The LUT domain has been subdivided into sub-domains, each associated with relevant heat transfer mechanisms. The sub-domains include high-pressure subcritical regions (sub-cooled liquid, superheated vapour and subcritical two-phase regions) and SC regions (high-density state or SC liquid-like region, low-density state or SC vapour-like region, and a near-critical or near-pseudo-critical region). For each region, the best correlations were used for the construction of the skeleton LUT. This skeleton table has been updated by including all experimental data available to date in suitably normalized forms. Discontinuities in the variations in HTC with the table parameters have been removed. To minimize unrealistic sudden transitions (i.e., transitions which are not based on experimental trends) and to avoid numerical instabilities when applying the trans-critical LUT in thermal-hydraulic codes, the LUT trends have been smoothened using the method of Huang and Cheng (1994).

3. Uncertainty and parametric trends of the LUT

The results of statistical error analyses showed that the uncertainty in predicting the trans-critical HTC using the smoothened LUT is much lower than that of the assessed correlations for all trans-critical sub-regions. The error analysis was performed on the smoothened LUT using the 2010-UO combined database (Zahlan et al., 2011a). The error is defined as

$$e = \mathrm{HTC}_{\mathrm{predicted}} / \mathrm{HTC}_{\mathrm{experimental}} - 1 \qquad (1)$$

Table 1 shows percentages of all data which were used for the LUT update (18460 data points) as predicted by the most promising correlations and the smoothened LUT within error bands of $\pm$10% (e_{10}), $\pm$20% (e_{20}), $\pm$30% (e_{30}), and $\pm$50% (e_{50}) for the three supercritical subregions. Figure 3 compares prediction errors by the most accurate SC heat transfer correlation and by the current smoothened LUT for all SC data used for the LUT update. The parametric trends of the skeleton table, the updated table and the smoothened table have been assessed and compared to experimental data (Zahlan et al., 2012). For the current version of the LUT, smoothening functions did not exclude regions of true physical enhancement and deterioration. To exclude these regions from smoothing, reliable criteria for deterioration in trans-critical heat transfer should be applied[1]. In addition, identification of LUT heat transfer sub-regions having limited numbers of data available (or no data at all) is required to determine whether these sub-regions correspond to unrealistic LUT predictions. The future SC experimental program at Carleton University is expected to provide new and reliable water data which can be used to validate the LUT's prediction capability as these data have not been used for the construction of the table.

[1] We are in the process of applying Jackson's (2011) criteria for deterioration and enhancement to the UO expanded database and are currently investigating the optimum values of the numerical coefficients in these criteria (see also Jackson (2011) for a discussion of the same issue).

Table 1 Error bands for the smoothed table and best correlations

Error band for 12739 points	Percentage of data predicted by a correlation (%)			
	Mokry et al. (2009)	Gupta et al. (2010)	Swenson et al. (1965)	Current LUT
Region near the critical point				
e_{10}	48	53	45	61
e_{20}	81	81	73	90
e_{30}	93	93	87	98
e_{50}	99	99	96	100
Error band for 1344 points	Mokry et al. (2009)	Watts & Chou (1982), DHT*	Kuang et al. (2008)	Current LUT
High density state region (liquid-like region)				
e_{10}	48	32	41	54
e_{20}	75	63	71	84
e_{30}	88	86	88	96
e_{50}	97	98	98	100
Error band for 3651 points	Mokry et al. (2009)	Gupta et al. (2010)	Bishop et al. (1965)	Current LUT
Low density state region (vapour-like region)				
e_{10}	49	36	47	72
e_{20}	81	74	77	95
e_{30}	95	91	90	99
e_{50}	100	99	97	100

*DHT – deteriorated heat transfer

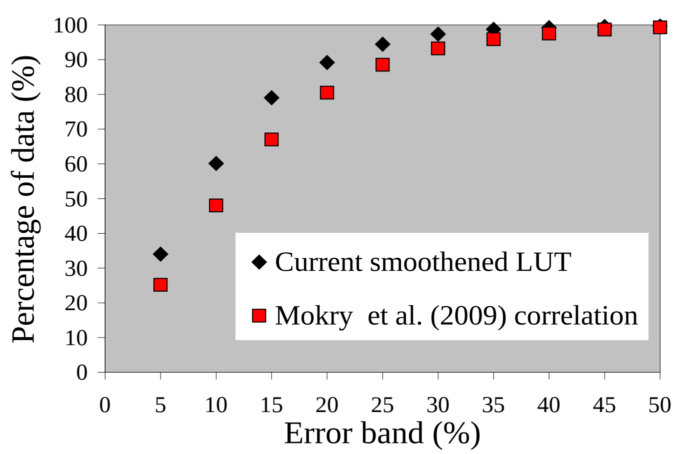

Figure 3 Comparison of predictions of the LUT and the Mokry et al. (2009) correlation in terms of percentage of data predicted for different error bands (all supercritical data; 17734 points).

4. Conclusions

- The skeleton table has been updated by including all screened experimental data available to date in suitably normalized forms.

- The updated table trends of heat transfer coefficient vs. various LUT flow parameters have been smoothened.

- The parametric trends of the skeleton table, the updated table and the smoothened table have been assessed.

- The results of statistical error analyses showed that the uncertainty in predicting the trans-critical HTC using the smoothened LUT is much lower than that of the assessed correlations for all trans-critical sub-regions.

5. References

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