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A successful general fluid-to-fluid similarity theory for heat transfer at supercritical pressure

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Abstract
The present paper introduces a successful and general fluid-to-fluid similarity theory for heat transfer to fluids at supercritical pressure, having a high degree of universality. This work shortly follows the recent publication of a "local" successful similarity theory developed for fluids at supercritical pressures in a range of conditions in which the values of their molecular Prandtl number were quantitatively similar, extending its conclusions to the case of different molecular Prandtl numbers. The reason why this further step requested a short time to be elaborated is due to recognising that previous work by the Authors had actually already solved the related problems, though in a slightly different way, now interpreted in a more significant frame owing to a better problem understanding.

The present similarity theory is based on first ideas developed more than one and a half decade ago by one of the authors, while addressing flow stability of supercritical fluids in heated channels, which encountered immediate problems to be applied in a straightforward way to heat transfer. These ideas were revised and considerably improved during the PhD thesis of the other author, also overcoming a sort of prejudicial assumption that finally resulted to limit their applicability. More recently, published DNS data triggered further reflections on the role of the Prandtl number, leading to the mentioned "local" form of the successful similarity theory. This led to the present step, by just recognising that the mentioned PhD thesis had already proposed a sufficient rationale to extend this local interpretation to a broader range of conditions.

The rather convincing results presented herein, obtained making use of RANS CFD analyses with four different fluids, demonstrate the interesting capabilities of this final form of the theory. The establishment of an effective set of dimensionless numbers for heat transfer problems is hoped to pave the way for the development of the still lacking successful engineering heat transfer correlations for supercritical pressure fluids. It further calls for dedicated experiments needed to confirm the suitability of the present theory beyond any reasonable doubt.

1. Introduction
Fluids at supercritical pressure exhibit a complex heat transfer and flow behaviour that is the subject of studies since decades. Early papers on the problems of heat transfer and flow dynamics can be mentioned in this regard, as the one by Jackson and Hall [1], on the curious and worrying heat transfer phenomena due to fluid laminarisation, and the one by Zuber [2], which forecasted a lot of the future findings about flow stability.

Predicting heat transfer behaviour and flow stability of fluids at supercritical pressure conditions is of great interest for energy technology and in particular for nuclear energy. The proposed General IV concept of a supercritical water reactor (SCWR) [3] is motivating worldwide efforts in this field, coping with the design problems involved in the challenge to achieve high safety standards and better long-term sustainability of nuclear energy from fission. This motivated additional commitment with respect to the relevant applications of supercritical fluids in the conventional energy sector, leading to national and international efforts, as reported, e.g., in references from [4–9].

Stimulated by this international frame of studies related to nuclear energy and being involved in them in the past years, effort was devoted to the establishment of a suitable fluid-to-fluid similarity theory for heat transfer at supercritical pressure, whose latest form and results are presented in this paper. Achieving a sound similarity theory is necessary in view of allowing the collection of experimental data by different simulant fluids, e.g. having a lower...
critical pressure than water, and more importantly to promote understanding of the basic dimensionless numbers playing a role in the complex phenomena observed. In this regard, the main emphasis is on the prediction of “deteriorated” heat transfer that, in difference with “normal” and “enhanced” heat transfer, also exhibited by supercritical pressure fluids, results much harder to be predicted by both engineering correlations and CFD models.

In particular, the present lack of suitable tools for predicting these heat transfer phenomena can be traced back to an incomplete understanding of the main dimensionless groups having a role on their appearance. The idea proposed in this paper and supported by the obtained results is that the development of the fluid conditions all along the duct, mainly in terms of density changes, plays a major role in determining the conditions for the occurrence of each heat transfer regime. In this view, the dimensionless inlet fluid conditions and power-to-flow ratio are found very relevant, together with the preservation of other selected dimensionless groups.

The conclusions finally reached in this paper are the result of a rather long elaboration of early embryonal ideas. These were firstly introduced in relation to the analysis of flow stability of heated channels with supercritical pressure fluids in an early paper [10] that proposed basic dimensionless numbers in analogy with those commonly used for boiling channels (see, e.g., [11]). The similarity theory worked very well in such purpose, owing to an interesting and rather universal relation found between the introduced dimensionless fluid density and specific enthalpy that has been discussed several times in previous works (see, e.g., [10,12,13, 15]). This relation holds with reasonably good approximation for different fluids at any supercritical pressure, granting the possibility to set up broadly applicable stability maps, useful for different fluids and supercritical pressures.

However, the application of the same principles to heat transfer problems encountered an immediate difficulty in the different thermophysical properties of the fluids, which could be hardly scaled by a similar rationale. Namely, the Prandtl number is rather different for different fluids and strongly depends on the value of pressure above the critical one, thus suggesting a much more difficult situation than coped with by the scaling of fluid density. This destroyed any hope to achieve a similar universality by simple extension.

First ideas concerning heat transfer similarity were proposed by one the authors during the participation in a Coordinated Research Project of IAEA [7] and were timidly contributed through an internal University of Pisa report [14]. Later on, these ideas were assessed by applications making use of Computational Fluid Dynamic (CFD) tools [15,16], selected to be used in support of the usual theoretical developments owing to at least two good reasons:

- CFD models are much more detailed than the theoretical considerations we can usually make on the basis of handwritten thermal and fluid-dynamic formulations and they are certainly better, to some extent, since they bring to direct quantitative conclusions the assumptions retained in those theories; as demonstrated in a recent paper [17], even rather imperfect turbulence models, in terms of their ability in predicting experimental behaviour, can show coherence in a fluid-to-fluid comparison perspective, whenever sound similarity principles are correctly applied;  
- it is sometimes very difficult to find real “counterpart” experiments performed with different fluids, allowing to draw conclusions in view of a general heat transfer similarity; just to mention the usual case of water and carbon dioxide, it is rather difficult to find experiments with CO2 that really compare with those performed with water in terms of subcooling with respect to the pseudo-critical conditions; this represents one of the hardest difficulties to be coped with, suggesting to perform specific experimental campaigns aimed at providing suitable validation data for any similarity theory.

Though the methodology at the basis of the early published papers [15,16] already contained some of the basic principles that later resulted successful, the first results showed the major problems suggested above. In particular, qualitative similarities were indeed found in coping with deteriorated heat transfer cases; however, it was anyway observed a much earlier heat transfer deterioration for fluids having a larger Prandtl number with respect to water.

A turning point in the research was represented by the doctoral thesis of one of the co-authors of this paper (A.P.) [18] which provided a contribution in two key areas for the establishment of a similarity theory:

- it improved the predictive capabilities of CFD models, successfully trying the use of Algebraic Heat Flux Models (AHFM)
suggested in previous literature [19]: this made more reliable the CFD predictions performed for comparing the behaviour of different fluids (see, e.g., [20, 21] and the more recent works [22, 23]);

- it revised and updated the old rationale for similarity proposed in previous works, also abandoning the preservation of geometrical similarity in circular pipes (in terms of the equality of the length over diameter ratio); in fact, it was noted that its effects for heated fluids at supercritical pressure are weaker in view of the continuous development of the flow due to property changes: this led to a first publication proposing an extended rationale for heat transfer similarity [24].

Then, a recent paper presented by the group of Prof. He [25] showed Direct Numerical Simulation (DNS) data which perfectly supported the old rationale proposed in the mentioned less successful applications of References [15, 16], just corrected by imposing also the equality of the Reynolds numbers at channel inlet. Discussing these new results, a step forward in understanding the capabilities of the already proposed similarity theory was made, leading to a common paper [17]. The reasons for the discrepancy observed in the previous work were thus explained, mainly recognising that the DNS calculations were performed in local conditions in which the Prandtl number was very similar for the four considered different fluids. This detail resulted in the prediction of strikingly similar behaviour, to be compared with the much poorer results of previous work operating in a wider range of Pr: a successful “local” similarity theory was finally available.

In this paper, a further and more advanced step is made towards a successful generalisation of the fluid-to-fluid similarity theory. This is now possible on the basis of the experience gained in the rather long period of elaboration of basic ideas, shortly summarised above, and as a consequence of better realising the role of the Prandtl number. This made it possible to interpret in a new light the step already made in the PhD thesis that paved the way for this work [18], bringing to a clearer view of the problem.

2. Physical basis for the proposed theory

A discussion of the principles at the basis of the “local” similarity theory has been recently reported in [17]. Hereafter, we systematically summarise the main findings supporting the assumptions of the more general theory, with reference to what already discussed in that paper and in previous ones.

2.1. Dimensionless relation between fluid density and specific enthalpy

Unlike previous similarity theories referring to the critical point for the main reference thermodynamic parameters (see, e.g., the reviews presented by Pioro and Duffy [4] and recently by Mouslim and Tavoularis [26]), the present one mostly considers the values of density, enthalpy and other thermodynamic parameters at the pseudo-critical temperature at any supercritical pressure to achieve dimensionless formulations. This choice is effective in discriminating between the conditions of liquid-like and gas-like fluid, though it is not granted to be the best to represent the threshold between the two regions, since other choices could be eligible (e.g., the locus of maximum magnitude of the negative slopes of density versus enthalpy or of the maximum thermal expansion coefficient, the maximum of the Prandtl number, etc.). This aspect was given some attention at the time of proposal of the dimensionless numbers for stability problems [10], but at the moment the selection of the maximum of the specific heat (i.e., of the pseudocritical point at any given pressure) as reference fluid condition can be considered as a reasonable choice, not too much different from any similar one.

Fig. 1. Dimensionless density vs. dimensionless specific enthalpy for four different fluids [17].

The adopted definitions of dimensionless density and enthalpy are respectively \( \rho^* = \rho / \rho_{pc} \) and \( h^* = (h - h_{pc}) \rho_{pc} / C_p \rho_{pc} \) at any assigned pressure above the critical one. Retrieving an old representation of the mutual relation of these quantities for fluids at different supercritical pressures, Fig. 1 shows the interdependence existing between them. It can be noted that a zero dimensionless specific enthalpy indicates pseudocritical conditions, where the dimensionless density is by definition equal to unity. The limited deviations observed in the liquid-like region from a unique trend, depending on the fluid, must be obviously taken into account, though they have shown to be relatively unimportant in comparing fluids in view of flow stability, something that can be presumed to apply also for the present similarity theory.

2.2. Definition of similarity

Owing to the role of dimensionless enthalpy in determining dimensionless fluid density and the influence of the distribution of the latter on heat transfer, e.g. through phenomena as fluid acceleration and buoyancy, it is straightforward to define “similar” two different fluid conditions in which the spatial distributions of the dimensionless enthalpy in the channel are the same (or nearly the same, to allow for unavoidable non ideally scalable behaviour of fluids). It can be anticipated that, since the relation between enthalpy and temperature is nonlinear, this simple definition brings about its own inconveniences with respect to a simple linear scaling of the latter variable. On the other hand, the usefulness of this definition can be appreciated in relation to the link to dimensionless density and also considering that the enthalpy increment along the channel in steady-state conditions is related to the power-to-flow ratio, another important parameter in view of the onset of heat transfer deterioration.

2.3. The dimensionless power-to-flow ratio and inlet subcooling

In this respect, other relevant dimensionless definitions, already adopted for flow stability [10], involve a dimensionless power-to-flow ratio, termed trans-pseudocritical number, \( N_{TFC} = (Q / W) \rho_{pc} / C_p \rho_{pc} \), and the dimensionless inlet channel subcooling with respect to pseudocritical conditions, termed pseudo-subcooling number, \( N_{SCP} = h_{in}^* - (h_{in}^* - h_{pc}^*) \rho_{pc} / C_p \rho_{pc} \). As indicated in Fig. 1, \( N_{TFC} = h_{out}^* - h_{in}^* = h_{out}^* + N_{SCP} \), in similarity with the role played by the phase change number and the subcooling number in boiling channels [11]. Imposing specific values for these two dimensionless parameters in steady-state conditions fully defines the trend of specific enthalpy in the bulk fluid, both in the assumption of uniform heat flux (implicitly retained in this discussion) or
of uneven heating per unit channel length: this satisfies a first criterion to declare similarity.

As shown in [24] and recently discussed in [17], the introduced dimensionless parameters lead to a dimensionless form of the Newton's law of convective heat transfer

\[ N_{TPC} = \frac{\overline{Nu}}{RePr} = \frac{4L}{D} + \frac{C_p h_w}{\overline{Nu}} \]

(1)

with the average specific heat over a cross section defined as \( \overline{C_p} = (h_w - h)/(T_w - T) \). In these subscripts, the subscript "w" indicates the local values of fluid properties at the interface with the wall and the variables without subscript refer to "bulk" values.

2.4. The Stanton number and the length over diameter ratio

A description of some relevant consequences of Eq. (1) is in order.

- Declaring similarity among two different fluid cases, while imposing the same values of \( N_{TPC} \) and \( N_{PC} \) in the aim to get a same trend of bulk fluid dimensionless enthalpy, requires also to achieve the same trends of \( h_w \), along the channel wall. Therefore, Eq. (1) implies that at any cross section of the duct the product of the average Stanton number \( \overline{St} \) by the length over diameter ratio is the same for different fluids.

- It is worth reminding that \( N_{PC} \) can be written as a function of the local heat flux (here assumed uniform along the channel), as

\[ N_{PC} = \frac{q' \overline{T}_L}{\overline{G}_A} \]

which a circular pipe is assumed. Thus, dropping the classical requirement of geometrical similarity, in view of the mentioned lesser importance that entrance conditions have in a case of continuously developing fluid properties, the value of \( N_{PC} \) can be kept in the same two different fluid cases also by changing the heat flux-to-mass flux ratio and the length over diameter ratio accordingly. Changing \( L/D \) is useful in view of attaining similarity, since it may be the case that the average Stanton number distribution is not the same for two fluids because of their different properties, while the difference \( h_w - h \) must be kept the same (see Eq. (1)).

- As already noted in [24], assuming a Colburn-type correlation for the local value of the Nusselt number, it is

\[ \overline{St} = \frac{\text{const.} \times Re^{0.3}}{Pr^{1/3}} = \text{const.} \times Re^{0.3}Pr^{-1/3} \]

(3)

This argument, which is not fully granted but at least useful if assumed, suggests that cases with different fluids having different Reynolds and Prandtl numbers can be scaled to each other by preserving the value of the product \( (Re^{0.3}Pr^{-1/3}) \times (L/D) \), provided the first factor is scaled by a sufficiently uniform ratio in the case of the two fluids.

- Actually, RANS calculations performed in [24] suggested that a different exponent should be used for the Prandtl number, resulting in the following relation to be preserved instead

\[ \left( Re^{0.3}Pr^{-1/3} \right)_{\text{fluid-1}} \times (L/D)_{\text{fluid-1}} \approx \left( Re^{0.3}Pr^{-1/3} \right)_{\text{fluid-2}} \]

(4)

where the approximate equality sign has been introduced because, even equating the values of the dimensionless number, e.g., at channel inlet, it is hopeless to keep the strict equality all along the channel, owing to different property changes. It must be noted that this corresponds to assume a heat transfer correlation having the form \( Nu = \text{const.} \times Re^{0.3}Pr^{2/3} \). This curious inversion among

the exponents 2/3 and 1/3, confirmed by the results of calculations performed in the present work (see below), is indeed interesting, though it may be an artefact of the turbulence model adopted to get a numerical validation of the theory and should be validated or corrected on the basis of experimental data. While in [24] the rationale to scale the corresponding cases only preserving the values of the inlet Froude number was used, letting the \( Re \) to be possibly different, there could be motivations to do otherwise.

2.5. Role of the Reynolds and of the Froude numbers

There is little need to remind about the important role played by the Reynolds number on turbulent heat transfer in forced convection. After the presentation of the first results later collected in [24], the authors received the suggestion to preserve also at least the inlet value of the Reynolds number [27], so that Eq. (4) should be rephrased as:

\[ \left[ Pr^{-1/3} \right]_{\text{fluid-1}} \times (L/D)_{\text{fluid-1}} \approx \left[ Pr^{-1/3} \right]_{\text{fluid-2}} \times (L/D)_{\text{fluid-2}} \]

(5)

This reduces the scaling of the length over diameter ratio to the assumption that the Prandtl number ratio is sufficiently constant (or constant in an average) along all the channel for the two fluids, to compensate for any difference between two fluids by changing the other constant factor, something being a key feature in the applications proposed herein. The strategy of changing the pipe diameter was used by Prof. He and his group in performing the DNS analyses [25] which triggered the common paper [17], owing to their choice to preserve also the inlet Reynolds number in addition to the inlet Froude number.

Concerning the Froude number, defined for convenience on the basis of the pipe diameter, \( Fr = w^2/\rho gD \), it was introduced as a group to be preserved at the channel inlet, in addition to the value of \( h_w = -N_{PC} \), in order to keep the same value of the inertia to buoyancy forces. In [24], it was in fact shown that

\[ F_{DD} = \frac{w^2}{\rho gD} = \frac{w^2}{ho gD} \frac{w^2}{gD} \frac{w^2}{gD} = \frac{w^2}{gD} \frac{w^2}{gD} = \frac{w^2}{gD} \frac{w^2}{gD} = \frac{w^2}{gD} \frac{w^2}{gD} = \frac{Fr_{DD}}{Fr_{DD}} \]

(6)

where the dimensionless velocity is defined as \( w^* = w/w_{in} \) and, in steady-state, it is \( C_*= \rho_{in} w^*_{in} = \rho_{in} \). Therefore, the dimensionless set of parameters adopted assure that if the value of the Froude number is preserved at the inlet, in steady-state conditions it is preserved everywhere along the channel, thanks to the preservation of the dimensionless distribution of density along the pipe. Another quite interesting feature in view of predicting mixed convection effects was shown in the mentioned paper [24], considering the Richardson number defined as

\[ Ri_D = \frac{(\rho - \rho_w)gD}{\rho w^2} = \frac{(\rho - \rho_w)gD}{\mu^2} \frac{\mu^2}{\rho^2 w^2 D^2} = \frac{Gr_{DD}}{Re^2} \]

(7)

In fact, it is

\[ Ri_D = \frac{\rho^* - \rho^*_{in}}{\rho^*} \frac{1}{Fr_{DD}} = \frac{\rho^* - \rho^*_{in}}{\rho^*} \frac{1}{Fr_{DD}} \frac{\rho^*}{\rho^*} \frac{\rho^*}{\rho^*} = \frac{\rho^* (\rho^* - \rho^*_{in})}{\rho^* (\rho^* - \rho^*_{in})} \frac{1}{Fr_{DD}} \]

(8)

suggesting that if inlet Froude number and the inlet dimensionless density (i.e., \( N_{PC} \) are preserved, the similarity implies also equal Richardson number values all along the pipe, ensuring the correct scaling of buoyancy and inertia effects in the two fluid cases.

2.6. Consequence of preserving the values of both Fr and Re at the pipe inlet

In [24], the similarity theory was applied imposing only the inlet Froude number and keeping the same pipe diameter for different fluids. If also the Reynolds number at pipe inlet must be
preserved, the diameter must be also adapted according to the following constraints:

$$\frac{w^2_{in, fluid - 1}}{gD_{fluid - 1}} = \frac{w^2_{in, fluid - 2}}{gD_{fluid - 2}} \quad \text{and} \quad \frac{w_{in, fluid - 1} D_{fluid - 1}}{v_{in, fluid - 1}} = \frac{w_{in, fluid - 2} D_{fluid - 2}}{v_{in, fluid - 2}}$$  (9)

We obtain

$$\frac{w_{in, fluid - 1}}{v_{in, fluid - 1}} = \sqrt{\frac{D_{fluid - 1}}{D_{fluid - 2}}} = \frac{v_{in, fluid - 1} D_{fluid - 2}}{v_{in, fluid - 2} D_{fluid - 1}} = \frac{D_{fluid - 2}}{D_{fluid - 1}}$$  (10)

and then

$$\frac{w_{in, fluid - 2}}{w_{in, fluid - 1}} = \left(\frac{v_{in, fluid - 2}}{v_{in, fluid - 1}}\right)^{1/3}$$  (11)

thus providing the appropriate ratio of diameters and inlet velocities as a function of the inlet kinematic viscosity ratios. It must be again remarked that, while the preservation of the Froude number at the inlet is a guarantee that both the Froude and the Richardson numbers are kept in similarity along the whole pipe length, unfortunately there is no hope that the Reynolds number will be the same for the two fluids. In fact, the changes in the dynamic viscosity along the pipe will make the Reynolds number to evolve according to the relation

$$Re = \frac{GD}{\mu} = \frac{GD_{in}}{\mu_{in}} = Re_{in}\left(\frac{\mu_{in}}{\mu}\right)$$  (12)

This was one of the reasons why in [24] it was not considered too important to impose the inlet value of the Reynolds number, preferring to keep the same pipe diameter in the two cases. However, on the basis of the almost ideal results obtained by the “local” similarity theory presented in [17], preserving the inlet Re is finally considered a good and theoretically more appealing option.

### 2.7. Role of the Prandtl number vs. the one of the Stanton number

One of the latest achievements in devising the present similarity theory has been a better awareness of the role of the Prandtl number in affecting the scalability of heat transfer conditions in the present context. This was obtained by reflecting on the exceptionally similar results obtained by the DNS calculations presented by Prof. He and his group [25]. This reflection, reported in [17], allowed reaching the conclusion that the most important contributor to the exceptional performance of the similarity theory, adopted in close similarity with what proposed in [15], was the selection of operating conditions in a window of dimensionless specific enthalpy in which the four selected fluids had nearly the same Prandtl number. This was in turn due to a specific selection of fluid supercritical pressures, making the peak Prandtl number in the vicinity of the pseudocritical threshold to be very close to a same value, being the one for water at 25 MPa, the design pressure of some reference SCWR concept. The match of the Prandtl numbers was of course a fortunate coincidence, due to the short range of dimensionless enthalpies involved in the considered DNS cases around the pseudo-critical threshold, and ideas were sought for in order to enlarge the applicability of what was called a successful “local” similarity theory.

Considering the previous discussion on the Stanton number and the length over diameter ratio, it is here suggested that reasonably similar results can be also obtained if the Prandtl numbers of the different fluids are different, but keeping a nearly constant ratio in a key region for the development of major heat transfer phenomena. In fact, in such a case Eq. (5) offers the possibility to restore similarity, by changing in accordance the length over diameter ratio.

In fact, the $N_{TPC}$ can be kept the same considering that

$$N_{TPC, fluid - 1} = \left[\frac{q^1}{\beta_{pc} C_{p, pc}}\right] \frac{4L}{D} \left(\frac{1}{D_{fluid - 1}}\right)$$

$$= N_{TPC, fluid - 2} = \left[\frac{q^2}{\beta_{pc} C_{p, pc}}\right] \frac{4L}{D} \left(\frac{1}{D_{fluid - 2}}\right)$$  (13)

or

$$\left[\frac{q^1}{\beta_{pc} C_{p, pc}}\right]_{fluid - 1} \left[\frac{L}{D}\right]_{fluid - 1} = \left[\frac{q^2}{\beta_{pc} C_{p, pc}}\right]_{fluid - 2} \left[\frac{L}{D}\right]_{fluid - 2}$$

According to Eq. (5), it is therefore

$$\left[\frac{q^1}{\beta_{pc} C_{p, pc}}\right]_{fluid - 1} = \left[\frac{L}{D}\right]_{fluid - 1}^{-1/3} \left[\frac{Pr_{fluid - 1}}{Pr_{fluid - 2}}\right]^{-1/3}$$  (15)

Defining the “local $N_{TPC}$” as

$$N_{TPC, loc} = \frac{q^2}{\beta_{pc} C_{p, pc}}$$  (16)

it is possible to state that

$$N_{TPC, loc, fluid - 2} = \left[\frac{Pr_{fluid - 2}}{Pr_{fluid - 1}}\right]^{-1/3} N_{TPC, loc, fluid - 1}$$

(17)

This change, anyway, results in the inconvenience to be unable to compare results in terms of the dimensionless axial coordinate $(x/D)$, while it will be much more meaningful to represent them in terms of dimensionless specific enthalpy that, owing to the preservation of the trans-pseudocritical number, $N_{TPC}$, and of the pseudo-subcooling number, $N_{SPC}$, has exactly the same trend along the channel for the different fluids.

It is therefore remarked that, whereas in [24] the criterion for the selection of the operating supercritical pressures making possible the similarity for the different fluids was related to the uniformity of the Stanton number (something a bit cumbersome to be judged), now it is related to the ratio of the Prandtl numbers in the real and the model fluid.

The interesting similarities obtained also in [24] by selecting the scaled pressures on the basis of the rationale concerning the Stanton number can be now explained in an a posteriori perspective by considering Figs. 2 and 3. These figures report respectively
As in an immediate application of the new criterion based on the Prandtl number, tentative values of pressure for establishing similarity have been identified in relation to the experimental data by Kline [29], collected with carbon dioxide at 8.35 MPa flowing in upward flow in heated pipes of different diameters. The resulting trends of the Prandtl numbers at the selected pressures are shown in Figs. 4 and 5. Using this criterion, it is understood that the selection of the appropriate pressures can be done by trials and errors, considering pressures closer or farther from the critical point that maintain a nearly constant ratio among the values of the Prandtl number in the liquid-like region, at the pseudocritical point and, as far as it is possible, beyond it. The favourable circumstance that close to the critical point the Prandtl number at the pseudocritical point approaches infinite values facilitates the selection of appropriate pressures for establishing a similarity by virtue of the Eq. (5) and its consequences represented by Eq. (17).

As it will be also shown later in this paper, at the time of writing some evidence is being provided by continuing work that an even more suitable choice of pressures with respect to the ones reported in Figs. 4 and 5 for the data by Kline [29] may be possible, considering average values of the Prandtl numbers over any specifically addressed enthalpy window.

3. RANS calculations and discussion of their results

The RANS analyses presented hereafter were performed by following (or rather establishing) the similarity rules reported as guideline for future applications in the next section. The adopted CFD code is STAR-CCM+, in one of its latest versions [30], and the turbulence model is the k-ε low-Reynolds one by Lien [31], modified by the adoption of available user features, equipping it with an additional transport equation necessary for the use of an Algebraic Heat Flux model (AHFM) (see, e.g., [20,22,23] for details). The discretisation techniques are typical of the applications of low-Reynolds number models and are quite the same as described in previous mentioned works, in which the reader can find thorough descriptions.

In short summary, the STAR-CCM+ code has been used with the mentioned low Reynolds number model in a two-dimensional axial-symmetric geometry, assuring the constraint of $y^+ < 1$ at the wall by a proper refinement of the meshes in a “prism layer” region. The numbers of nodes in the radial and axial directions were adapted according to the length of the addressed pipes and the
diameter, following the experience gained in the mentioned previous works. The segregated flow model was used for the solution of the coupled pressure and velocity equations together with the energy balance equation. Second order advection was used as in the default options of the code for most of the equations. A passive scalar equation was introduced to represent the transfer of the averaged square temperature fluctuations, while an algebraic equation was used for its dissipation. Again, for further details the reader may consider references [20,22,23].

The reference experimental data were selected to represent different degrees of deteriorated heat transfer conditions, being in general the toughest ones to be correctly predicted by CFD models and represented by similarity principles. They belong to sets of data already addressed in past analyses with the same model, the mentioned ones by Watts [28], related to water at 25 MPa, and those by Kline [29], obtained with carbon dioxide at 8.35 MPa. The selected calculation cases were identified among those showing some of the best experiment to CFD model comparisons possible to date in this field.

The comparisons in dimensional form of model results and experiments is reported in Figs. 6, 11 and 16, showing a good agreement, while Figs. 7–10, Figs. 12–15 and Figs. 17–22 report the corresponding “similar” calculation results in dimensionless form. These results were obtained by a trial and error procedure aiming at identifying the value of heat flux providing the best comparison among fluids. This procedure is needed as a consequence of the mentioned uncertainty in the exponent to be adopted for the Prandtl number in a suitable heat transfer correlation, leading to expressions as the one reported in Eqs. (5) and (17). As it was mentioned in the previous section, in fact, the exponent \(-1/3\) for the Prandtl number may depend on the adopted turbulence model, as well as on the reference value considered for this parameter (e.g., at the inlet, average in the channel, etc.) and an experimental validation over a conveniently broad set of experimental data specifically performed in similar conditions for different fluids would be necessary in order to assess it.

The following comments apply to the obtained results. The experimental cases shown in Fig. 6 exhibit different levels of heat transfer deterioration for a same heating flux and inlet temperature. The higher deterioration is observed at the lowest mass flux, confirming a rather obvious relevance of the power-to-flow ratio in causing the phenomenon and determining its extent. The predictions obtained by the code are in reasonable agreement with experimental data and represent a good quantitative and qualitative depiction of the observed trends. This represents a good basis for a reliable discussion of similarity in front of the available experimental data though, as already noted, even wrong predictions by models may show similar predicted trends for different fluids, in the case in which proper similarity principles are defined. Figs. 7–9 illustrate the high sensitivity of the deterioration phenomenon to slight changes in the heat flux when searching for similar behaviour for the most deteriorated of the two experimental cases. This effect, to be considered as an inherent feature of the deteriorated heat transfer phenomenon, shown also by experimental data, represents a challenge in the design of experimental facilities aiming at reproducing targeted phenomena, suggesting prudence and flexibility in boundary conditions to adapt them in...
the achievement of the expected or requested results. As an overall consideration, owing to the adopted similarity rules, suitable values of the heat flux can be always identified to achieve similarity of the trends of the dimensionless specific enthalpy at the wall for the four fluids, obtaining a good representation of the phenomena observed for water. It must be noted that the fluid pressures adopted for CO₂, NH₃ and R23 were kept the same as in [24], though they could have been better optimised on the basis of the new criterion based on the molecular Prandtl number values.

Fig. 10 reports in a single chart the final trends obtained for the three fluids by iteration on the heat flux for the less deteriorated case of Fig. 6. The results again show a very good level of matching from both the qualitative and the quantitative points of view among the curves of wall dimensionless specific enthalpy for the four fluids, confirming again the adequacy of the “similar” imposed boundary conditions.

While the cases in Fig. 6 refer to values of bulk and wall temperature well below the pseudocritical value, one of the two cases Fig. 11, owing to a larger inlet temperature, exhibits a more severe heat transfer deterioration, with a temperature excursion beyond this threshold. This case is of particular interest in view evaluating the effectiveness of the present similarity theory since, as already noted, the ratios of the Prandtl numbers of water and of the other fluids are not uniform across the pseudocritical threshold, with much similar values observed in the gas-like phase. This is shown in Fig. 2 and is further evident in the normalised form reported in Fig. 3, suggesting that an accurate basis for achieving similarity may be lacking in the gas-like region.

Nevertheless, the results presented in Figs. 12–14 show a quite similar behaviour, though in the case of CO₂ and R23, the fluids having a larger difference in the molecular Prandtl number with respect to water, oscillations in the predicted wall temperature trends appear which have no real similarity with the water predicted and observed trend. This is much less the case of ammonia,
having a Prandtl number closer to the one of water in the considered range.

The milder deterioration observed for the second case in Fig. 11 keeps the values of specific enthalpy at the wall below the pseudocritical value, a case for which an almost perfect scaling is possible (see Fig. 15).

The two experimental cases reported in Fig. 16 from the carbon dioxide database by Kline [29] were selected both for the good prediction obtained by the adopted model (see [23] for a thorough discussion of model capabilities and limitations in relation to these data) and because they represent bounding phenomena. On the one side, the case with lower inlet temperature exhibits a severe deterioration, beyond the pseudocritical threshold, with wall temperature oscillations and the occurrence of a final recovery of heat transfer at the transition to the gas-like phase (see [23] for a discussion of the phenomenon). The second case is instead characterised by the lack of deterioration phenomena, since the inlet subcooling is very low and buoyancy forces have not enough strength to produce laminarisation and the subsequent deterioration. So, both cases address the gas-like fluid region, where the present rationale for similarity could fail.

Actually, this does not seem to be completely the case since the trends shown in Figs. 17–22 for fluids other than CO₂ display exactly the same phenomena observed in the experiment, with just some quantitative deviation at a level that is fully expected for the usual approximations involved in similarity theories. In particular, it is remarkable the prediction of the onset of deterioration, of the consequent oscillations in wall temperature, observed even at a larger extent in the experiment, and of the final restoration at the transition to the gas-like region for all the considered fluids, in the case with lower inlet temperature (Figs. 17–19). Also the results obtained for the case with higher inlet temperature, whose evolution is mostly in the gas-like region, are in line with expectations from both the qualitative and the quantitative points of view (Figs. 20–22). This confirms that accepting a lower degree of fi-
Fig. 20. Dimensionless enthalpy trends at different values of the heat flux. Reference Case – CO$_2$ 8.35 MPa, G=300 kg/m$^2$s, $T_m$=35°C, $q^*=20$ kW/m$^2$

Fig. 21. Dimensionless enthalpy trends at different values of the heat flux. Reference Case – CO$_2$ 8.35 MPa, G=300 kg/m$^2$s, $T_m$=35°C, $q^*=20$ kW/m$^2$

Fig. 22. Dimensionless enthalpy trends at different values of the heat flux. Reference Case – CO$_2$ 8.35 MPa, G=300 kg/m$^2$s, $T_m$=35°C, $q^*=20$ kW/m$^2$

delity in the bases for similarity in the gas-like region may result tolerable in view of achieving reasonably similar trends.

Fig. 23 finally displays the results obtained in this work by the trial and error procedure for determining the most appropriate value of heat flux and the corresponding scaling factor for L/D, as a function of the ratio of the inlet values of the Prandtl number for the different fluids. As it can be noted, these data match very well with those from the previous paper (labelled P&A 2016) [24] and with the $-1/3$ power law obtained from them. Again, it must be remarked that the value of this exponent can be only guessed at the moment, basing on the presently adopted turbulence model and asking for an experimental assessment to be reliably established. In addition, it must be noted that the plot is representing data as a function of the inlet value of the ratio between the Prandtl numbers, while a more meaningful representation could be made on the basis of averaged values of this ratio along and across the channel.

In order to consider the level of similarity obtained in the different cases, Figs. 24 and 25 present the comparison of the radial trends of dimensionless enthalpy and normalised velocity obtained for water and CO$_2$, by far the most interesting cases for applications, for two reference cases by Watts and by Kline. As it can be noted, the comparison is reasonable in both cases, though it is better for the case by Watts.

In order to understand how much the choice of the reference pressure may have an influence on the quality of the obtained similarity, the reference case by Kline showing a greater deterioration ($T_m=24°C$) was reconsidered at a pressure at which the peak Prandtl numbers for water and CO$_2$ are the same. As it can be noted in Fig. 26, the predictions improve considerably with respect to those reported in Fig. 17 suggesting that the choice of the dimensionless specific enthalpy window in which the Prandtl number ratio can be considered nearly constant or constant in an average should be given great attention. This offers matter for further refinements in the application of the present similarity theory, being performed in work that is ongoing at the time of writing.

4. Summary of the similarity rules

After the discussion of the basic principles at the root of the above proposed choices and presenting what are believed to be convincing results, we are now in the position to list the phases of the methodology to be applied for establishing the fluid-to-fluid similarity between a reference case and one or more other simulant fluid cases. At the moment, this must not be considered a precise procedure for establishing similar conditions, but just as a collection of guidelines to be further assessed by computations and to be validated by experimental activities before being fully relied upon. Moreover, as for any similarity theories, only approximate results can be expected owing to distortions with respect to ideal behaviour. In the present case, the highly nonlinear behaviour of fluids at supercritical pressure further adds uncertainties as a consequence of the high sensitivity shown by phenomena.
1 **Select the operating pressure.** In this purpose, the rationale just described in the previous sections should be applied in order to find a pressure of the simulant fluid at which a sufficiently uniform ratio between the Prandtl numbers of the fluids is observed in the region of dimensionless specific enthalpy addressed in the test. For a trans-pseudocritical case (i.e., a case in which the specific enthalpy in bulk or at the wall crosses the pseudocritical threshold), the liquid-like region could be privileged with respect to the gas-like one, because it is hardly possible to satisfy this criterion in both regions and whenever it is found that the former is more important for the onset of excursive phenomena as deterioration. However, as shown in the previous section, this aspect must be looked at with due care, e.g. by computations as in the present work, assessing the best pressure to be selected for the targeted phenomena in a specific window of dimensionless enthalpy. Work to further assess the best strategy with respect to the selection of pressure is presently in progress considering a wider basis of data to provide better guidance in the future especially for trans-critical cases. This work will suggest the best criteria for pressure selection for trans-pseudocritical cases that are now only guessed.

2 **Assign the inlet temperature.** This must be done by equating the dimensionless specific enthalpy at the inlet for the two cases, i.e. applying the same $N_{SPC}$.

3 **Select the values of the pipe diameter and of the inlet velocity.** Making use of Eqs. (10) and (11), impose the same inlet Froude and Reynolds number values. As an alternative to be considered with better experience than at present, especially coming from experiments, it might be decided to preserve the average value of the Reynolds number instead of the value at the inlet; this aspect needs further considerations to be assessed. On the contrary, as already shown, imposing the Froude number at the inlet in steady-state conditions assures its preservation in perfect similarity all along the pipe, as well as the preservation of Richardson number.

4 **Identify the reference length over diameter ratio.** Making use of Eqs. (5) and (17), determine the appropriate value of the $L/D$. Here a word of caution must be introduced in relation to the exponent of the Prandtl number to be used. The suggested $-1/3$ value is coming from computations and may be not fully adequate in all the cases, especially when considering values of Pr that may change too much, to establish a reasonable, though approximate, equality. In this regard, as shown in our computations, it is prudent to allow for a longer test section than strictly indicated by Eq. (5) (or Eq. (17)), in order to make possible changes of the heating flux while preserving the $N_{SPC}$ without having to change it at any iteration. This provision holds for both experimental activities and calculations, avoiding to make serious mistakes “in defect” that may waste money

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**Fig. 24.** Comparison of the radial profiles for water and CO$_2$ for the reference case of Watts. Water 25 MPa, 25.4 mm ID, $T_{in} = 200^\circ$C, $q' = 250$ kW/m$^2$, $G = 318$ kg/(m$^2$.s), upward flow.

**Fig. 25.** Comparison of the radial profiles for CO$_2$ and water for the reference case of Kline. CO$_2$, 8.35 MPa, $T_{in} = 24^\circ$C, 4.6 mm ID, $G = 300$ kg/(m$^2$.s), $q' = 20$ kW/m$^2$, upward flow.
and/or time: in fact, longer test sections maybe only partly significant, but they can contain the region with the wanted phenomena while, vice versa, having a too short test section may not allow to see phenomena which are expected. Again, a further word of caution must be introduced on the evaluation of the ratio of the Prandtl numbers, here chosen at channel inlet for a quick reference but whose determination in trans-pseudocritical cases may require more complex reasoning.

5 Iterate on the heating flux. Aware of the above mentioned problems and uncertainties, change the heating flux and the exact L/D ratio to find the best agreement with the expected phenomena, while preserving the \( N_{TPC} \). This iterative procedure is necessary because, especially for the conditions leading to deterioration, limited changes may result in substantially different behaviour. This step is obviously fundamental in order to establish the accurate boundary conditions, whenever a reference case to be reproduced by calculations or by an experiment has been defined. Of course, in experiments such a trial and error is possible if the experimenter has in mind a reference phenomenon or a target trend of wall temperature.

5. Conclusions

Achieving a successful theory for fluid-to-fluid similarity at pressures beyond the critical threshold has been the goal of researchers, including the present authors, for several decades. The first suggestions in regard were based on the critical thermodynamic parameters for proposing dimensionless variables and were not found sufficiently attractive for grasping the main observed phenomena. The rationale presented in this paper seems to be quite successful at least in front of RANS calculations, which show very promising features, with high fidelity descriptions of the addressed phenomena in close similarity for different fluids.

The present paper and the previous one in Ref. [17] present coherent findings and considerations about the bases for scaling different fluid parameters at supercritical pressure. The most relevant idea at the basis of the present rationale is to preserve the same expansion capabilities of the fluids along a heated pipe, thanks to the universal link observed between the dimensionless density and specific enthalpy that is the most helpful feature we made use of herein. In this regard, it must be stressed that trends as the ones shown in Fig. 16 for the data by Kline [29], exhibiting a full range of phenomena from the onset of deterioration to the final restoration at the transition to gas-like conditions, would not be predicted in so close similarity for such different fluids without correctly accounting for fluid expansion on the basis of the preservation of \( N_{TPC} \) and \( N_{SP} \).

The theory presented in this paper is mostly the same proposed in [24] and elaborated in the PhD thesis of Dr. Pucciarelli [18]; now, this theory is proposed in a more refined version after developments that made the awareness about its sound bases to grow and made it more friendly to be understood and used.

The achieved results will hopefully facilitate setting up engineering correlations for heat transfer capable to predict the onset of deterioration and the consequent deteriorated heat transfer phenomena, something still difficult in the present state-of-the-art. This hope is based on the fact that the adopted rationale was capable to preserve qualitatively and quantitatively the description of full trends 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. If these results can be confirmed by other researchers, something on which we have very little doubt, efforts can be focused on developing the consequences of the presented theory on various modeling aspects still requesting better understanding.

While waiting for an experimental confirmation of the proposed scaling principles, it is wise to plan for a further validation and refinement of this theory that is now general enough to allow for a thorough assessment. This work of further study and assessment represents the ongoing activity of the authors and their collaborators at the present time.

Role of the authors

The authors shared ideas and commonly contributed to establish the basis for the presented material in multiple brainstorming meetings in presence and in the distance, making their awareness about the phenomena being addressed to grow up to the establishment of a coherent theory. In particular, starting from first ideas published in [15], the precious work of Dr. Pucciarelli in performing more refined RANS calculations than presented in that paper and his further suggestions made it possible to check and correct assumptions, leading to the presented general rationale.

Dedication

The present paper and the related computations have been prepared operating in the distance in the period from the end of March to mid May 2020, when Italy was in a strict lockdown because of the COVID-19 pandemic. Beyond any merely rhetoric purpose, the authors wish to dedicate this effort to the tens of thousands who died in that period in Italy, together with the more many who died worldwide, and to those who were desperately trying to heal them, while they could sometimes just witness their tragedy. We hope that, though this work was hardly useful in any way for helping these persons during the dark days of lockdown, it may result a bit useful in the future to develop an even safer and more reliable nuclear energy, thus sustaining the welfare and health of humankind in the centuries to come.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Andrea Pucciarelli: Investigation, Formal analysis, Writing - review & editing. Walter Ambrosini: Conceptualization, Supervision, Writing - original draft, Writing - review & editing.
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