CONSIDERATIONS ABOUT CORRELATIONS FOR HEAT TRANSFER TO SUPERCRITICAL PRESSURE FLUIDS SPANNING ALL REGIMES

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ABSTRACT

In this paper an assessment of the performance of existing correlations for heat transfer to supercritical fluids is proposed making use of an approach including the direct observation of experimental trends and the knowledge acquired from the recent development and assessment of a fluid-to-fluid similarity theory. The correlations are revised and discussed in detail on this new basis, trying to highlight the reasons for their failure to predict key regimes as deteriorated heat transfer. As known, though many correlations have been proposed in the past, none can be actually relied to predict all the regimes encountered spanning from the liquid like region to the gas-like one in bulk and at the wall of a heated duct, with main reference to the phenomena of deterioration, often occurring when buoyancy or acceleration become dominant on forced convection. Suggestions for the development of more consistent correlations are then proposed on the basis of the new rationale, trying to stimulate interest for new approaches in dealing with the tough problems involved in predicting normal, enhanced and deteriorated heat transfer and to propose new promising modelling techniques. The work is performed in the frame of studies devoted to enable the design of supercritical water cooled light water reactors (SCWRs). The fluid-to-fluid similarity theory provides guidance for devising correlations, having up to now received support from CFD calculations and requesting at least an indirect experimental confirmation in terms of the prediction of heat transfer data to be correlated on the basis of the dimensionless numbers identified by its underlying theory.

KEYWORDS
SCWR, heat transfer, correlation, fluid-to-fluid, similarity, deteriorated heat transfer

1. INTRODUCTION

Super Critical Water cooled Reactor (SCWR) is the only design concept among the six advanced nuclear reactor systems proposed by the Generation IV International Forum (GIF) [1] that is directly evolved from the current nuclear power plants designed and in operation for over 50 years. The technology for developing SCWR concepts still needs further R&D focusing mainly on materials, chemistry, thermal-hydraulics and safety.

Certainly, the need for new safety criteria for nuclear reactor operation has emerged, since the current safety criteria, based on the departure from nucleate boiling (DNB) or dry-out, are no longer applicable to SCWRs. Alternatively, in literature designers have suggested the peak cladding and fuel centerline temperatures as the adopted safety criteria [2]. In this regard, a better understanding of the heat transfer phenomena at supercritical pressures and accurate prediction methods for heat-transfer coefficients are required.

Due to the nature of fluids at supercritical pressures and the lack of phase change, heat transfer characteristics can be represented with a single-phase heat transfer correlation, such as the well-known Dittus and Boelter correlation. However, the sharp variations in the thermophysical properties in the vicinity of the pseudocritical point challenge the application of this heat transfer correlation in these conditions. In addition, the complex buoyancy and acceleration effects at the near-wall region have led to significant changes to the single-phase heat-transfer characteristics.

Among the challenges faced in the development of heat transfer correlations for fluids at supercritical pressures, are the density changes that cause a decrease of the heat transfer efficiency because of the mentioned effects on buoyancy and acceleration. Despite the efforts in experimental and theoretical studies, the precise mechanisms of heat transfer deterioration are not well quantitatively grasped; however, interesting descriptions shaded light on basic mechanisms at the root of the observed behavior. The work by Kurganov et. al [3], based on experimental analyses, suggested that a distortion of the shear stress and an M-shaped velocity distribution are the major causes of heat transfer deterioration and recovery; nevertheless further quantitative analyses need to confirm and assess their observations. Actually, the adoption of CFD models, having still limited capabilities, could anyway confirm the suggested mechanisms.

In literature, a number of empirical correlations have been proposed to calculate the heat transfer coefficient (HTC) in forced convection for various fluids including water at supercritical pressures. However, differences in the calculated HTC values can be noted and can reach up to several hundred percent (see e.g., the nice review in the well-known textbook by Pioro and Duffey [4]).

In this work two among the most accredited of these empirical correlations are considered by comparing their results when applied to two sets of experimental data, being the one by Watts [5], obtained with water at 25 MPa, and by Kline [6], obtained with carbon dioxide at 8.35 MPa. These two data sets have been used in recent works by the authors on fluid-to-fluid similarity (see [7]–[11]) due to the observed full range of heat transfer phenomena they exhibit, involving normal and deteriorated heat transfer and the final restoration at the transition to the gas-like phase. The next step in the research is trying to predict the wall temperature trends using the existing or improved correlations when using a simple iteration 1D model that starts by guessing this variable on the basis of the inlet conditions. As it will be shown in the following sections, it is found that the two correlations, namely the ones by Jackson [12] and Mokry et al. [15], were not able to successfully catch heat transfer deterioration or even its onset as observed in the addressed experiments.

The recently developed fluid-to-fluid similarity theory (see [7]–[10]) obtained results, supported by DNS, LES an RANS calculations, that show the capability to preserve qualitatively and quantitatively the behavior of wall temperatures as well as of the corresponding bulk parameters for quite different fluids, including the very interesting cases of water and carbon dioxide. The dimensionless parameters whose preservation was found essential in determining the success of the similarity theory are obviously the best candidates to be used in correlations for heat transfer capable to predict the same deteriorated heat transfer phenomena well represented by CFD for different fluids. This theoretical and numerical support to the use of these dimensionless groups is something that was lacking in the present state-of-the-art and that is presently considered for the purpose of proposing new and possibly more successful correlations.

In this paper, which shows the first results and challenges encountered in this research, an analysis of the effectiveness of the two well-known existing correlations is presented, trying to highlight the problems involved in setting up more effective correlations on the basis of the new perspectives disclosed by the recently developed similarity theory. Though the work in this field is just at the beginning, the conclusions reached up to now are considered interesting enough and are found fully in line with difficulties already highlighted by other researchers to be discussed in the present paper.

2. EVALUATION OF SOME OF THE EXISTING CORRELATIONS

This analysis takes into account the original formulation of the Jackson's [12] and the Mokry et al. [15] empirical correlations as defined by their authors and whose coefficients are reported in Table I. In addition, the analysis includes trials to establish variants of the same empirical correlations obtained by optimizing their coefficients on the basis of the chosen data sets, which are composed by a number of local data in the order of 33,000. In other words, the correlations are firstly applied in their original form and then their coefficients are customized for the specific data set by a regression analysis. This procedure allows showing firstly the capability of the proposed correlation to reproduce different phenomena as observed in the targeted experiments and then to ascertain at what extent these correlations could be better customized to fit the specific data set. Of course, while it is clear that correlations should be based on the broadest possible experimental data base (much broader than the one considered herein), the present exercise is anyway useful to understand if the specific features of the data herein addressed can be reproduced by the suggested form of the considered correlations possibly with a change in the numerical values of the coefficients.

Jackson [12] proposed an empirical correlation after reviewing extensive experimental data from various sources, that is formulated in the following equation:

$$Nu_b = C\, {Re_b}^{C1} {Pr_b}^{C2} \left(\frac{\rho_w}{\rho_b}\right)^{C3} \left(\frac{\overline{Cp}}{Cp_b}\right)^{n} \quad (1)$$

where, $n = 0.4 \quad for\ T_b < T_w < T_{pc}$ and for $1.2T_{pc} < T_b < T_w$

$$n = 0.4 + 0.2\left(\left(\frac{T_w}{T_{pc}}\right) - 1\right) \text{ for } T_b < T_{pc} < T_w$$

$$n = 0.4 + 0.2\left(\left(\frac{T_w}{T_{pc}}\right) - 1\right)\left(1 - 5\left(\left(\frac{T_w}{T_{pc}}\right) - 1\right)\right) \text{ for } T_{pc} < T_b < 1.2T_{pc} \text{ and } T_b < T_w$$

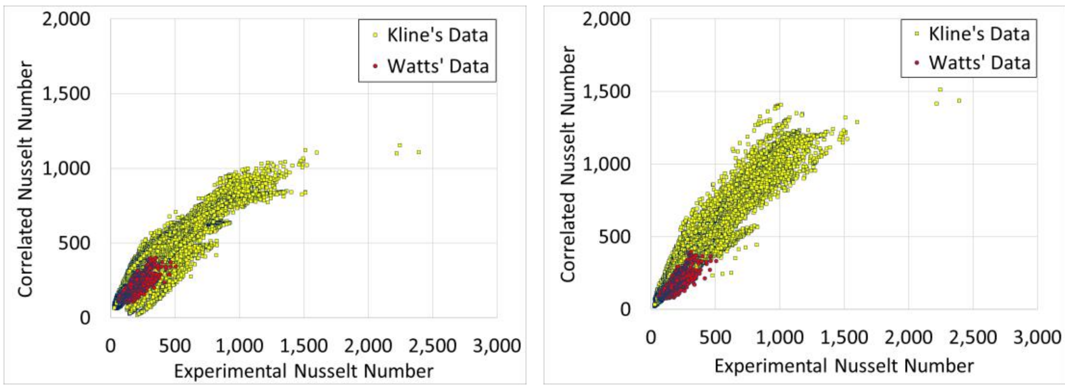
The coefficients not specified above are the ones reported in the first row of Table I. It is important to note that this correlation did not address the deteriorated heat transfer regime. Figure 1 reports the calculated values of the Nusselt number; according to Jackson's correlation, compared to the experimental ones for the two data sets of interest. Based on the analysis of Fig. 1b it is clear that the optimized coefficients provide values of the Nusselt number that are slightly more accurate than those calculated by Eq. 1 in Fig. 1a. However, this improvement is better represented in Fig. 2 and Fig. 3, reporting the qualitative trends obtained by the original and the optimized correlations for selected reference data. It must be noted that the latter way of presenting the data is by far more meaningful than the overall comparison on the full data base, because it shows the fidelity in the phenomenological representation of actual trends instead of the overall quantitative performance.

Table I. Values of the coefficients used in the analysis of the correlations.

Correlation	C	C1	C2	C3	C4
Jackson	0.0183	0.82	0.5	0.3	n
Optimized Jackson	0.0017	1.015	0.611	0.454	0.567
Mokry	0.0061	0.914	0.654	0.518	-
Optimized Mokry	0.0017	1.018	0.576	0.441	-

In particular, Fig. 2 reports the values of the Nusselt number as well as of the wall temperature along the channel for the case of CO_2 flowing upwards in an electrically heated circular channel at pressure of p =

8.35 MPa, inlet temperature of T_{in} = 16 °C, mass flux of G=300 kg/(m^2s) and uniform heat flux of q''=20 kW/m^2. The optimized correlation apparently managed to predict in closer resemblance the "dynamic behavior" of the Nusselt number along the channel compared to the original one. The expression "dynamic behavior" is here used with reference to the oscillatory response shown by wall temperature and Nu number in many experimental data trends involving deteriorated heat transfer. In fact, the first overshooting of the wall temperature, due to the impairment of the heat transfer owing to laminarization of the flow, is often followed by subsequent damped peaks, in similarity with a second order oscillatory system characterized by a first excursion and a subsequent damped settling to a different signal level. The related phenomena have been commented in recent papers also providing an attempt of explanation [13], [14].

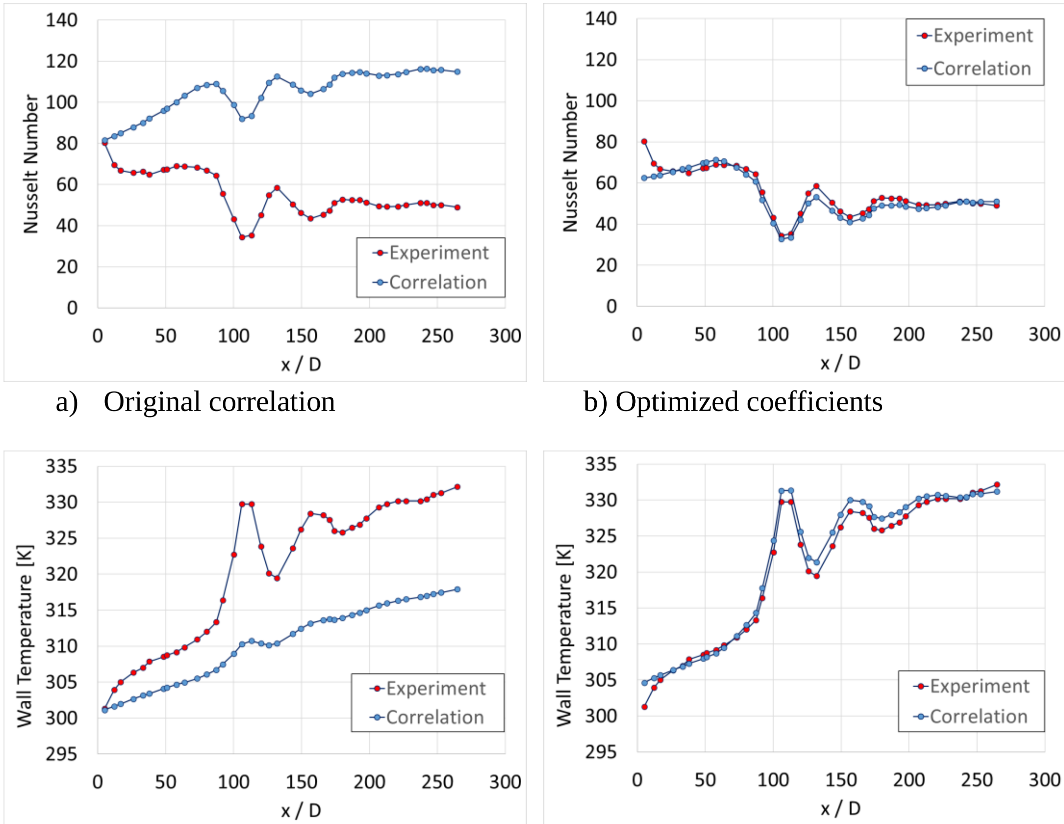


a) Original correlation b) Optimized coefficients

Figure 1. Comparison of data fits with experimental data for the Nusselt number using Jackson's correlation.

Similarly, Fig. 3 reports the trends of the Nusselt number and of the values of wall temperature along the channel for the case of Watts' with H_2O at 25 MPa, inlet temperature of 200 °C, mass flux of 375 kg/(m^2s) and heat flux of 340 kW/m^2 still using Jackson's correlation. As it can be noted, the qualitative trends are only slightly better represented using the optimized coefficients but, in this case, they are not reproducing correctly the qualitative trends, mainly in relation to deterioration.

Indeed, the very close behavior of the correlation, seen in Fig. 2b and d, requires further verification that considers the prediction of the wall temperature, using the proposed coefficients, when applied in a 1D model and requires iterations on T_w to be solved. In fact, the Nusselt number or the HTC and the corresponding wall temperature are unknowns, owing to the effect of wall temperature on the dimensionless groups appearing in the correlation; therefore, the wall temperature value must be guessed by an iterative process starting from a suitable initial approximation. Figure 4 shows the trends of wall temperature along the channel predicted using the original Jackson's correlation (Fig. 4a) and its optimized version (in Fig.4b). Though in Fig. 2 the enhancement obtained by modifying the coefficients on the prediction capabilities was clearly shown, it is now evident that a correlation tuned on data with specific values of wall temperature is not necessarily reproducing a similar trend when applied in a 1D model, in which will be called later a "predictive mode".



a) Original correlation b) Optimized coefficients

c) Original correlation d) Optimized coefficients

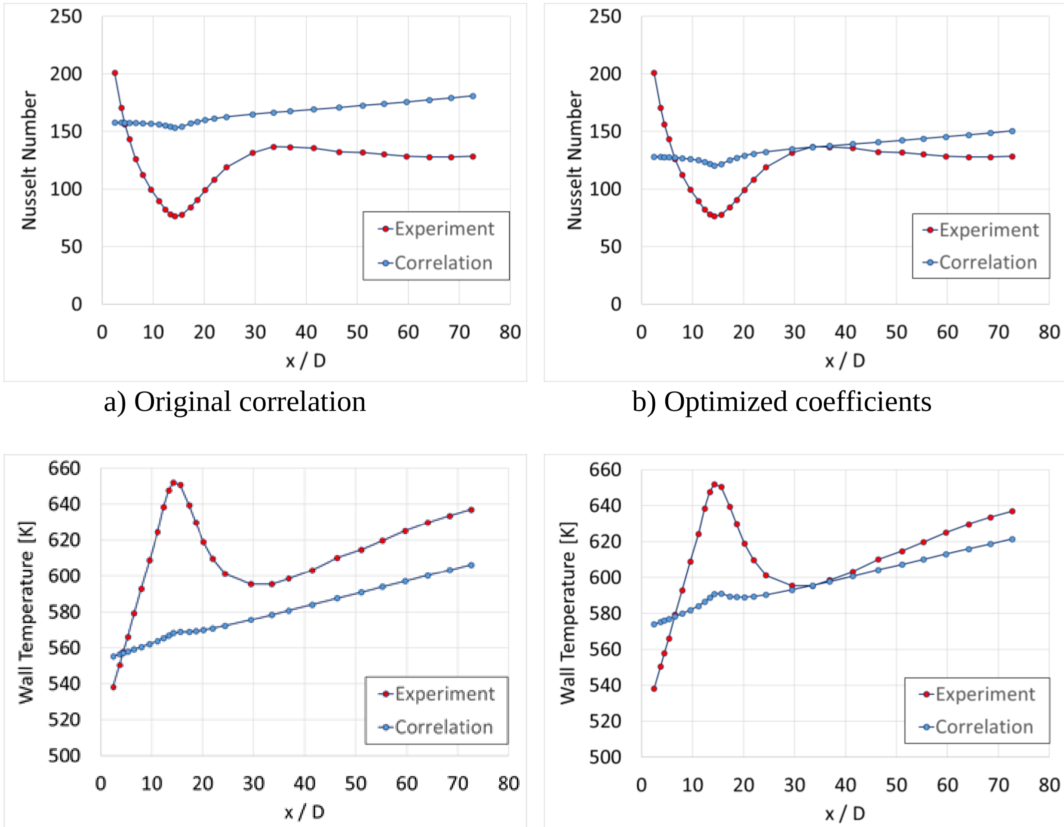
Figure 2. Trends of the calculated Nusselt number and wall temperatures along the channel, for the case of CO_2 Kline's Data at p = 8.35 MPa, Tin = 16 °C, G=300 kg/(m²s) and q"=20 kW/m² using Jackson's correlation.

As mentioned, another interesting correlation that is often used in literature is the one proposed by Mokry et al. [15]. This rather recent correlation was developed based on the on the older Bishop correlation [16] as a starting point to come up with the following updated correlation in Eq. 2 whose coefficients have been already reported in the above Table I:

$$Nu_b = C\, {Re_b}^{C1} \overline{Pr_b}^{C2} \left(\frac{\rho_w}{\rho_b}\right)^{C3} \tag{2}$$

Also, the Mokry et al. correlation is able to predict normal and improved heat transfer, being definitely much less useful in accounting for the deteriorated one. The same analysis as performed above using Jackson's correlation is carried out using Mokry et al. correlation and Fig. 5, 6 and 7 report the values of Nusselt number as well as of the wall temperature trends along the channel obtained using both the original and the optimized coefficients.

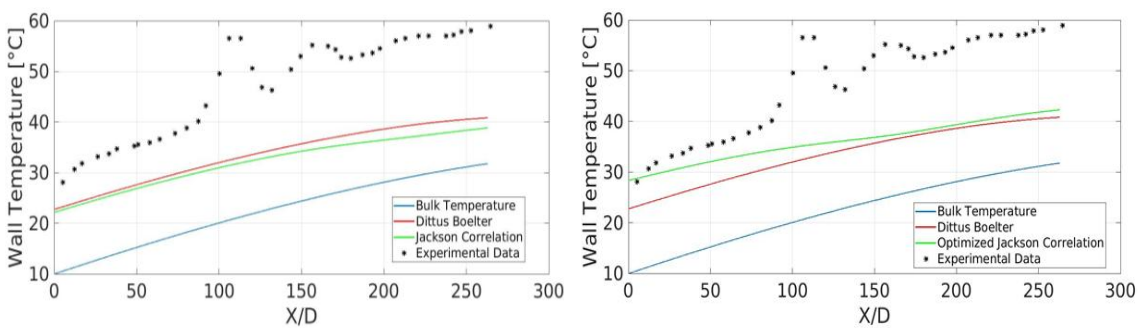
Although, the Nusselt numbers predicted in Fig. 5b using the optimized Mokry's correlation are improved compared to the case of the original coefficients in Fig. 5a, the wall temperature values for CO_2 case Fig. 6d as well as for H_2O case, Fig 7d, are still underestimating the experimental wall temperature. Moreover, by comparing the trends of the wall temperature using a simple iteration method, the correlations fail to predict the physical phenomena observed in the experiment. In particular, Fig. 8 reports the prediction of



a) Original correlation b) Optimized coefficients

c) Original correlation d) Optimized coefficients

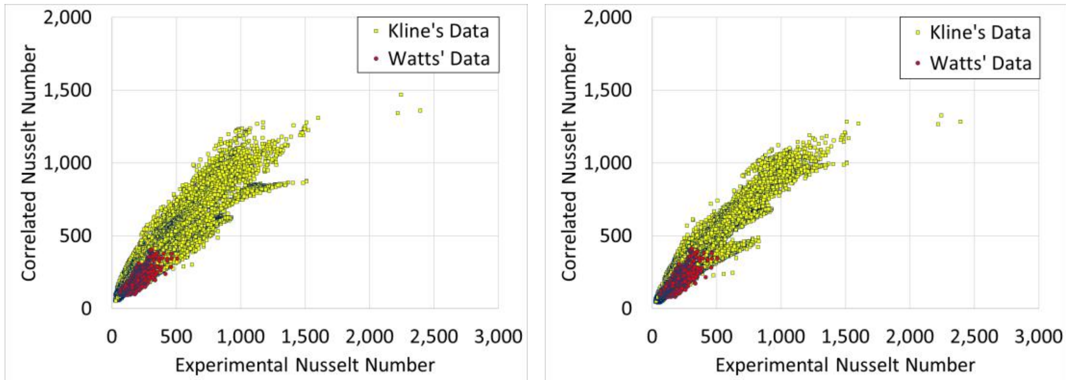
Figure 3. Trends of the calculated Nusselt number and wall temperatures along the channel, for the case of H_2O Watts' Data at p = 25 MPa, T_{in} = 200 °C, G=375 kg/(m²s) and q"=340 kW/m² using Jackson's correlation.



b) Original correlation b) Optimized coefficients

Figure 4. Values of predicted wall temperature along the channel for the case of CO_2 Kline's Data at p = 8.35 MPa, Tin = 16 °C, G=300 kg/(m²s) and q"=20 kW/m² using Jackson's correlation.

the wall temperatures using both the original and the optimized Mokry's correlation. These results again confirm the problem that strictly speaking the correlation cannot be applied without the prior knowledge of the wall temperature and then of the heat transfer coefficient it has to evaluate.



a) Original correlation b) Optimized coefficients

Figure 5. Comparison of data fit with experimental data for the Nusselt number using Mokry's correlation.

3. DIMENSIONLESS PARAMETERS FROM THE SIMILARITY THEORY

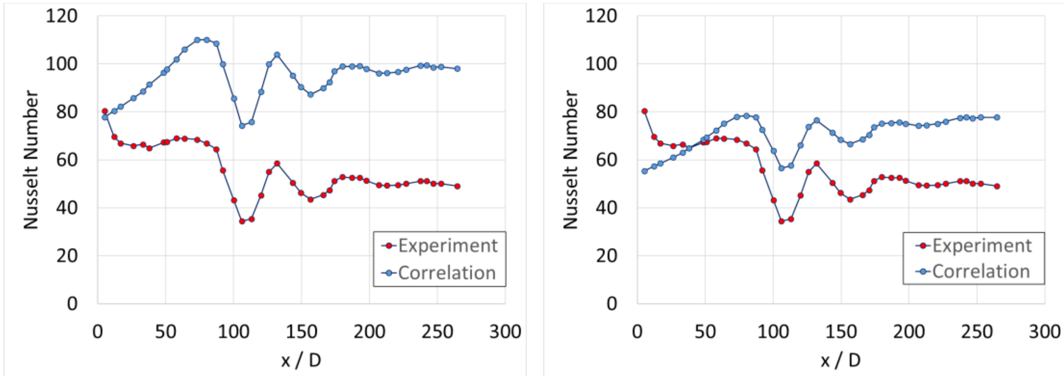
The mentioned fluid-to-fluid similarity theory is based on a set of non-dimensional parameters used to specify boundary conditions to be applied in RANS calculations with different fluids in close similarity from the phenomenological point of view and, in dimensionless form, also from the quantitative one [8-9]. The rationale was developed based on successful attempts obtained in the case of stability analysis for heated channels, which led to the proposal of new dimensionless numbers suitable for supercritical pressure fluids, in analogy with those adopted for boiling channels [17].

In fact, in view of the present rationale, two different fluid conditions are considered similar when the spatial distributions of the dimensionless enthalpy along and across the channel are nearly the same. This was found possible owing to a nearly universal trend of dimensionless density as a function of dimensionless enthalpy that is applicable to almost all of the fluids investigated up to now; being water, carbon dioxide, ammonia, R23 and R134a and in a wide range of supercritical pressures. Though some discrepancies in this trend for the fluids were found in the liquid-like region (especially for R134a which represented a sort of exception among the considered fluids) they resulted somehow of limited relevance for most of the considered operating conditions.

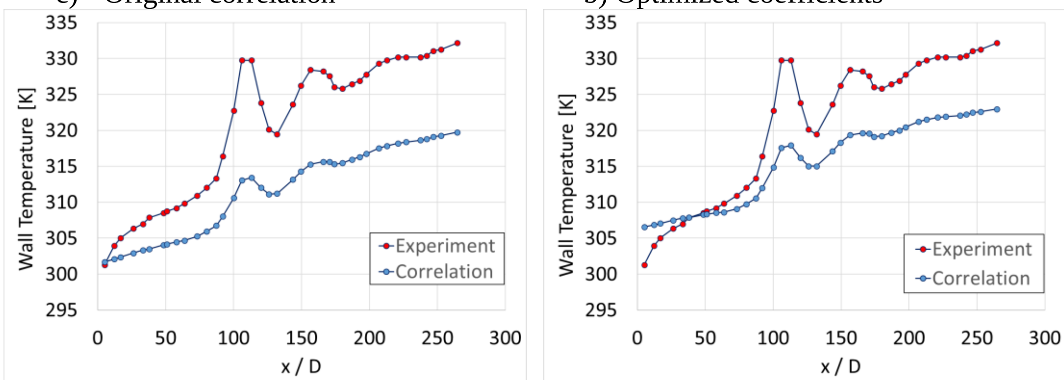
After the selection of the operating pressures basing on a specific rationale, the inlet dimensionless enthalpy, N_{SPC}, together with the dimensionless power-to-flow ratio, N_{TPC}, fully specifies how the fluid expands along the pipe; together with the radial distribution of density, this expansion affects the heat transfer regimes.

In order to highlight the major outcomes of the similarity theory for the scope of the present paper, the reader is referred to the latest work by the authors, where a detailed discussion on the rationale is reported [14]. For purpose of illustration, Figure 9 reports the original trends of wall temperature for carbon dioxide data by Kline at 20 kW/m^2 and the related predictions by the RANS calculations, compared with the trends obtained in close phenomenological similarity using water at 25 MPa, the pressure adopted in the design of several SCWR concepts.

As it can be noted, the present similarity theory is able to translate the relevant qualitative information about the different heat transfer regimes from the case of one fluid to the other. In particular, heat transfer phenomena like normal, enhanced and deteriorated regimes, up to the final restoration at the transition to gas-like conditions, are very similarly observed with water when scaled up from carbon dioxide.



c) Original correlation b) Optimized coefficients

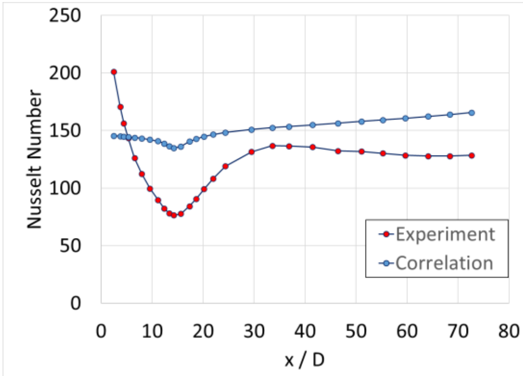


c) Original correlation d) Optimized coefficients

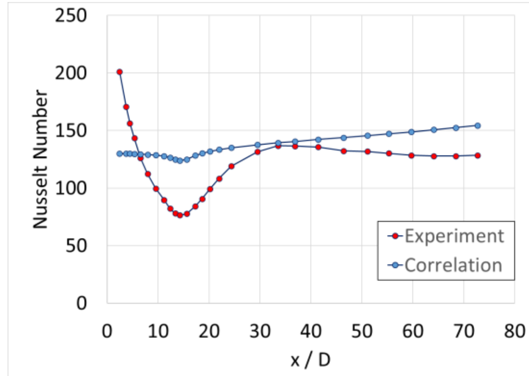
Figure 6. Trends of the calculated Nusselt number and wall temperatures along the channel, for the case of CO_2 Kline's Data at p = 8.35 MPa, Tin = 16 °C, G=300 kg/(m^{2}s) and q"=20 kW/m^2 using Mokry's correlation.

Moreover, the wall temperature oscillations observed in the experiment at inlet temperatures of 0, 6, 16 and 24°C are also represented in very close similarity with water at the corresponding values of temperature.

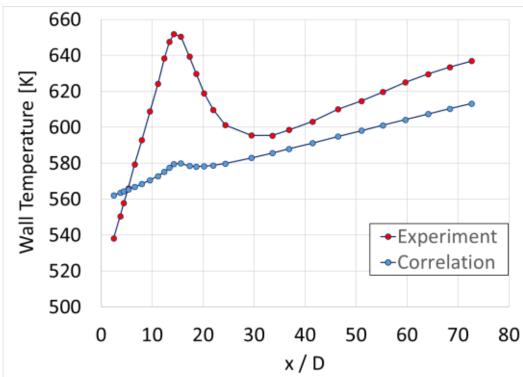
Another way for displaying the results of the similarity theory is represented by the dimensionless parameters reported in Fig. 10, referring to the case of Kline's data at inlet temperature of 16 °C and heat flux of 20 kW/m^2. This quantitative representation shows the onset of deterioration, presented by the peak observed in wall temperature that occurs at almost the same values of dimensionless bulk specific enthalpy in the flows of different fluids. The distribution of the wall dimensionless enthalpy confirms the success of the similarity theory, based on the assumption to achieve similar distributions of dimensionless enthalpy and then of dimensionless density along and across the channel for different fluids. As it can be noted, the values of the Nusselt number are instead different along the channel, as a consequence of the fact that the similarity theory preserves instead the values of the group $\overline{St}\,(L/D)$. Moreover, the value of the Nusselt number ratio, defined as the ratio of the Nusselt number to the one calculated by the Dittus-Boelter correlation (Nu/Nu_DB), shows very close trends for water and carbon dioxide.



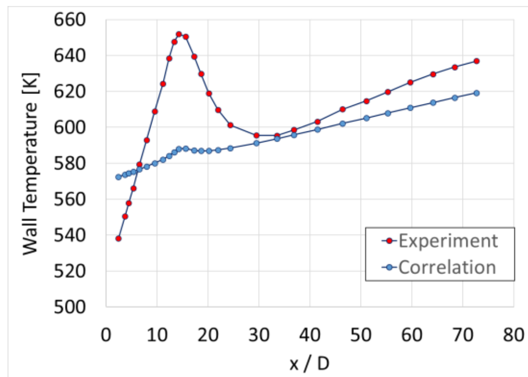
a) Original correlation



b) Optimized coefficients

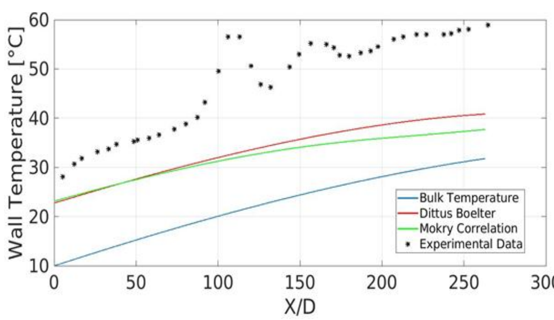


c) Original correlation

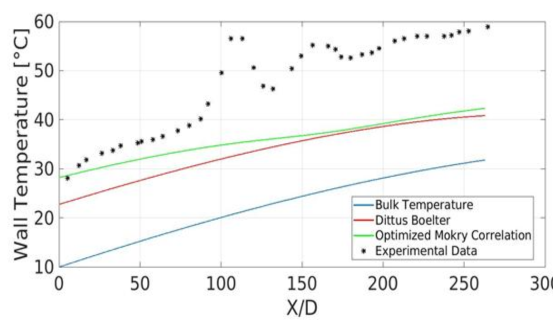


d) Optimized coefficients

Figure 7. Trends of the calculated Nusselt number and wall temperatures along the channel, for the case of H_2O Watts' Data at p = 25 MPa, T_{in} = 200 °C, G=375 kg/(m^{2}s) and q"=340 kW/m^2 using Mokry's correlation.



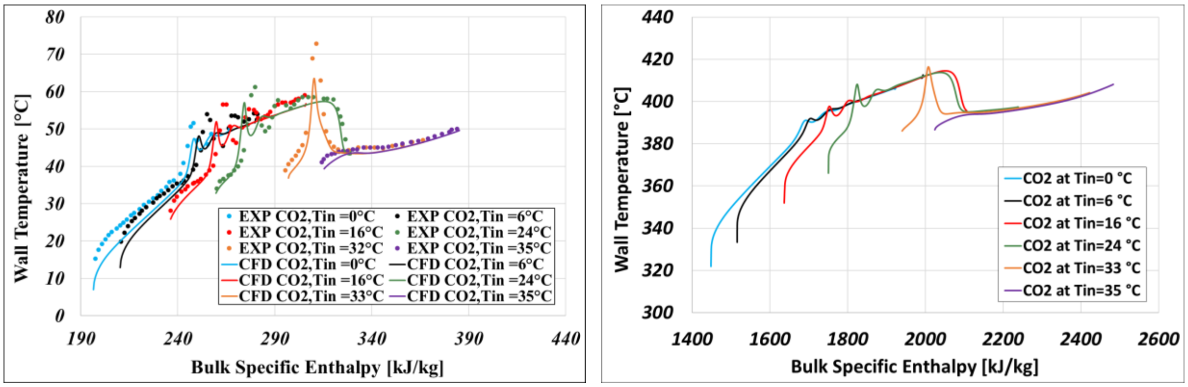
d) Original correlation



b) Optimized coefficients

Figure 8. Values of predicted wall temperature along the channel for the case of CO_2 Kline's Data at p = 8.35 MPa, Tin = 16 °C, G=300 kg/(m^{2}s) and q"=20 kW/m^{2}using Mokry's correlation.

The comparison with the Dittus-Boelter correlation stems from the fact that, as already mentioned earlier in this paper, most of the present heat transfer correlations at supercritical pressure are based on corrections to the Dittus-Boelter one. The example of correlation devised by the findings of the similarity theory considered below, to be considered just a first trial to stimulate scientific speculation in this regard, is following the same lines.



a) Experimental and RANS trends with CO_2 b) RANS calculation with water at 25 MPa

Figure 9. Trends of the wall temperature along the channel, Reference cases by Kline at q" = 20 kW/m^2.

Fig. 10 is also showing the trends of the Richardson and of the Froude numbers along the channel. It must be emphasized that according to the similarity rationale, the Froude number and the Reynolds number are preserved at the inlet of the channel. Though the Reynolds number evolves differently for the different fluids, indicating that it is not necessarily preserved along the channel, the Froude and the Richardson numbers are instead preserved all along the channel. Since the Richardson number is defined as a ratio of buoyancy to inertia forces, it is expected to affect the heat transfer regimes and, in particular, the onset of heat transfer deterioration.

It is definitely too early in the present research aiming to develop correlations possibly spanning over the full range of flow regimes to propose a new functional form basing on the similarity theory. However, for the only purpose of showing the challenges encountered in this frame, a first attempt is discussed below. The following form of correlation is still based on a Dittus-Boelter-like structure, though it includes the use of some dimensionless numbers identified in discussing the similarity theory:

$$Nu = 0.026\, {Re_b}^{1.01} \overline{Pr_b}^{\,1.04} Fr^{-0.328} Ri^{-0.403}\, NTPC_{loc}^{0.514} \left(\frac{\rho_w}{\rho_b}\right)^{0.339} \tag{3}$$

where

$$NTPC_{loc} = \frac{q"}{G} \frac{\beta_{pc}}{C_{p,pc}} \tag{4}$$

This correlation form in fact contains some of the dimensionless groups that were found important during the assessment of the similarity rationale. More specifically, it was noted that while the Richardson number increases the heat transfer capabilities are impaired and the Nusselt number decreases till it reaches a minimum value, causing a peak in wall temperature to be observed. Another important dimensionless group is the $NTPC_{loc}$, being a dimensionless heat flux over mass flux ratio. The coefficients appearing in the correlation have been as usual optimized on the basis of the data set by Kline and Watts already considered for the other two correlation forms by Jackson and Mokry et al. discussed in the previous sections.

Figure 11 shows the overall performance of the correlation on the full data set (Figure 11a) presenting a somehow better accuracy than the previous considered correlations, though some systematic deviations appear, highlighted by the clustering of data along specific stripes in the plot. However, as shown by Figure 11b and Figure 11c the two selected trends for wall temperature are now both represented by reasonable qualitative trends following closely enough the experimental measured trends.

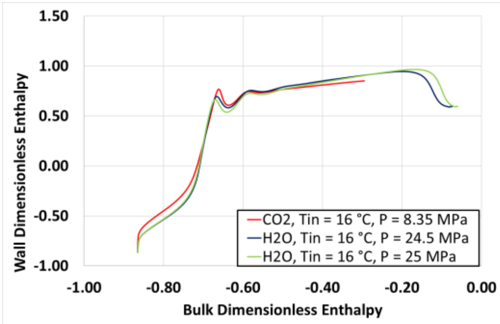
However, as shown in Figure 11d, this cannot be considered yet a success (to say the least) since when applying the correlation in "predictive mode", i.e. when considering a 1D channel and imposing the boundary conditions, again the correlation predicts trends of wall temperature that are not reproducing the deteriorated heat transfer behavior that they were able to reproduce nicely enough in "correlation mode". This apparently strange behavior requests a supplementary reflection that we report in the following section as a discussion of the results obtained up to now and in order to plan for further steps in the search for correlations suitable for predicting heat transfer in deteriorated conditions.

4. CORRELATION MODE, PREDICTIVE MODE AND RELATED CHALLENGES

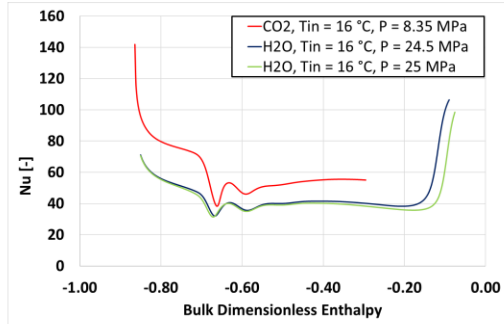
The results presented in the previous section, on the basis of the correlation forms by Jackson and Mokry et al., together with those obtained by the correlation introduced for the purpose of illustration based on the outcomes of the similarity theory, ask for a basic reflection on the development of heat transfer correlations depending on wall temperature.

As it was shown, if used with properly fitted coefficients the three forms at different extents were able at different extents to reproduce deteriorated heat transfer behavior when used in "correlation mode". With this expression we mean that while fitting a given correlation on a selected base of experimental data, the values of the Nusselt number are predicted basing on experimental values of the involved dimensionless parameters, trying to get the best match between experimental and correlated Nusselt values. When some of the dimensionless numbers involved in the classical power-law formulations adopted so far depend on the wall temperature (as it is in all the three correlation forms addressed in this paper) the experimental values of some dimensionless groups retain the information on the experimental values of wall temperature; this means that the fitting process is made achieving values of the constants and exponents that optimize the value of the Nusselt number basing on wall temperature information that is not necessarily coherent with the values of this variable as it could be obtained by the correlation itself. In fact, the resulting Nusselt number will be finally more or less different from the experimental value and this is a clear warning that the predicted wall temperature is not exactly the same as the one that was used in evaluating the coefficients appearing in the correlation.

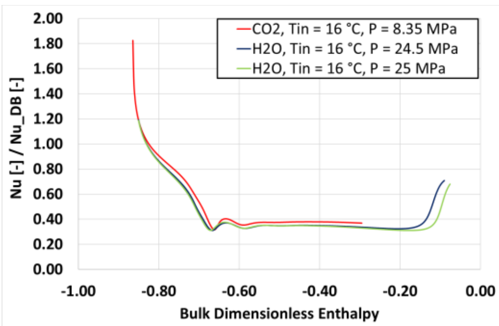
This is the major difference between what we here called "correlation mode" as opposed to the what we further define as "prediction mode", the latter being the process by which on the basis of some defined bulk fluid parameters the correlation is adopted to predict the wall temperature in a heated channel. In this case, some of its dimensionless parameters will be evaluated depending on the actual value obtained for wall temperature. This difference was clearly shown in the plots of the previous sections while it was demonstrated that correlations reasonably fitted on an experimental data set, showing what could be judged a rather good representation of phenomena in "correlation mode", were found to poorly predict the observed wall temperature while applied in conjunction with steady-state balance equations along the channel.



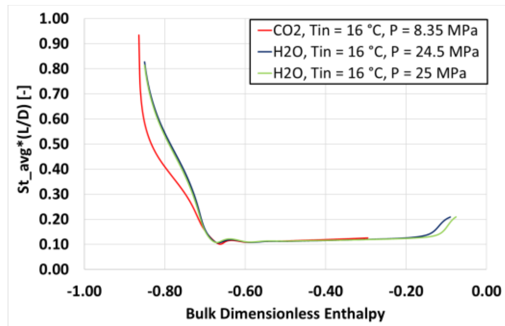
a) wall dimensionless enthalpy



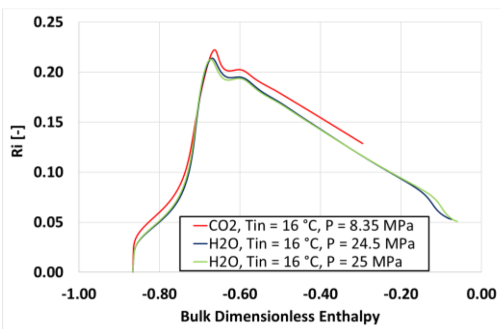
b) Nusselt number



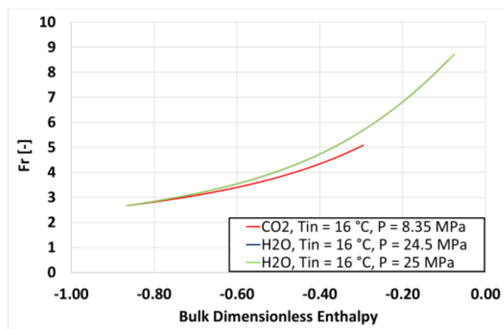
c) Nusselt ratio



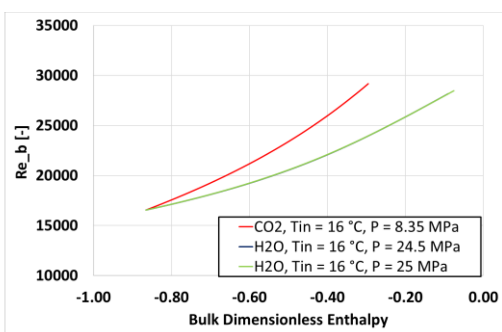
d) $\overline{St}\,L/D$



e) Richardson number

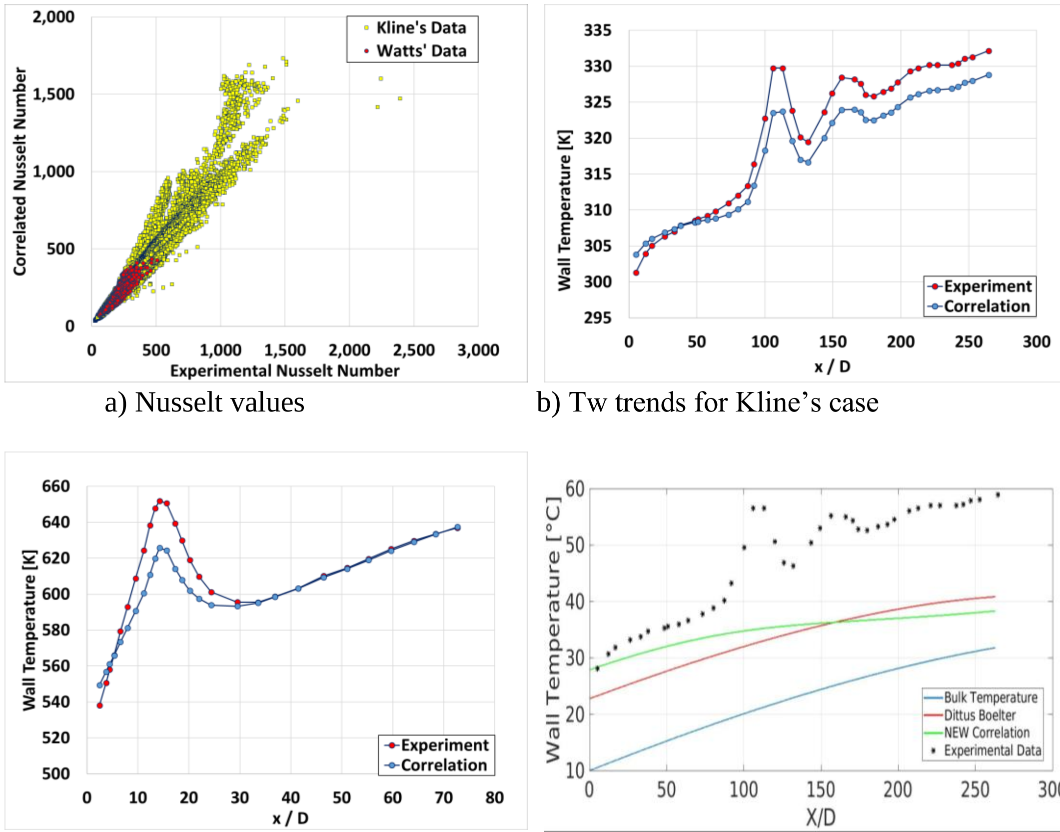


f) Froude number



g) Reynolds number

Figure 10. Trends of the relevant dimensionless numbers along the channel showing similarity for the case of Kline's data with q" =20 kW/m^2 and T_{in}= 16 °C



a) Nusselt values b) Tw trends for Kline's case

c) Tw trends for Watts' case d) Prediction of Kline's case

Figure 11. Values of Nusselt number and wall temperature trends using the new correlation. a) comparison of Nusselt numbers. b) the case of CO_2 Kline's Data at p = 8.35 MPa, Tin = 16 °C, G=300 kg/(m^2s) and q"=20 kW/m^2. c) the case of H2O Watts' Data at p = 25 MPa, Tin = 200 °C, G=375 kg/(m2s) and q"=340 kW/m^2. d) Prediction of Kline's case.

Difficulties in iterating on wall temperature while applying correlations containing dimensionless numbers depending on wall temperatures were actually reported recently by other researchers while applying correlations in what we define "predictive mode" (see e.g., [18]), referring about iteration problems and convergence issues, together with the possibility to find multiple solutions for wall temperature at given bulk fluid conditions and heat flux values. This represents a serious challenge, because heat transfer deterioration is a phenomenon having an excursive nature at its onset, with the already mentioned phenomena showing the tendency to overshoot and behave in an oscillatory way depending on the radial distribution of velocity and on the related turbulence production dynamics.

Whether such complex phenomena, which are grasped with some difficulty even by CFD models, can be predicted by engineering correlations having mostly an algebraic nature is a matter for further investigation. Indeed, the considerable number of existing correlations for fluids at supercritical pressure, mostly useful for predicting normal or enhanced heat transfer, suggests that at the moment the problem was not yet solved in a satisfactory way.

5. CONCLUSIONS

In this paper, the challenges involved in the development and application of correlations for heat transfer with fluids at supercritical pressure have been discussed. The starting point of the research being conducted in this regard has been the proposal of a rationale for establishing a fluid-to-fluid similarity that proved to be sound enough on the basis of supporting CFD calculations. This rationale is suggesting dimensionless numbers having an important role in determining the onset of heat transfer deterioration, whose use in correlating the observed behavior could be therefore a key aspect in developing new correlations spanning over the normal, enhanced and deteriorated regimes.

However, it was shown that the selection of the appropriate dimensionless numbers may not be sufficient while using the classical techniques for optimizing exponents and constants appearing in correlations based on dimensionless groups depending on wall temperature. The difference between the comparison of correlations with experimental data in modes which were named respectively as "correlation" and "predictive" ones is highlighting a fundamental difficulty, confirming similar ones suggested by other researchers, that deserve to possibly change the techniques adopted in power-law fitting, taking into account the intimate link between wall temperature, the predicted Nusselt number and the dimensionless groups appearing in the correlation.

It must be recognized that this paper represents more the statement of a problem than the proposal of a solution; however, it was considered worth to share with the scientific community the present reflections and the encountered problems concerning the challenges being faced in trying to improve the still unsatisfactory state-of-the-art in the field of predicting deteriorated heat transfer at supercritical pressure.

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Nomenclature

Latin letters

C_p	specific heat at constant pressure [J/(kgK)]
D	diameter [m]
Fr	Froude number
G	mass flux [kg/(m^{2}s)]
L	length [m]
N_{TPC}	trans-pseudocritical number
Nu	Nusselt number
$\overline{Pr}$	averaged Prandtl number
q''	heat flux [W/m^2]
Re	Reynolds number
Ri	Richardson number
$\overline{St}$	averaged Stanton number
T	temperature [K, °C]

Greek letters

β	isobaric thermal expansion coefficient [1/K]
ρ	density [kg/m^3]

Subscripts

b	bulk
pc	pseudocritical
w	wall

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