LOOK-UP TABLE FOR TRANS-CRITICAL HEAT TRANSFER

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Abstract

This paper presents a progress report on the derivation of a heat transfer look-up table (LUT) for the region near the critical point. The intended range of application of the LUT is sufficiently wide to span all conditions for which conventional single-phase correlations do not apply.

The UO database has been compared to existing correlations for single phase, near-critical (NC) and supercritical (SC) heat transfer. The parametric trends of the predicted accuracy of the more promising correlations are described. The LUT domain is subdivided into sub-regions such as subcritical liquid, subcritical vapour, subcritical two-phase heat transfer, SC liquid-like, SC vapour-like and near-critical or pseudo-critical region. For each sub-region, the best correlation is identified – this correlation will subsequently be used for the construction of a preliminary skeleton LUT, which will be updated by experimental data suitably normalized.

1. Introduction

Fluids exhibit large thermodynamic and heat transport property changes near the critical point. These property changes become smaller at supercritical pressures but remain evident near the pseudo-critical temperature, which is characterized by a maximum in the specific heat capacity. Because of these abnormal changes in the properties, the near-critical heat transfer coefficient is difficult to predict, especially in the range of relatively low mass velocities and high heat fluxes.

More than twenty correlations are available in the literature for the prediction of heat transfer in the near-critical and supercritical region; most of the available correlations are modified versions of the Dittus-Boelter (1930) equation. Although these correlations account for the change in properties in the near critical region, they usually do not account for heat transfer enhancement or deterioration in the vicinity of the pseudo-critical temperature T_{pc}. Some prediction methods considered the enhancement and deterioration in heat transfer when $T_b < T_w < T_{pc}$, where T_w is the wall temperature and T_b is the bulk temperature. The objective of this work is to construct a trans-critical heat transfer look-up table (LUT), which will cover a wide range of flow conditions, whereas each of the current correlations is bounded by a much narrower range. In addition, this trans-critical LUT will include the high pressure subcritical region and will thus provide for the transition from the subcritical into the supercritical region.

2. Trans-critical heat transfer database

2.1 Range of interest

The derivation of a reliable heat transfer prediction method requires a data base which covers all conceivable conditions that can be encountered in a supercritical water reactor (SCWR) during normal and abnormal operation. For the subcritical single-phase and two-phase regions, they have been thoroughly investigated and the available heat transfer prediction methods are deemed to be of sufficient accuracy. The trans-critical region of interest to SCWR thermal analysis has been defined in this investigation as follows:

(i) pressure: 19–30 MPa,

(ii) mass velocity 100–5000 kg $m^{-2}s^{-1}$,

(iii) bulk enthalpy: corresponding to 100K below and above the critical or pseudo-critical temperature.

2.2 Available data sets

Many heat transfer experiments using SC water have been reported during the past sixty years. Most of these SCHT data were obtained in support of the SC fossil fired plants, which have been constructed around the world since the early nineteen sixties. Pioro and Duffey (2005) reviewed the literature of SCHT experiments in water and found more than a hundred data sets. Although these data should, in principle, be available to investigators worldwide, in practice data availability is a real problem for the following reasons.

- Several data sets have been lost, especially those data obtained prior to 1965, when computers were not used in the laboratory. Most of the early investigators have died or retired, and, in many cases, their data have never been properly archived. In other cases, the laboratories where the data were obtained have ceased to exist (e.g., UKAEA), making it very difficult to retrieve the archived data.
- The data are classified as proprietary or commercial.
- The data may still be available, but it would require significant motivation, effort, and expense to retrieve them from archives and have them restored in a usable form.
- The data are only available in graphical form, often created manually. Values can be extracted from the graphs using data digitization software, but they would generally be less accurate than tabulated values, because of loss of resolution in small-size graphs, averaging of data on plots, and averaging of flow conditions for each graph.

An exhaustive literature review that was performed at the University of Ottawa (UO) has revealed 28 data sets containing 6663 trans-critical heat transfer data. The data sets and their ranges of conditions that have been used in this study were presented previously by Groeneveld and Zahlan (2009). Figure 1 shows the ranges of the trans-critical water data in normalized

coordinates, by plotting P/P_c vs. Re_b and T/T_c. Figure 2 presents the ranges of the data expressed as T/T_c vs. Re_b and $Pr_{avg,b}$ vs. P/P_c.
Additional data sets, tabulated and/or identified by Lowenberg et al. (2005, 2008; University of Stuttgart), and by Cheng (2009; Shanghai JiaoTong University) have been included in the expanded UO trans-critical heat transfer database of Figures 1 and 2. Some of these data were extracted from graphs using data digitization software (as were some of the data included in the original UO database) but these data sets are subject to the inaccuracies mentioned previously. The reason for including more than one set of SCHT data set for the same flow conditions was to enhance the reliability of the LUT.

Data compilation has proceeded by following these steps:

- Review of all relevant SCHT papers and identification of data sources not tabulated previously.
- Extraction of data from graphs.
- Determination of data selection criteria (ranges of length-to-diameter ratio, diameter, mass flux, wall temperature, bulk enthalpy, Reynolds number) needed prior to deriving the trans-critical look-up table,
- Screening of the data for outliers, duplicates and data having high scatter using the so-called "slicing methodology" developed previously at UO (Durmayaz et al., 2004).
- Establishment of a secondary data base for SC and NC CO_2 to augment the original water database at conditions for which water data are missing of unreliable.
- Normalization of the data to account for variations in diameter and possibly other parameters deemed to be important in SCHT.

2.3 Data screening for duplicates

2.3.1 The dissimilarity measure criterion

When working with a large data base that consists of many data sets, some duplication can be expected. Data duplication occurs because large data compilations do not always clearly specify the origins of the data sets and because some authors report their data in more than one publication. To identify duplicate data, several methodologies have been developed. Shan et al. (2004) proposed a criterion called "dissimilarity measure" for a CHF (critical heat flux) data base. They defined a modified Euclidean distance between two data points $\boldsymbol{x_1}$ and $\boldsymbol{x_2}$ as:

$$Dis(\boldsymbol{x}_1,\boldsymbol{x}_2)=\sqrt{\sum_{j=1}^{p} w_j\left(x_{1j}-x_{2j}\right)^2} \qquad (1)$$

where p is the number of parameters in the data base, x is a normalized multi-variable vector, which has p dimensions, and w_j is the weight given to each parameter. A different weight is assigned to each parameter such that the sum of all weights is equal to unit. Then, two data points are considered as duplicates if $Dis < 0.01$. To apply this technique to the trans-critical data base, the following parameters were identified: diameter, heated length, pressure, mass flux, heat flux, local bulk enthalpy, inlet enthalpy or temperature, and wall temperature. This approach may occasionally identify two data sets as duplicates, although they may not be so. This might happen, for example, if the weighted difference in one parameter is relatively large and the others are very small. To prevent this, an improved methodology, to be described in the following subsections, was used in the assessment of the UO SCHT database.

2.3.2 Identification of duplicate data points within each data set

Duplicate data pairs inside each data set are defined as a pair of data points for which all screening parameters identified previously have identical values. The method is based on the assumption that, even for the same author and the same experimental conditions (system geometry, pressure, mass flux, inlet temperature, and measuring devices), it is highly unlikely that results would be identical for all recorded parameters, because even for repeat runs some differences in the measurements would normally be recorded. These duplicates are not removed from the database; they are labeled as duplicates and one of the duplicates is ignored during subsequent LUT development steps.

2.3.3 Identification of duplicate runs and points between two data sets

Directly measured parameters, including diameter, heated length, pressure, inlet temperature and wall temperature, would be unaffected by fluid property subroutines and might only be slightly affected by conversion errors and round-off or truncation errors. Therefore, margins for the differences between the values of such parameters for duplicate points were set to small values (< 0.1%). The calculated parameters, including bulk enthalpy, mass flux and heat flux, could be influenced by conversion subroutines and/or fluid property subroutines. Consequently, the margins for differences in these parameters were set to higher values (1 – 3%). The criterion to determine whether a data point was duplicate is defined such that all parameters for the point under consideration must fall within the specified margins. Additional confirmation of whether a suspected data point is a duplicate will be made visually using the slice method. Sometimes, entire runs were found to be duplicates.

2.3.4 Additional screening concerns

Many of the data from the collected data sets are questionable and may need to be qualified prior to their use for the development of the look-up table. Some of the reasons for questioning the validity of these data are the following.

- The data display significant scatter and do not follow a smooth trend. This suggests that flow conditions in the tests may have been unstable.
- At locations near the inlet or outlet, the temperature distribution suddenly changes. This is usually due to significant axial conduction due to the presence of a nearby heat source/sink, e.g., a copper power clamp with large power copper cables, or a high contact resistance (poor electrical contact) of the power terminals, which causes high local heat generation.
- The data demonstrate some obvious inconsistencies, e.g., local or outlet enthalpies that cannot be reproduced from a simple heat balance.

- Data sets obtained at roughly comparable conditions do not have comparable wall temperatures.
- The experimenter provided inadequate documentation regarding flow conditions or geometry and the missing information was extracted from calculations.
- The data were reconstructed from graphs of poor quality.
- The data were obtained in the entrance region where the boundary layers were not sufficiently developed.

3. Prediction methods

Several authors have reviewed or tabulated correlations that have been used to predict SCHT. Hall et al. (1968) and Jackson and Hall (1979a, 1979b) have presented overviews of SCHT correlations and assessments of SC heat transfer correlations against both SC water and SC CO_2 data. Pioro et al. (2004) recently presented a more up-to-date review of such correlations that have been applied to SC conditions. In this paper, four single-phase correlations and nine SCHT correlations) have been assessed against the UO database. The correlations were tabulated by Groeneveld and Zahlan (2009). These correlations are described below.

3.1 Single-phase correlations

Most of the correlations used have a form similar to that of the Dittus-Boelter (1930) equation, but with different exponents. The Dittus-Boelter equation was originally based on water data only and evaluates the fluid properties at the bulk fluid temperature, whereas the Sieder-Tate (1936) equation includes a viscosity ratio term to account for the difference in fluid viscosity at the wall and in the bulk flow. The Hadaller and Banerjee (1969) equation is based on high-pressure superheated steam data. The most recent single phase heat transfer equation is that of Gnielinski (1976) for fully developed turbulent flows, which includes a friction factor term to account for the increasing heat transfer with an increase in friction factor.

3.2 SCHT correlations

One of the earliest SCHT correlations is that of Bishop et al. (1965) who modified the Dittus-Boelter (1930) equation by including a density ratio (ratio of the density at wall temperature and the density at bulk fluid temperature) and replacing the specific heat in the Prandtl number by the effective integrated specific heat capacity. The Swenson et al. (1965) correlation has similar parameters to the Bishop et al. (1965) correlation, except that T_w was used as the reference temperature for Nu, Re, and averaged Pr number. Krasnoscheckov et al. (1967) proposed a modified version of a SCHT correlation previously derived in 1959 and 1960. Jackson's (2002) correlation is basically a modified form of the Krasnoscheckov et al. (1967) equation. Yamagata et al. (1972) introduced a correction factor to the Dittus-Boelter equation, which is a function of the Eckert ($E = (T_{pc}-T_b)/(T_w-T_b)$) and Prandtl numbers at the pseudo-critical temperature or the effective integrated specific heat capacity ratio. Watts and Chou (1982) correlated mixed convection (forced and natural) water and CO_2 data for upwards and downwards flows; they used the deterioration criterion of Jackson and Hall (1979b) in the development of their correlations for normal and deteriorated heat transfer. Griem (1996) modified the Dittus-Boelter equation by considering C_p at five reference temperatures from T_b to T_w; the selected C_p is based on excluding the largest two C_p values and averaging the other three. Griem also introduced a correction factor to cover the whole enthalpy range; this factor is a function of H_b.

Kuang et al. (2008) used their SCHT databank for water in vertical upwards flow in tubes to develop their correlation. They investigated the enhanced and deteriorated heat transfer region based on the normal heat transfer coefficient predicted by Dittus-Boelter (1930). Kuang et al. used the modified Grashof number term Gr^* first introduced by Jackson et al. (1989) to account for buoyancy effects (strong variations in density causing mixed instead of pure forced convection). In addition they used the McEligot et al. (2004) non-dimensional heat-flux number q^+ to consider the streamwise thermal acceleration effect from heating on the HTC. Gospodinov et al. (2008) used the SCHT water data of Kirillov et al. (2005; 89 runs with 81 data points per run) in deriving their correlation. In the development of their correlation, Gospodinov et al. (2008) excluded the data with both enhanced and deteriorated heat transfer. Cheng et al. (2009) derived a simple SCHT correlation to predict the deviation from the normal heat transfer predicted by the Dittus-Boelter (1930) equation. This correlation is a function of the dimensionless acceleration number π_A.

3.3 Assessment of the heat transfer prediction methods

Initially, the prediction accuracy of all correlations was assessed based on a comparison against the UO SCHT databank and the most promising six heat transfer correlations were selected for further assessment. As expected, the agreement of the single-phase correlations with the data obtained near the pseudo-critical temperature is poor, whereas the agreement with the data obtained at higher temperatures is much better (Groeneveld and Zahlan, 2009). Subsequently, five additional SCHT correlations and two additional single-phase correlations were included for evaluation against the expanded database. The results for single-phase correlations (Table 1) show that the Gnielinski (1976) correlation provided the best agreement with the data for the subcritical subcooled liquid region, while the Hadaller and Banerjee (1969) correlation presented the best agreement for the superheated steam region. The SCHT region was divided into three distinctive sub-regions: (i) high density state (liquid-like) region (T_w, $T_b < T_{pc} - \Delta T$), (ii) near-critical or near-pseudo-critical region ($T_{pc} - \Delta T < T_w$ and $T_b < T_{pc} + \Delta T$), and (iii) low density state (gas-like) region ($T_{pc} + \Delta T < T_w$, T_b), where the numerical value of ΔT in degrees K is taken to be equal to the ratio P_c/P. To reduce the bias caused by duplicates in the data sets of Herkenrath (1967) and Kirillov et al. (2005) from different sources, a weighting factor of 0.6, estimated from an initial screening of duplicates, was introduced in the average and RMS error, which were calculated as follows.

$$\begin{aligned}
&avg\quad error_{weighted} = \frac{1}{(l + 0.6\times(k+h))}\left(\sum_{i=1}^{ii}\sum_{j=1}^{l} error_{i,j} + 0.6\times\left(\sum_{j=1}^{k} error_{m,j} + \sum_{j=1}^{h} error_{n,j}\right)\right)\\
&RMS\quad error_{weighted} = \sqrt{\frac{1}{(l + 0.6\times(k+h))}\left(\sum_{i=1}^{ii}\sum_{j=1}^{l} error^2_{i,j} + 0.6\times\left(\sum_{j=1}^{k} error^2_{m,j} + \sum_{j=1}^{h} error^2_{n,j}\right)\right)}\\
&error = \frac{HTC_{pred}}{HTC_{\exp}} - 1
\end{aligned} \tag{2}$$

where i denotes dataset number excluding the Herkenrath (1967) and Kirillov et al. (2005) data sets, which were denoted by m and n respectively. In the SCHT regions, the correlations by Kuang et al. (2008) and Gospodinov et al. (2008) showed the best agreement with the compiled data (the latter showed a slightly better agreement with the data). Table 2 presents the overall weighted average and RMS error for the expanded UO database. Tables 3 to 5 show the percentages of data predicted within certain error band by the leading correlations for the near-critical or pseudo-critical, the gas-like, and the liquid-like region. Figures 3 to 5 show the average and RMS error for Re_b, $Pr_{avg,b}$, and P/P_c, for the three supercritical regions for the combined UO, SJTU, and U of S database.

4. Derivation of the trans-critical look-up table

The derivation of a look-up table requires first the construction of a skeleton table to provide the initial estimate of the heat transfer coefficient (HTC) values at discrete values of the independent flow parameters, including pressure (P), mass flux (G), coolant enthalpy (H_b) and heat flux or wall temperature. The skeleton table values are used for evaluating the slopes of HTC vs. P, G and H_b. The skeleton table also provides the default heat transfer values based on predictions from leading heat transfer correlations at conditions for which no experimental data are available.

The skeleton table is not expected to be smooth and will likely display an irregular variation (i.e., devoid of physical basis) with the three table parameters (pressure, mass flux and coolant enthalpy). These fluctuations are attributed to data scatter, systematic differences between different data sets, and possible effects of secondary parameters such as heated length, surface conditions and flow instability. Sharp variations in heat transfer coefficient will also likely be observed at boundaries between regions where experimental data are available and regions where correlations or other approaches need to be employed and at the lower pressure limit where a transition to subcritical prediction methods for film boiling, CHF or single phase heat transfer takes place. Note that predictions at conditions at which no data are currently available are expected to be complex and require an understanding of the physics and thermodynamics of SCHT, including near-wall phenomena. This also requires a close examination of the trends of the data vs. P, G and enthalpy at conditions closest to those of the missing data.

To minimize unrealistic sudden transitions (i.e., transitions which are not based on experimental trends), the smoothing procedure developed by Huang and Cheng (1994) will be applied. The smoothing procedure will not be applied at conditions near the pseudo-critical temperature where rapid changes in HTC are expected to be present.

An assessment of the prediction accuracy of the look-up table will be performed by comparing the predicted and experimental HTC and providing detailed overall error statistics, and error statistics for various sub-regions. The prediction accuracy of the new trans-critical look-up table will also be compared to the prediction accuracy of leading SC or single-phase prediction methods.

The distribution of the prediction error with respect to the primary table parameters will also be examined to identify any systematic trends; if systematic trends are identified, the look-up table will be corrected to remove such biases.

5. Summary and concluding remarks

In addition to compiling supercritical and near-critical heat transfer data for water, many papers containing supercritical and near-critical heat transfer data for CO_2 and R-134a have been identified; they will be used as a secondary source of data for conditions for which water data are unavailable or unreliable.
In the subcooled liquid region, the correlation of Gnielinski (1976) had the best agreement with the compiled data, while the Gospodinov et al. (2008) had the best agreement with data for the superheated steam region.

In the supercritical region, the correlation of Gospodinov et al. (2008) showed the best agreement with the data for all three sub-regions.

The LUT versions will be based on directly measured or calculated parameters, i.e., HTC = f(P, G, H_b, q and D) and HTC = f(P, G, H_b, T_w and D). In view of the rather large number of table entries when using 5 independent LUT parameters, modified versions of the LUT using fewer parameters may be derived subsequently, including versions using only dimensionless parameters.

The ideal LUT will have (i) good prediction accuracy, (ii) few independent parameters, (iii) the least number of LUT entries, and (iv) smooth convergence with existing single phase and film boiling prediction methods.

Nomenclature

D	tube inside diameter	(m)
G	mass flux	(kg m^{-2} s^{-1})
H	enthalpy	(kJ kg^{-1})
P	pressure	(kPa)
q	heat flux	(kW m^{-2})
T	temperature	(˚C)
h	heat transfer coefficient	(kW m^{-2} K^{-1})

Subscripts

b	bulk
c	critical
pc	pseudo-critical

w	wall	
av., avg	average	

Dimensionless numbers

Re	Reynolds number	$(= G\ D\ \mu^{-1})$
$\overset{*}{Gr}$	modified Grashof number based on q	$(= g\beta q D_{hy}{}^{4} / k\upsilon^{2})$
q^{+}	non-dimensional heat flux number	$(= (q/G)\ (\beta/Cp))$
Pr	Prandtl number	$(=\mu C_p/k)$
Pr_{avg}, $\overline{Pr}$	averaged or modified Prandtl number	$(= (H_w-H_b)\mu_b/\ (k_b\times(T_w-T_b)))$

Abbreviations

CP	critical point
SCHT	supercritical heat transfer
HTC	heat transfer coefficient

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Table 1 Overall average and RMS error in the subcritical region

Correlation	Subcritical liquid		Superheated steam	
	Av.er, %	rms, %	Av.er, %	rms, %
Sieder and Tate (1936)	27.6	37.4	83.8	137.8
Gnielinski (1976)	-4.3	18.3	80.3	130.2
Hadaller and Banerjee (1969)	27.3	35.9	19.1	34.4
Dittus-Boelter (1930)	10.4	22.5	75.3	127.3
Gospodinov et al. (2008)	-1.06	19.21	-4.78	19.57

Table 2 Overall weighted average and RMS error in the three supercritical sub-regions

Correlation	Liquid-like region		Gas-like region		Close to CP or PC point	
	Av.er, %	rms, %	Av.er, %	rms, %	Av.er, %	rms, %
Bishop et al. (1965)	6.3	24.2	5.2	18.4	20.9	28.9
Swenson et al. (1965)	1.5	25.2	-15.9	20.4	5.1	23.0
Krasnochekov et al. (1967)	15.2	33.7	-33.6	35.8	25.2	61.6
Watts and Chou (1982), Normal	4.0	25.0	-9.7	20.8	5.5	24.0
Watts and Chou (1982), Deter.	5.5	23.1	5.7	22.2	16.5	28.4
Griem (1996)	1.7	23.2	4.1	22.8	2.7	31.1
Jackson (2002)	13.5	30.1	11.5	28.7	22.0	40.6
Gospodinov et al. (2008)	-3.9	21.3	-8.5	16.5	-2.3	17.0
Kuang et al. (2008)	-6.6	23.7	2.9	19.2	-9.0	24.1
Cheng et al. (2009)	1.3	25.6	2.9	28.8	14.9	90.6
Hadaller and Banerjee (1969)	7.6	30.5	10.7	20.5	-	-
Sieder and Tate (1936)	20.8	37.3	93.2	133.6	-	-
Dittus-Boelter (1930)	32.5	46.7	87.7	131.0	-	-
Gnielinski (1976)	42.5	57.6	106.3	153.3	-	-

Table 3 Error bands for the region near the critical or pseudo-critical point ((T_w> (T_{pc}- ΔT), and (T_{pc}+ ΔT) >T_b))

Error band, 15718 data point	Percentage of data predicted by a correlation, %				
	Gospod-inov et al. (2008)	Kuang et al. (2008)	Swenson (1965)	Watts and Chou (2000) normal HT	Dittus and Boelter (1930)
±10%	46.7	30.5	44.4	42.6	17.6
±20%	80.6	57.9	71.9	70.0	32.1
±30%	94.0	81.0	85.8	87.3	41.9
±50%	99.3	98.0	95.6	96.9	52.6

Table 4 Error band for the gas-like region (T_w, T_b > T_{pc}+ ΔT)

Error band, 5273 data points	Percentage of data predicted by a correlation, %					
	Gospod-inov et al. (2008)	Kuang et al. (2008)	Swenson (1965)	Bishop (1965)	Dittus and Boelter (1930)	Hadaller and Banerjee (1969)
±10%	48.8	45.6	30.4	43.6	9.3	36.2
±20%	81.4	76.6	65.4	74.0	16.0	68.3
±30%	94.2	91.1	88.5	90.9	23.3	88.2
±50%	99.5	98.8	99.2	98.8	37.6	99.0

Table 5 Error band the liquid-like region (T_w, T_b< T_{pc}- ΔT)

Error band, 4483 data point	Percentage of data predicted by a correlation, %					
	Gospod-inov et al. (2008)	Kuang et al. (2008)	Griem (1996)	Watts and Chou (2000) Deter. HT	Dittus and Boelter (1930)	Hadaller and Banerjee (1969)
±10%	48.3	37.7	47.0	29.3	22.9	14.4
±20%	72.7	64.6	73.0	59.3	45.8	27.2
±30%	85.9	84.5	86.6	82.5	69.5	45.8
±50%	97.0	96.9	95.8	96.9	88.7	80.0

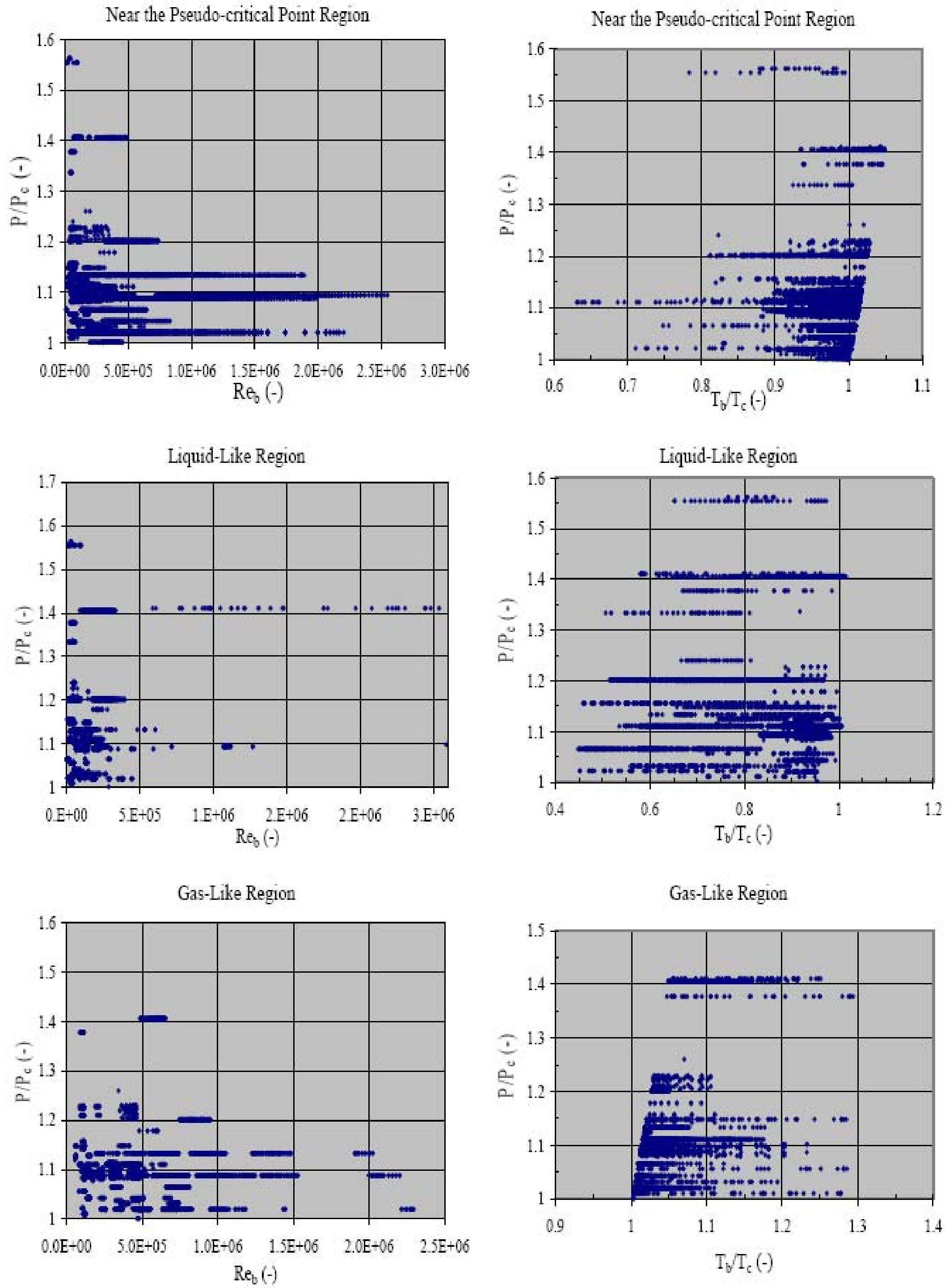

Figure 1: Ranges of available SCHT data for water

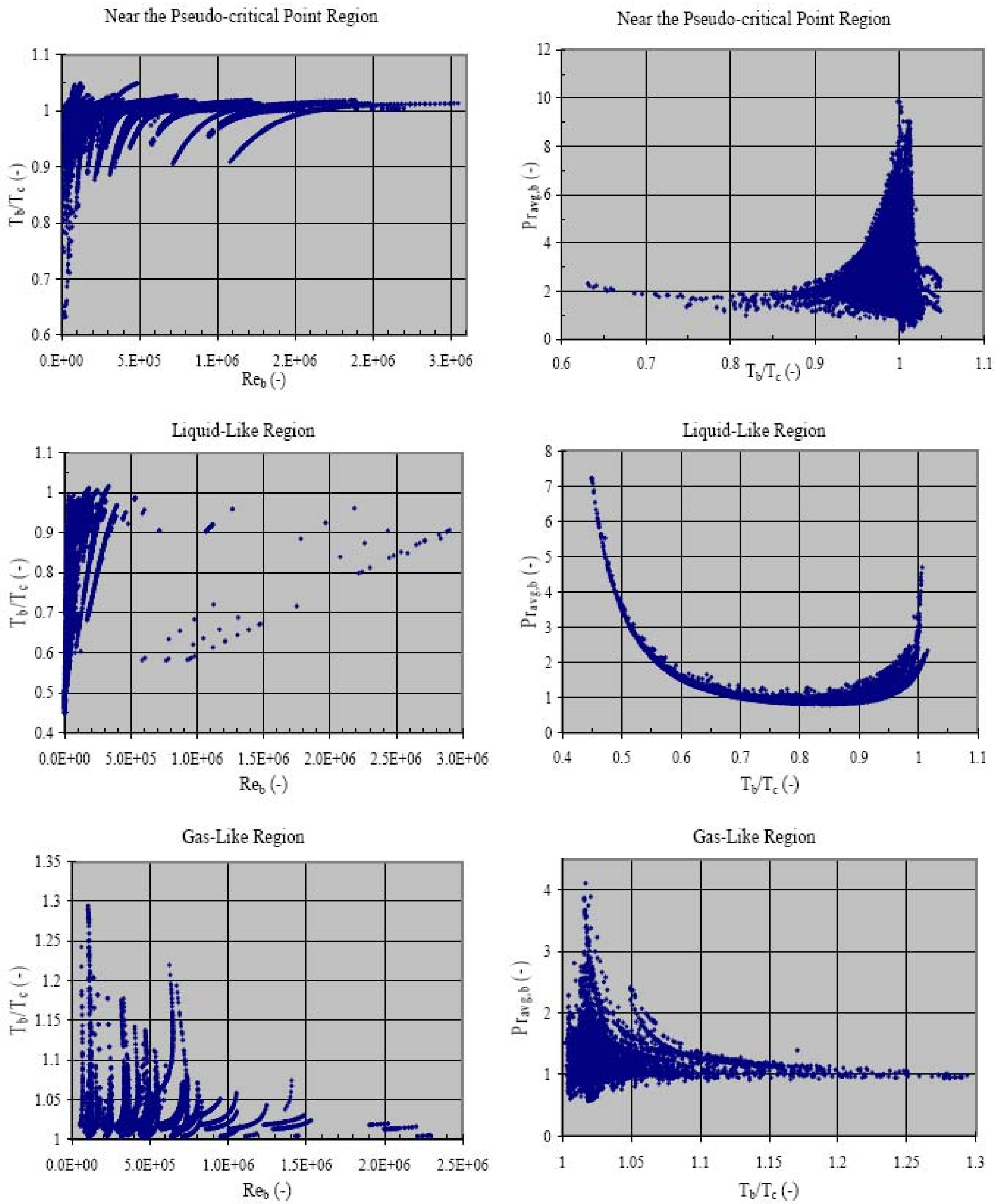

Figure 2: Ranges of available SCHT data for water

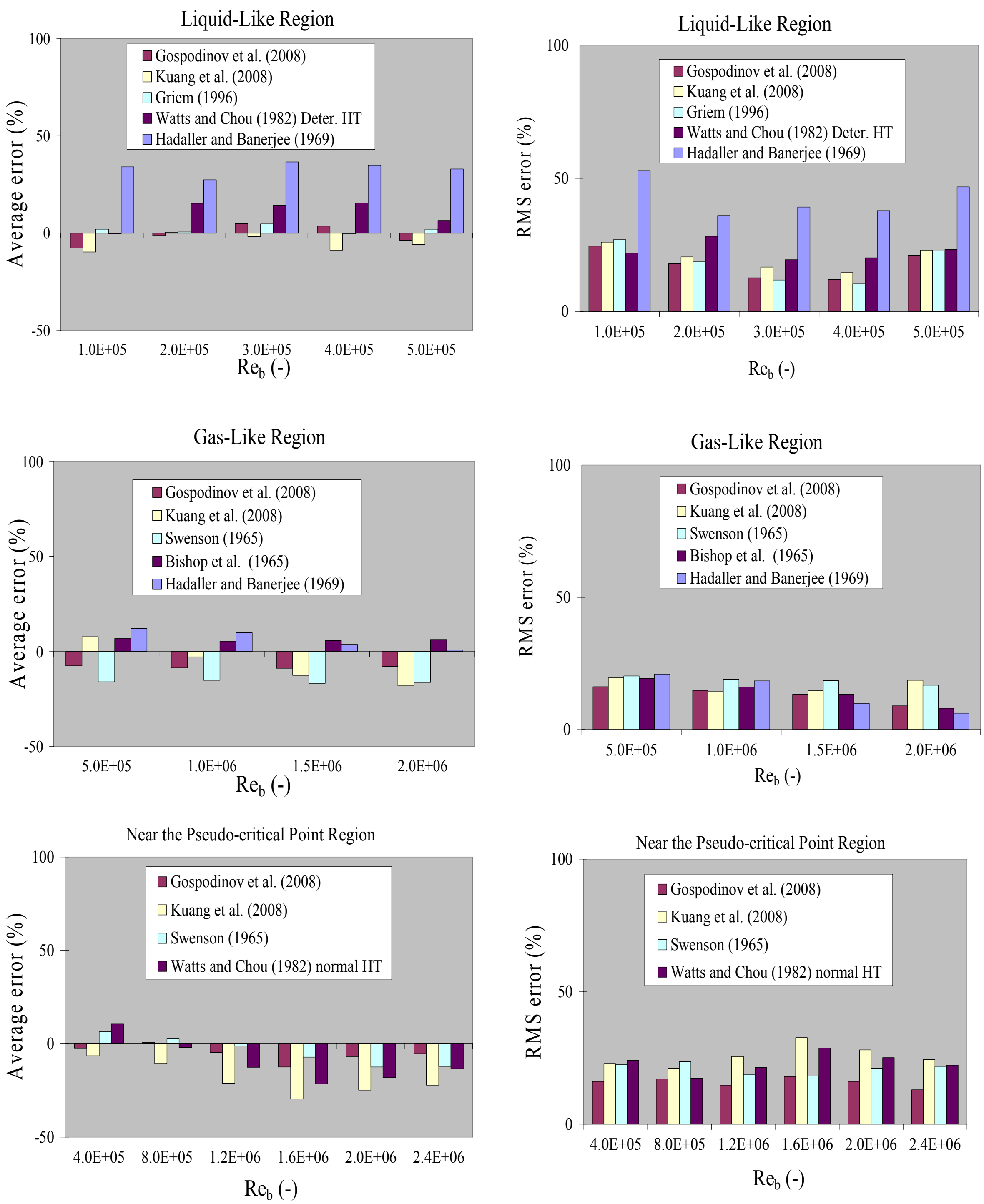

Figure 3 Average and RMS error for Re in the near-critical and liquid/gas-like regions after eliminating outliers

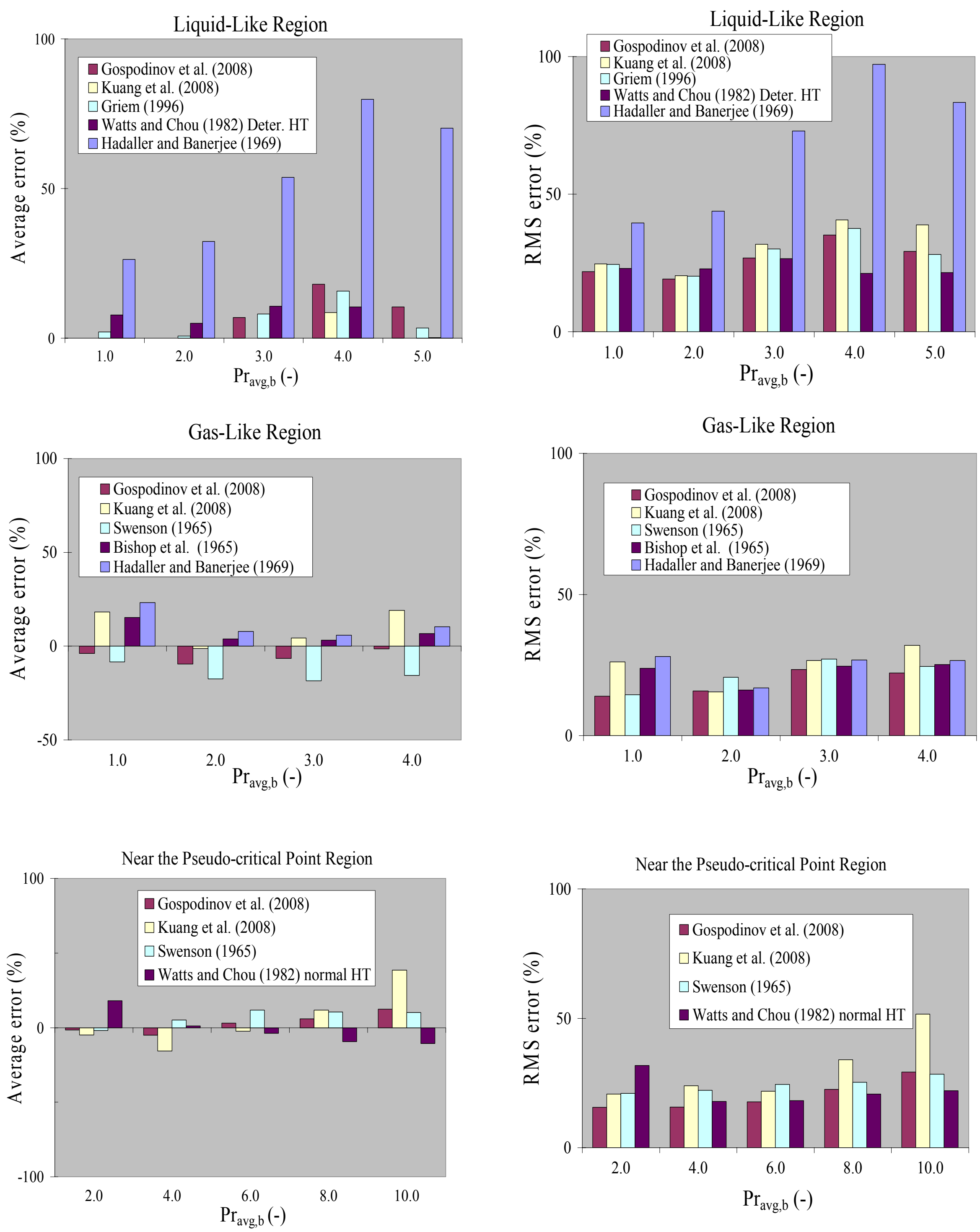

Figure 4 Average and RMS error for P_{ravg} in the near-critical and liquid/gas-like regions after eliminating outliers

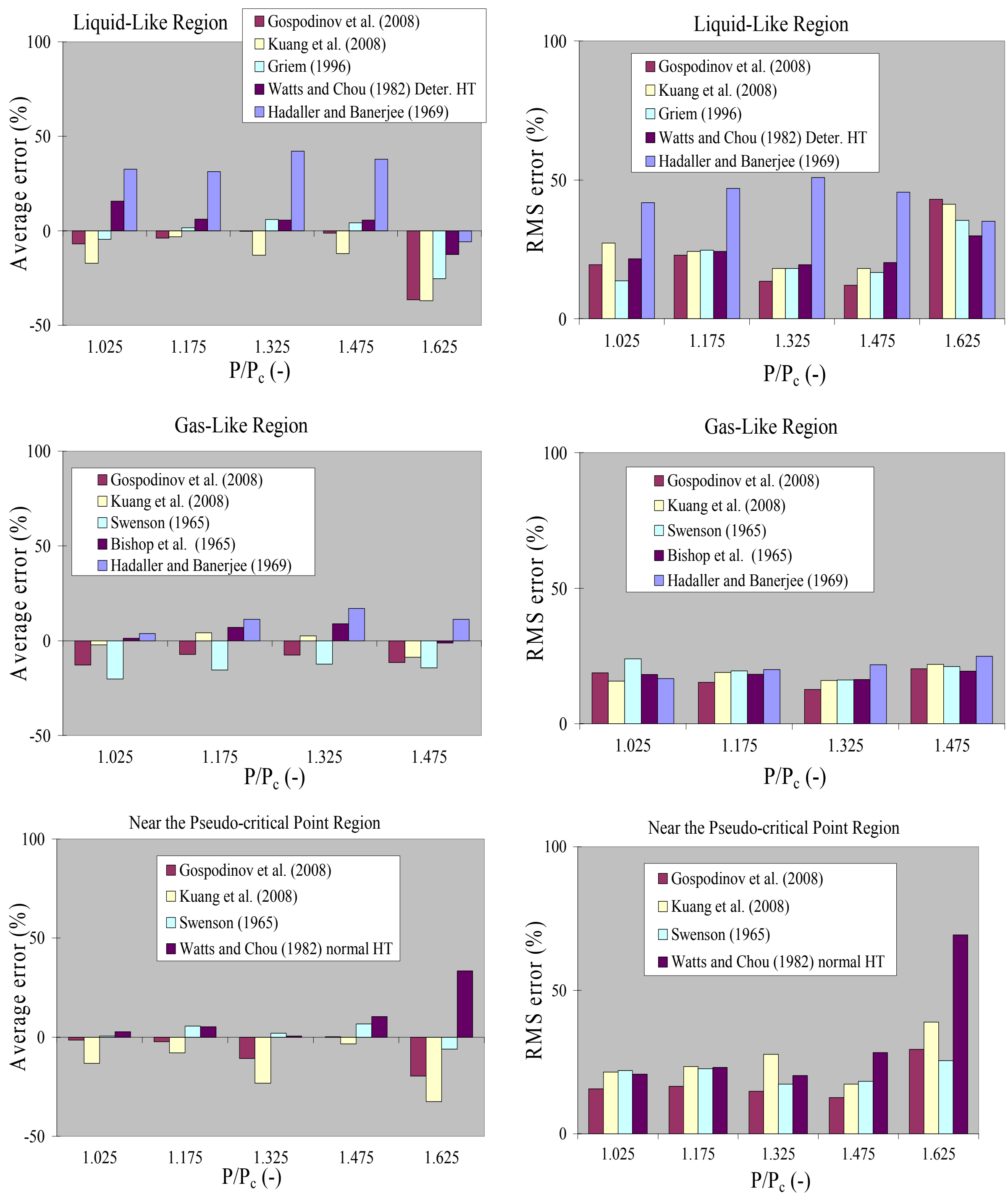

Figure 5 Average and RMS error for P/P_c in the near-critical and liquid/gas-like regions after eliminating outliers