Preliminary Evaluation of Single-phase Turbulent Heat Transfer Correlations' Applicability on Narrow Rectangular Channel Flow

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1. Introduction

During thermal-hydraulic design of research reactor core, single-phase heat transfer correlations play a key role in predicting its thermal margins. Especially, engineering hot channel factors are quite sensitive to their uncertainties. The uncertainties or applicability of the correlations can be quantified by comparing predicted values with analytic solutions or well-controlled experiment data. In this study, single-phase heat transfer experimental results from Sudo et al. (1985) are predicted by selected general turbulent correlations, and their applicabilities are discussed [1].

2. Methods and Results

In this section, the experiment carried out by Sudo et al. (1985) is described in brief along with prediction results by selected heat transfer correlations.

2.1 Sudo et al.'s Heat Transfer Experiment (1985)

In order to investigate heat transfer characteristics of JRR-3's core coolant channel, Sudo et al. (1985) have carried out a series of heat transfer experiments on a single rectangular channel having channel thickness and height equivalent to those of the model reactor. Table I summarizes its test section geometry and experimental conditions. The geometry and test parameter ranges contain or are similar to those of typical open pool type research reactor core in normal operation [2]. In the experiment, the cooling channel is formed between two parallel NCF 600 plates attached to Teflon blocks. Its sides are covered by transparent polycarbonate window for visual inspection. The wall heat flux is generated by flowing direct current to the heating plates. The local convective heat transfer coefficients are measured by combining wall heat flux and temperatures, obtained using digital multimeter and thermocouples, respectively.

In the same literature, the authors have compared experimental results on convective heat transfer coefficient with existing turbulent heat transfer correlations (Dittus-Boelter, Sieder-Tate, and Colburn), and gave rough estimation on prediction accuracy and applicable Reynolds number ranges [3, 4, 5]. Unfortunately, the presented results lack statistical data (mean, normality, and standard deviation) to estimate its applicability in terms of tolerance limits.

Table I: Summary of Experiment Conditions

Item	Test value [1]	KJRR [2]
Equivalent diameter [mm]	~ 4.3	~ 4.5
Heated length [mm]	750	600
Velocity [m/s]	up to 7	6
Tin [K]	281~315	~ 308
Re [-]	100~50,000	~ 38,000
Heat flux [kW/m^2]	up to 500	~ 415

2.2 Applicability of Selected Heat Transfer Correlations

In this study, following 5 correlations are selected and their applicable ranges are evaluated. First to third are widely utilized reference correlations. Petukhov et al. (1973) correlation is selected because it is one of the latest among the set of correlations developed by Petukhov and co-authors. Jo et al, (2014) correlation is selected since it is based on KAERI test data on narrow rectangular channel flow, and it is also one of the most up-to-date correlations for the flow.

Dittus-Boelter (or McAdams (1942) [6,7]) (1930) [3]:

$$Nu = 0.023Re^{0.8}Pr^{0.4} \tag{1}$$

Petukhov-Popov (1963) [8]:

$$f = [1.82\, log_{10}\, Re - 1.64]^{-2} \tag{2}$$

$$Nu = \frac{\left(\frac{f}{8}\right)RePr}{1.07+12.7\sqrt{\frac{f}{8}}(Pr^{2/3}-1)} \tag{3}$$

Gnielinski (1975) [9]:

$$Nu = \frac{\left(\frac{f}{8}\right)(Re-1000)Pr}{1+12.7\sqrt{\frac{f}{8}}(Pr^{2/3}-1)} \tag{4}$$

Petukhov et al. (1973) [10]:

$$Nu = \frac{\left(\frac{f}{8}\right)RePr}{1.07+\frac{900}{Re}-\frac{0.63}{1+10Pr}+12.7\sqrt{\frac{f}{8}}(Pr^{2/3}-1)} \tag{5}$$

Jo et al. (2014) [11]:

$$Nu = 0.0058Re^{0.9383}Pr^{0.4} \tag{6}$$

Figure 1 shows the assessment process. First, set of M/P (measured-to-predicted) data of convective heat transfer coefficient are generated for given lower

Reynolds number limit for turbulent region (Re_T). Here, M/P data are utilized instead of P/M, since the preliminary testing shows commonly found reciprocal normal behavior [12]. Next, the data undergo transformation to satisfy normality. In this study, Box-Cox transformation and expanded Shapiro-Wilk normality test are utilized [13, 14]. Next, one-sided lower tolerance limit of M/P data for desired confidence level of containing specified proportion of population (usually 95%/95%) are evaluated and scaled back by inverse transformation [15]. Next, upper tolerance limit for P/M data are estimated by Eq. (7). The above procedures are repeated for given range of Re_T (3,000~5,000 used in this study) until the minimum upper tolerance limit is found.

$$\left(\frac{\mathrm{P}}{\mathrm{M}}\right)_U = \frac{1}{\left(\frac{M}{P}\right)_L} = \frac{1}{\mu\left(\frac{M}{P}\right) - k \cdot s} \tag{7}$$

where, μ, k, and s are sample mean, one-sided tolerance limit factor, and sample standard deviation, respectively.

Table II summarizes the assessment results of the selected correlations. The study shows that in both terms of applicable *Re* ranges and prediction uncertainty, Dittus-Boelter (1930) and Jo et al. (2014) correlations show better performance over other correlations tested. In addition, the difference in Re_T between up flow and down flow conditions is seen in the most correlations, which is also reported in the original publication [1].

Table II: Assessment Results

Correlation	Re_T (downward/ upward flow)	Upper tolerance limit (95/95)
Dittus-Boelter (1930)	3,000/4,000	1.36
Petukhov-Popov (1963)	3,000/4,000	1.48
Gnielinski (1975)	5,000/4,000	1.41
Petukhov et al. (1973)	5,000/4,000	1.37
Jo et al. (2014)	4,000/4,000	1.32

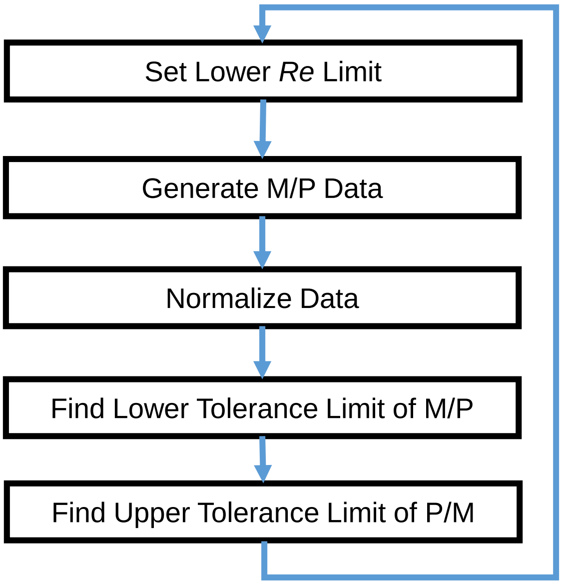

Fig. 1. Assessment Process

3. Summary

In this study, applicability of the existing heat transfer correlations on narrow rectangular channel flow is checked by utilizing heat transfer experiment data from JAEA. A simple assessment method is developed which gives statistical prediction uncertainty in terms of tolerance limit, and applicable flow conditions in terms of Reynolds number. Preliminary application of the method showed that classic general heat transfer correlation Dittus-Boelter (1930) and recently developed rectangular channel heat transfer correlation Jo et al. (2014) exhibit better overall prediction performance over other correlations. It is expected that the developed method can be readily utilized to other similar type of uncertainty/applicability assessment problems.

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