EXTENDING A FLUID-TO-FLUID SIMILARITY RATIONALE FOR HEAT TRANSFER AT SUPERCRITICAL PRESSURE TO R134a

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ABSTRACT

In the frame of the development of Gen-IV supercritical water reactors (SCWRs), making use of the experimental data collected so far by different fluids in view of simulating the behavior of water is an important and very useful step. However, conducting experiments with simulant fluids poses the problem of establishing a clear rationale for inferring the expected water behavior from the information gathered with other fluids.

In literature, several attempts have been made to suggest dimensionless groups to be preserved in establishing a similarity. However, difficulties were encountered in getting appreciable success from these attempts and relevant reviews declared a generally unsatisfactory behavior of available theories.

Recently, some of the authors of this paper were able to demonstrate the good success of their proposal for a fluid-to-fluid similarity theory addressing mainly four relevant fluids being water, carbon dioxide, ammonia and R23. In the frame of the EU ECC-Smart Project, the refrigerant R134a will be used as a simulant fluid for performing experimental analyses in support to the achievement of the project objectives. Hence, the present paper is aimed to show the capabilities of the similarity theory when applied to R134a, proposing a rationale to be used in selecting the boundary conditions of experiments in order to make them really representative of the addressed water plant conditions.

Keywords: Place Supercritical pressures, R134a, Heat Transfer, fluid-to-fluid similarity

NOMENCLATURE

D	pipe diameter [m]
Fr	Froude number
h	specific enthalpy [J/kg]
L	pipe length [m]
N_{TPC}	trans-pseudocritical number
Nu	Nusselt number
Pr	Prandtl number
q''	heat flux [W/m^2]
Re	Reynolds number
St	Stanton number
β	Isothermal expansion coefficient [1/K]
ρ	Density [kg/m^3]
C_p	Specific heat at constant pressure [J/(kgK)]

Superscripts

*	starred variables are dimensionless
-	overbar quantities are averaged between bulk and wall values

Subscripts

w	wall

1. INTRODUCTION

The use of supercritical pressure water (SCW) in nuclear power plants was first explored in the 1960s. Since the years 2000, there is a renewed interest in developing the Super-Critical Water-cooled Reactor (SCWR) to improve the economic, safety, proliferation resistance and sustainability of the current generation of nuclear systems. A collaborative effort has been established for Research and Development (R&D) in support to the development under the Generation-IV International Forum (GIF) [1]. Thermal-hydraulics has been identified as one of the critical knowledge areas for the SCWR development and there are extensive efforts devoted to understand heat transfer,

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hydraulic resistance, stability and critical flow phenomena having a strong impact on the design of the core.

Thermophysical and transport properties of SCW undergo sharp and non-linear variations in the vicinity of the pseudo-critical temperature. In view of the lack of phase change, a fluid at supercritical pressure is considered a single-phase fluid with associated single-phase heat transfer characteristics in a heated channel. However, the mentioned sharp variations in the thermophysical properties in the vicinity of the pseudo-critical point challenge the application of the existing heat transfer correlations.

In literature, many studies were conducted for further investigation on heat transfer with supercritical pressure fluids using water, CO_2 and refrigerants [2-3]. Heat Transfer Deterioration (HTD) was observed at relatively low mass fluxes or high heat fluxes with a rapid increase in the wall temperature. Notwithstanding the availability of experimental heat transfer data at supercritical pressures, the physical mechanisms of the HTD phenomena are still not fully understood; hence, the need for additional heat transfer experiments with fluids at supercritical pressures and for elaborating a better understanding of the available experimental information.

In the light of this demand, some of the authors of this paper developed a rationale for a fluid-to-fluid similarity theory trying a better use of information obtained with simulant fluids in place of water. It is in fact believed that the establishment of a rationale for heat transfer similarity between two fluid conditions, with the aid of the correct dimensionless parameters, will make clearer how to set up suitable heat transfer correlations for predicting the relevant observed phenomena.

In the development of the present similarity theory, Reynolds-averaged Navier–Stokes (RANS) calculations were adopted based on the standard k-ε Lien model [4] implemented in the STAR-CCM + code [5] with the addition of an algebraic heat flux model (AHFM) [6]. This work was developed and supported by comparisons with different experimental data, among which those by Watts [7], by Pis'menny [8] and lately by Kline [9].

Recently, the EU ECC-SMART project was initiated, aimed to establish R&D studies for the design of a Small Modular Reactor (SMR) cooled by supercritical water. In the frame of this project, R134a will be used as a simulant fluid for performing various kinds of experimental analyses in support to the achievement of the project objectives. As a consequence, the objective of the present paper is to better highlight the main features of the similarity theory, to clarify some up to now uncertain aspects and to show its capabilities when applied to R134a. This will support the proposal of a rationale to be used within the project in order to select the boundary conditions of experiments in order to make them as far as possible representative of the addressed water cooled plant conditions.

Starting with carbon dioxide data already analyzed with success in previous work [10], [11], by showing their relation to postulated water conditions, the corresponding R134a cases are here identified, showing similar trends in the range of the operating pressures proposed for the experiments to be run in the frame of the ECC-SMART project.

2. CHARACTERISTICS OF THE REFRIGERANT R134a

Although R134a is known for its moderate critical parameters and stability, there are less studies with R134a compared with water and CO_2. Experimental studies, such as the ones by Kline [9] and Watts [7], have shown that the significant property variations, shown in Fig. 1 for R134a, can lead to abnormal heat transfer phenomena, with heat transfer enhancement or deterioration depending on the operating conditions. As most heat transfer correlations were developed based on experimental data having limited parameter ranges and also due to the complexity of supercritical heat transfer, the work by Zhang et al. [12] showed that the water based correlations exhibited large deviations with experimental data for R134a, especially as the enthalpy approaching the pseudo-critical point. This discrepancy can be attributed to the difference in the thermophysical properties.

The rationale developed by some of the authors of this paper in the last years [2-5] enabled to demonstrate a good success in establishing a fluid-to-fluid similarity theory aiming to compare the behavior of simulant fluids in place of water. Moreover, in the latest work by the authors [11], the identified dimensionless groups were found very effective for both fluid-dynamic aspects and heat transfer, allowing to demonstrate, at least on the basis of CFD RANS calculations, a very good representation of relevant phenomena. For instance, normal and deteriorated heat transfer, together with heat transfer restoration after deterioration, were predicted in strictly close similarity for four fluids being water, carbon dioxide, ammonia and R23.

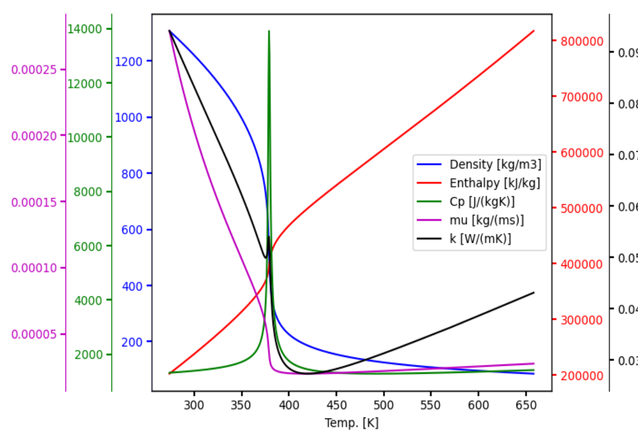

FIGURE 1: Thermophysical properties for R134a at p= 4.47 MPa using property package Refprop7 by NIST [15].

Hence, for the sake of generalization of the proposed fluid-to-fluid similarity theory, further analyses using R134a fluid are performed, to be used in selecting the proper boundary conditions for the experiments. This work is developed and supported by comparisons with Kline's experimental data due to its wide range of wall temperature excursions, below and above the pseudocritical threshold.

3. THE SIMILARITY THEORY AND THE ADDRESSED EXPERIMENTAL DATA

As previously discussed in [10] and [13], two fluids are considered similar in view of the present rationale when the spatial distributions of the dimensionless enthalpy in the channel are the same or nearly the same. This is thankfully owing to a nearly universal trend of dimensionless density as a function of dimensionless enthalpy holding with limited discrepancies for the fluids investigated up to now and in a wide range of supercritical pressures. In this context, the dimensionless density and the dimensionless specific enthalpy are defined as $\rho^* = \rho / \rho_{pc}$ and $h^* = (h - h_{pc}) \beta_{pc} / C_{p,pc}$, where the subscript "pc" refers to the pseudocritical conditions at any pressure [14].

R134a is found to have a slightly different behavior in this relation between dimensionless density and dimensionless enthalpy that was found approximately valid for water, CO_2 and R23 in previous work. As shown in Fig. 2, in the liquid like region, this discrepancy in comparison with water provides a lower dimensionless density at a same subcooling with respect to pseudocritical conditions. This may result in different fluid acceleration and buoyancy effects, which may lead to different heat transfer phenomena, among which an onset of heat transfer deterioration occurring in different conditions.

The main steps for achieving similarity are discussed in [10]; they are not repeated here for the sake of brevity. We just mention that:

- to obtain similarity it is crucial that the same inlet pseudo-subcooling and the same change in dimensionless bulk enthalpy is imposed;
- the Froude and the Reynolds numbers must also be equal at the inlet;
- the operating pressures must also be scaled according to a rationale which considers the values of the Prandtl and the Stanton numbers along the channel;
- iterations on the heating flux and the length-over-diameter ratio must be performed aiming to achieve the same dimensionless enthalpy at the wall, as well as in bulk.

Two different strategies in choosing the operating pressure can be followed, as discussed in the latest work by the authors [11]; however, choosing similar values of the Prandtl number at the peak was found to be the best strategy when simulating Kline's data. Hence, in this paper the same strategy is followed in order to choose the proper operating pressure for R134a while addressing the same data. Figure 3 shows the trend of Pr number for the reference case by Kline, CO_2 at 8.35 MPa, where the fluid R134a at p=4.47 MPa has almost the same value of the Pr number at the pseudo-critical point.

The addressed experimental data are taken from the work by Kline [9] in the Super Critical University of Ottawa Loop (SCUOL) facility for CO_2 flowing upwards in electrically heated vertical tubes at supercritical pressures of about 8.35 MPa. The numerical analysis performed in this work involved 18 reference experimental cases that correspond to 6 different inlet temperatures (0, 6, 16, 24, 33, 35 °C) and 3 different wall heat fluxes (15, 18 and 20 kW/m^2). First of all, a CFD validation of the adopted RANS model is performed using the experimental data in order to soundly base the outcomes of the present similarity theory on a credible CFD model application.

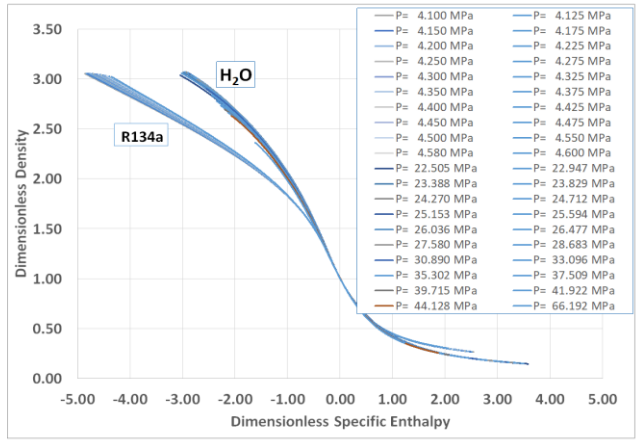

FIGURE 2: Comparison of dimensionless density trends as a function of dimensionless enthalpy for water and R134a.

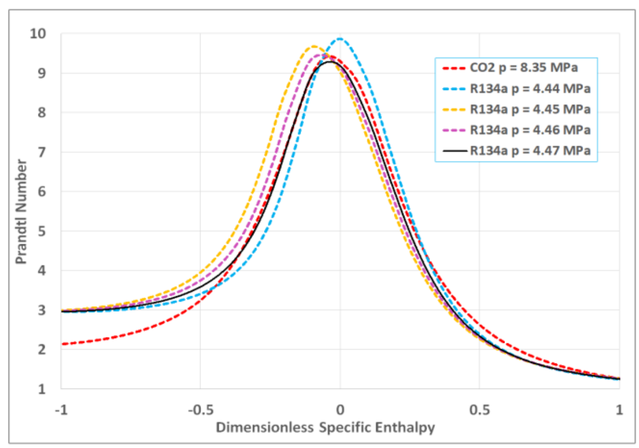

FIGURE 3: Values of the Prandtl number at different pressures for analyzing Kline's data using R134a.

The analysis considers five different fluids, being water, CO_2, ammonia, R23 and R134a. The optimization of the value of the heat flux, *q"*, resulted in few hundreds of calculations to be performed using the STAR-CCM+ code with a 2D RANS model already used in recent works, based on the Lien k-ε low-Re turbulence model with the use of an Algebraic Heat Flux Model (AHFM) (see previous works for details). All the needed fluid properties were obtained using the REFPROP-7 software by NIST [15].

4. SUMMARY OF PREDICTIONS OF KLINE'S DATA

The main outcomes of the proposed theory can be discussed by first considering the trends of the dimensional parameters along the heated channel as predicted in a previous work [11].

Figures 4 to 6 present the comparison between calculated and experimental values of wall temperatures for the experimental data by Kline at heat fluxes 15 ,18 and 20 kW/m^2 and mass flux G =300 kg/m^{2}s at different inlet temperatures. The RANS model managed to predict the different phenomena occurred along the channel with reasonable accuracy. It is important to mention that, due to the complexity of the phenomena at supercritical pressures, the adopted CFD model has some discrepancies compared to the experimental data as can be seen in Fig. 4 at the inlet temperature 16 °C, where it predicts a deterioration at the exit of the channel. However, in most of the addressed cases the model predicted in a good way the various phenomena occurring along the channel, as normal and deteriorated heat transfer, up to the final restoration of heat transfer for a gas-like fluid.

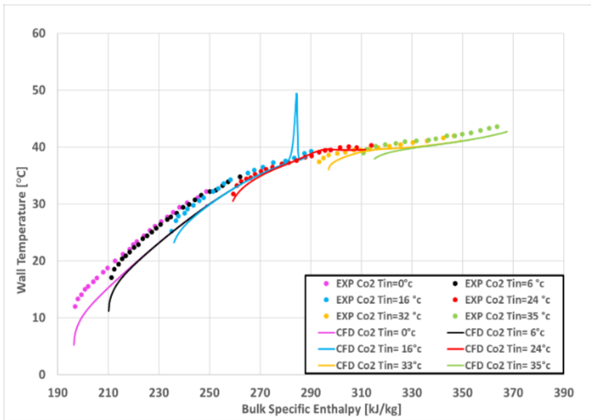

FIGURE 4: Trends of the wall temperature along the channel, Reference cases by Kline at *q'' = 15 kW/m²*.

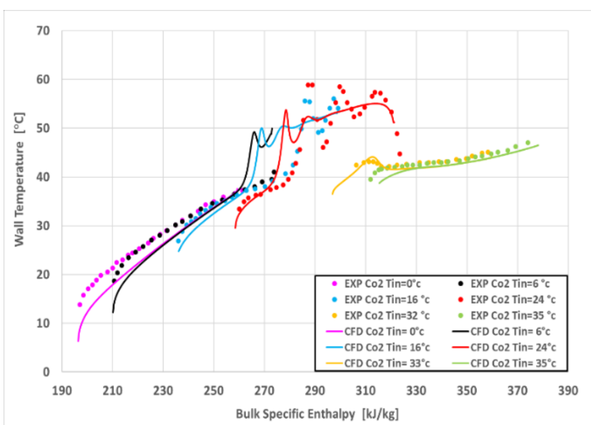

FIGURE 5: Trends of the wall temperature along the channel, Reference cases by Kline at *q'' = 18 kW/m²*.

The differences between the numerical predictions and the experimental ones are mainly due to the sensitivity of the phenomena and to the limited capabilities of the model. In particular, for some heat fluxes, the code anticipated the onset of the heat transfer deterioration, as in the cases of Fig. 5 with inlet temperatures of 16 and 24 °C. From the physical point of view, this may be interpreted as an anticipation of the effect of the buoyancy force due to the large density difference between the near wall fluid and the bulk fluid, leading to local heat transfer deterioration in upward flows, with the flow pattern changing to mixed convection.

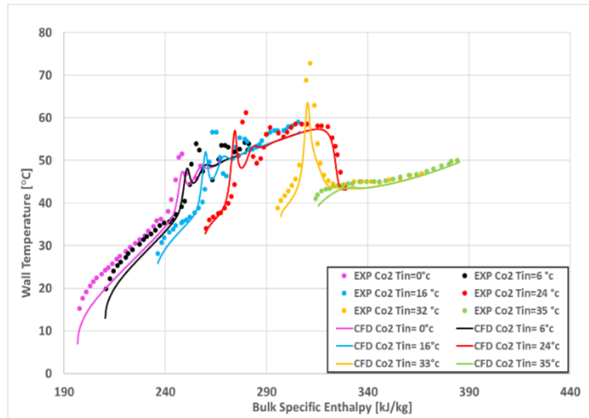

FIGURE 6: Trends of the wall temperature along the channel, Reference cases by Kline at *q'' = 20 kW/m²*.

5. SCALING WITH R134a

Several scaling attempts using R134a were performed in order to reproduce the data by Kline when subjected to "similar" boundary conditions. In particular, Fig. 7-9 show the wall temperature trends evaluated via the similarity theory for R134a at 4.47 MPa, the pressure selected for this analysis. The close qualitative similarity with the phenomena experimentally observed with CO_2 observed in most of the cases (compare with Figures 4 to 6) can be considered a further success of the present theory showing how Kline's data would behave if the experiments were made with the R134a in "similar" conditions.

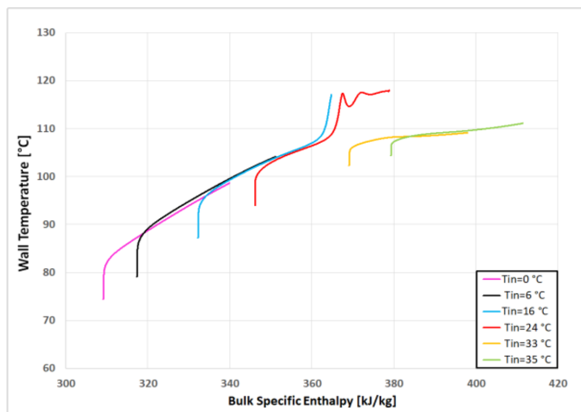

FIGURE 7: Trends of the wall temperature along the channel, RANS calculation with R134a for reference cases by Kline at *q'' = 15 kW/m²*.

Nevertheless, some differences can be noted suggesting that the behaviour of R134a is predicted to be somehow different from the one of CO_2. For instance, in Fig. 7 deteriorated heat transfer is predicted for some inlet temperatures, while this is not the case in the original CO_2 data (see Fig. 4). These differences may be due to the only partial match that the dimensionless trend of density has a function of dimensionless enthalpy for this fluid with respect to water.

It is now interesting to consider a set of dimensionless parameters that reflect some of the outcomes of the similarity theory. This information is presented in the figures below integrating the charts already obtained for four different fluids in a previous work [11] with the new data achieved for R134a.

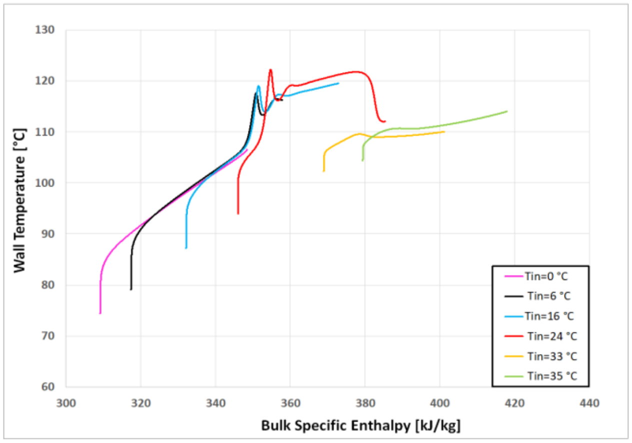

FIGURE 8: Trends of the wall temperature along the channel, RANS calculation with R134a for reference cases by Kline at *q" = 18 kW/m²*.

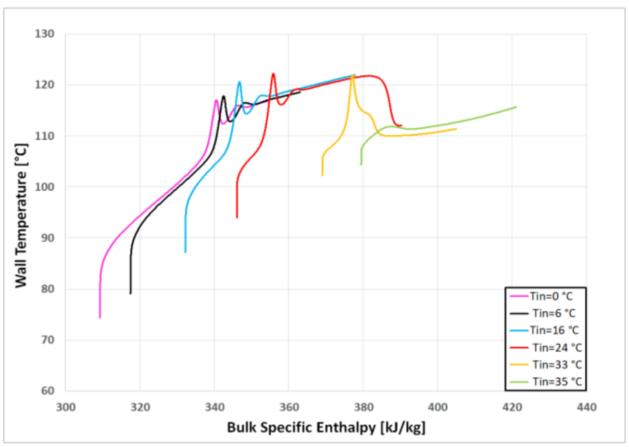

FIGURE 9: Trends of the wall temperature along the channel, RANS calculation with R134a for reference cases by Kline at *q" = 20 kW/m²*.

Fig. 10-13 show comparisons for the four previously selected fluids and R134a in terms of some relevant dimensionless parameters for the reference case of Kline's data at *q"* = 20 kW/m² and two inlet subcooling temperatures 24 and 33 °C, *q"* = 18 kW/m² and inlet subcooling 16 °C and for the case with *q"* = 15 kW/m² and inlet subcooling 0 °C. The figures report in sequence the trends of the dimensionless wall specific enthalpy, of the ratio of the computed Nusselt number to the one evaluated on the basis of the Dittus-Boelter correlation (named as Nusselt ratio), of the Reynolds, the Richardson and the Froude numbers and, finally, of the group $\overline{St}\,L/D$, having a particular significance for the similarity.

It must be noted that the comparison of the trends of the dimensionless specific enthalpy at the wall represents a direct indication of the achievement of similarity, according to its definition. The Nusselt ratio instead is used in literature as an indicator of the degree of heat transfer deterioration, as the deviations in defect from unity indicate that the well-known forced convection correlation is overestimating the actual heat transfer capabilities of the fluid.

The importance of the Richardson number stems from the fact that it affects heat transfer; the higher the Richardson number the more dominant is natural convection causing a possible laminarisation with heat transfer deterioration. On the other hand, the Froude number is preserved at the inlet of the channel and it can be shown that imposing the same inlet subcooling and dimensionless power-to-flow ratio it is preserved all along the channel. So, the deviations exhibited from a common trend by some fluid give an account to their differences in the expansion trends shown by dimensionless density vs. the dimensionless specific enthalpy curve. Since the Richardson number depends on the Froude number and the difference between wall and bulk densities, corresponding deviations are caused by this discrepancy also in Ri.

It is worth to mention that, though the values of the Reynolds numbers were preserved at the inlet of the channel following the suggestion made in [6] and [13], the trends for the different fluids unavoidably depart from each other.

Although the values of Nusselt numbers are not the same, a similar heat transfer behaviour may be obtained by changing the L/D ratio over which thermal phenomena occur for fluids having different values of Stanton number, as explained in previous work [10], [11], [13] on the basis of the dimensionless form of the Newton's law for convection (Eq. 1)

$$N_{TPC} = \overline{St}\left(h_w^* - h_{bulk}^*\right)4L/D \qquad (1)$$

The trends of average Stanton number multiplied by the (*L/D*) ratio are finally confirming the extent of similarity reached by the obtained results, by virtue of the previous formula. In fact, if the bulk and wall dimensionless specific enthalpies are nearly the same, also this product should be.

6. CONCLUSIONS

The present work confirmed the sound rationale developed in applying a fluid-to-fluid scaling theory using RANS calculations. Despite the fact that the adopted CFD model has limited capabilities, it can be anyway considered a solid foundation to highlight the consequences of the adopted theory when used with different fluids. Certainly, the presented rationale is waiting to be validated against experimental data with different fluids in order to assess its capabilities.

The main outcome of the proposed similarity theory is obviously that the identified dimensionless parameters are able to allow reproducing similar results for different fluids when similar boundary conditions are applied. Special attention has to be given to organic fluids or Freons when used in experiments at supercritical pressures, due to their different thermophysical properties compared to water.

Further enhancement of the present RANS model and comparison with DNS and LES calculations are important in order to assess the present theory.

The need for heat transfer correlations that are able to predict the physical phenomena at supercritical pressures is also urgent. On this basis, it can be expected that the set of dimensionless parameters presented here can clarify the issue of establishing the most important groups necessary to be considered in setting up engineering correlations for heat transfer allowing to identify the conditions at which the important phenomena such as heat transfer deterioration may occur.

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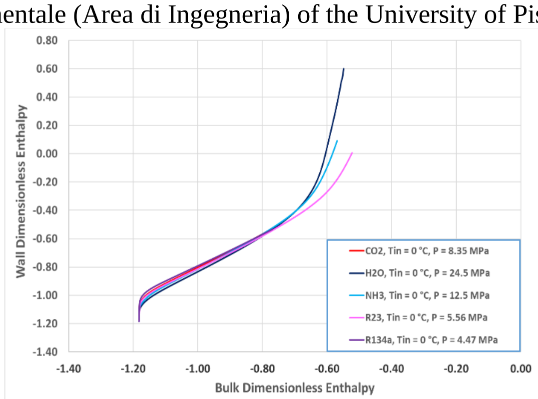
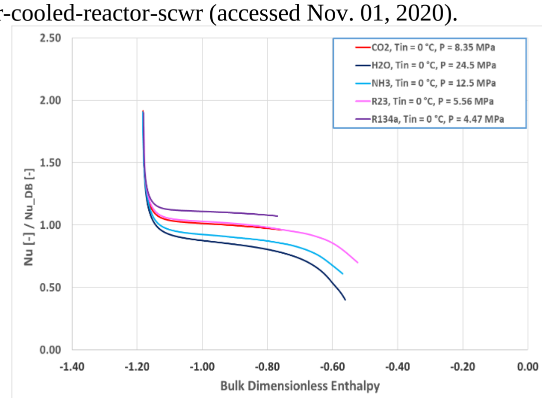
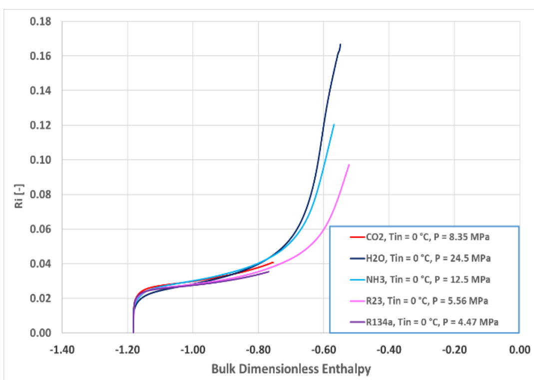


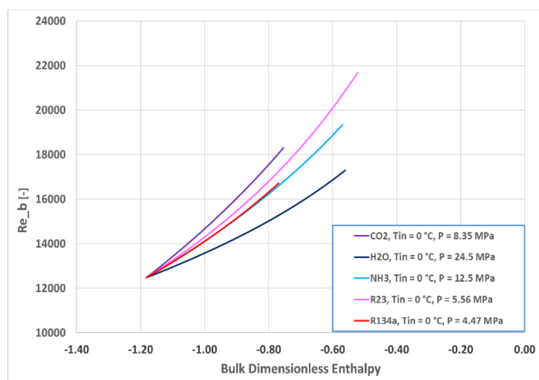
(a) Wall dimensionless enthalpy



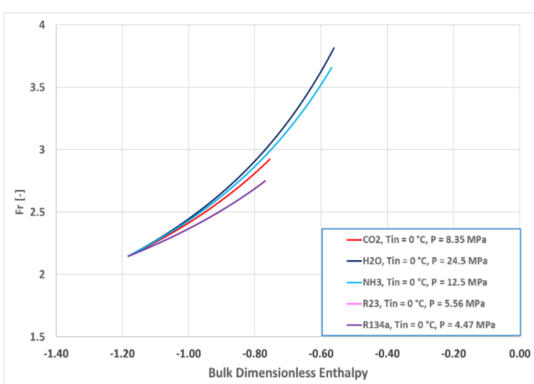
(b) Nusselt ratio



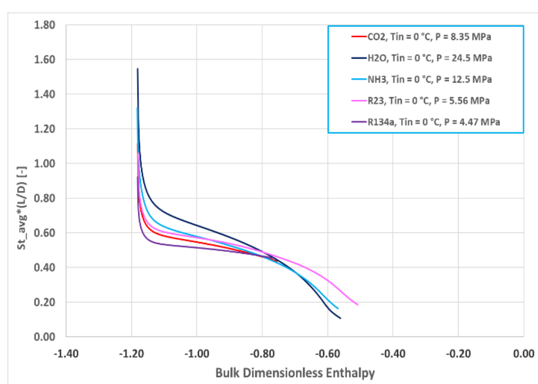
(c) Richardson number



(d) Reynolds number

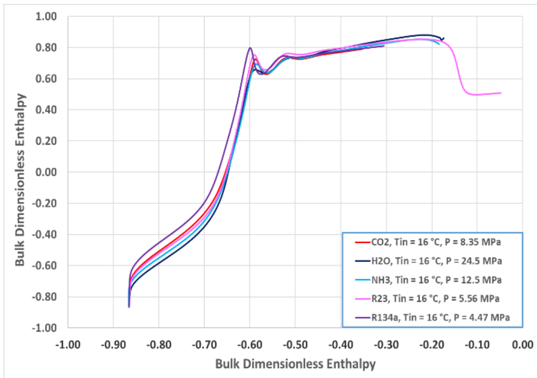


(e) Froude number

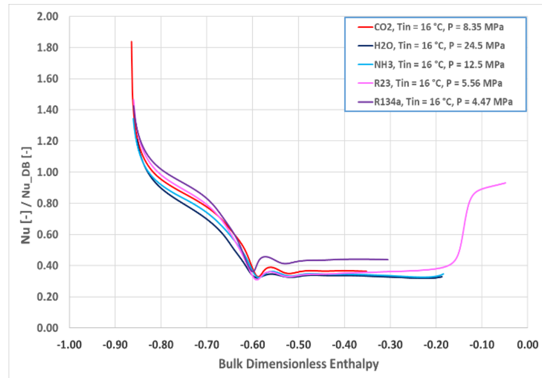


(f) $\overline{St} * (L/D)$

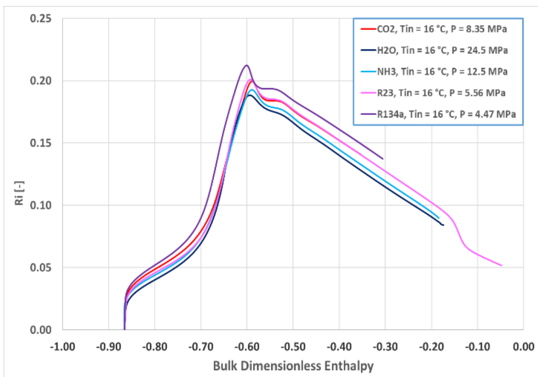
FIGURE 10: Trends of the dimensionless parameters for the reference CO_2 case at q'' =15 kW/m^2 and T_{in}= 0 °C.



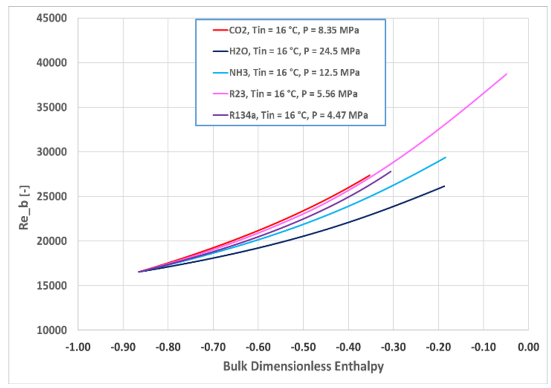
(a) Wall dimensionless enthalpy



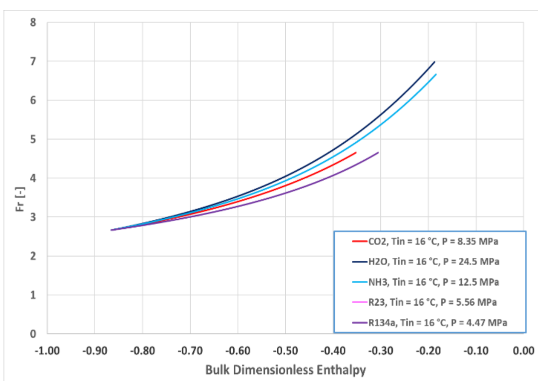
(b) Nusselt ratio



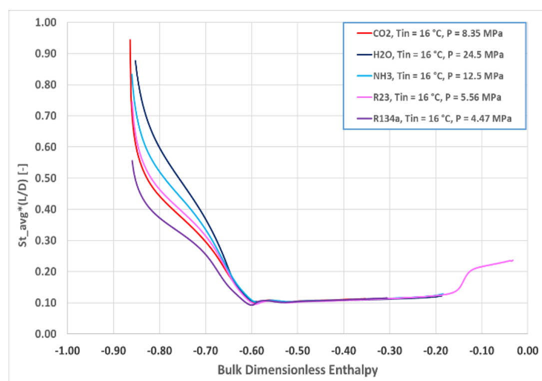
(c) Richardson number



(d) Reynolds number



(e) Froude number



(f) $\overline{St} * (L/D)$

FIGURE 11: Trends of the dimensionless parameters for the reference CO_2 case at q'' =18 kW/m^2 and T_{in}= 16 °C

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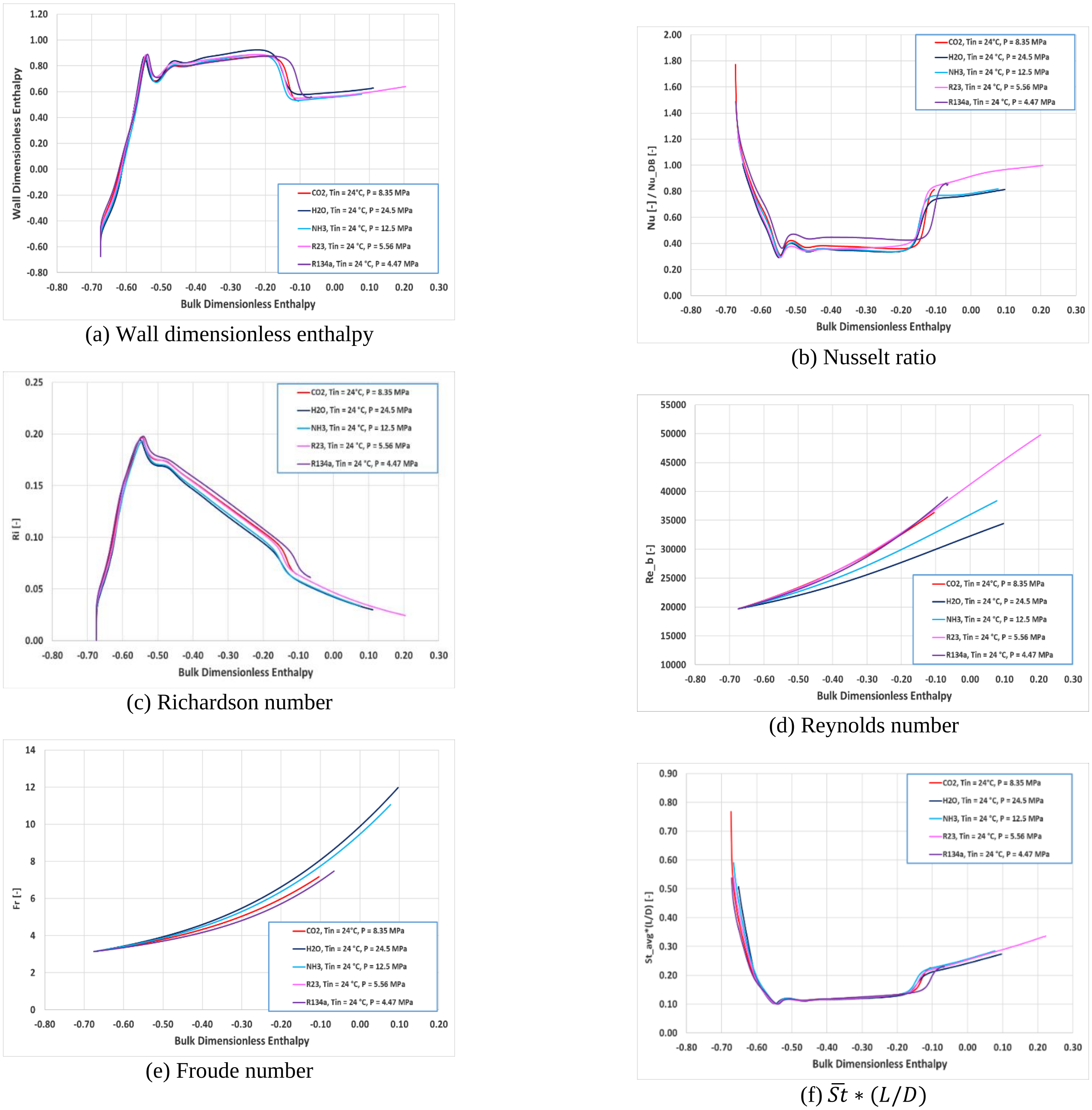

(a) Wall dimensionless enthalpy

(b) Nusselt ratio

(c) Richardson number

(d) Reynolds number

(e) Froude number

(f) $\overline{St} * (L/D)$

FIGURE 12: Trends of the dimensionless parameters for the reference CO_2 case at q'' =20 kW/m^2 and T_{in}= 24 °C.

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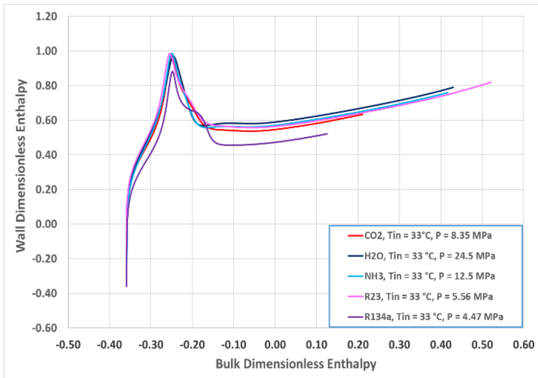
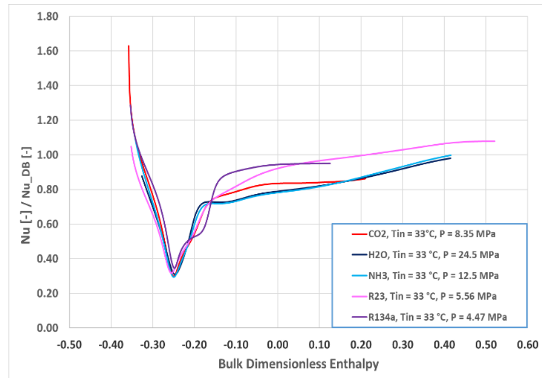
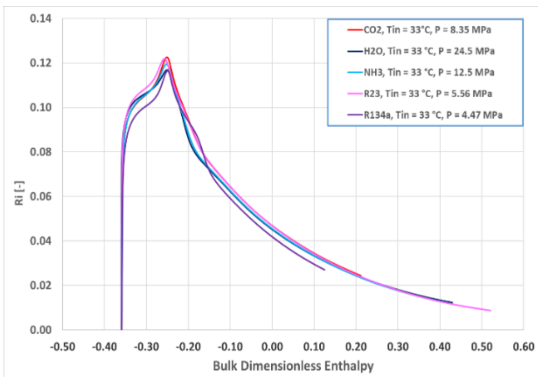


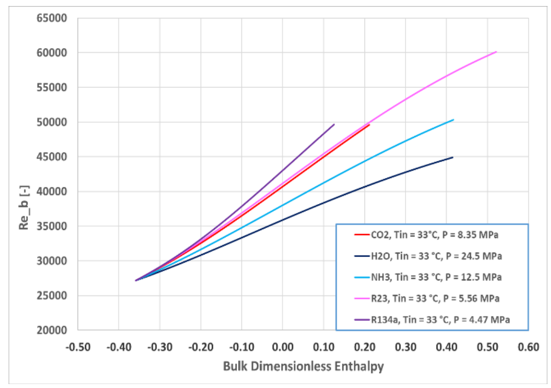
(a) Wall dimensionless enthalpy



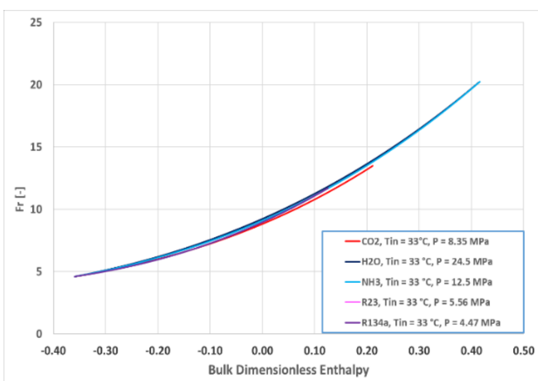
(b) Nusselt ratio



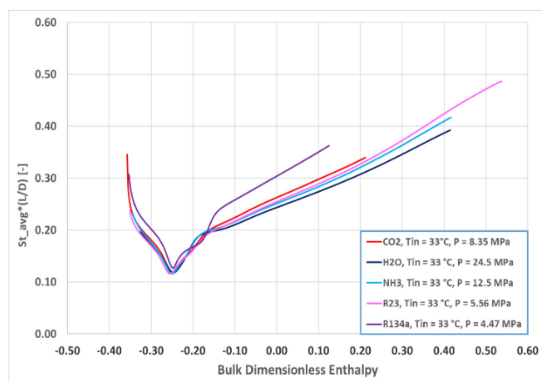
(c) Richardson number



(d) Reynolds number



(e) Froude number



(f) $\overline{St} * (L/D)$

FIGURE 13: Trends of the dimensionless parameters for the reference CO_2 case at q'' =20 kW/m^2 and T_{in}= 33 °C.

[13] A. Pucciarelli, S. He, and W. Ambrosini, "A successful local fluid-to-fluid similarity theory for heat transfer to supercritical pressure fluids: merits and limitations," Int. J. Heat Mass Transf., vol. 157, p. 119754, 2020.

[14] W. Ambrosini, "Discussion of similarity principles for fluid-to-fluid scaling of heat transfer behaviour at supercritical pressures," Nucl. Eng. Des., vol. 241, no. 12, pp. 5149–5173, 2011.

[15] "NIST Standard Reference Database 23 - NIST Thermodynamic and Transport Properties REFPROP, Version 7.0 | NIST." https://www.nist.gov/publications/nist-standard-reference-database-23-nist-thermodynamic-and-transport-properties-refprop (accessed Nov. 02, 2020).