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SCALING LAWS IN SUPERCRITICAL FLUID APPLICATIONS

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Objectives

Objectives of this Lecture are:

- To discuss the importance of general scaling in SCWR related studies
- To discuss some approaches proposed for scaling heat transfer and flow stability behaviour
- To describe proposed approaches for fluid-to-fluid scaling

Introduction

- **The application of dynamic similarity principles is a powerful tool in physics and engineering, often adopted in "scaling"**

- **Some of the relevant purposes of adopting similarity principles can be summarised as follows:**

  1. **to express in a compact and relatively universal form the results of calculations or experiments**
  2. **to highlight the importance of particular phenomena in some range of operating conditions**
  3. **to establish engineering correlations and closure laws applicable to a vast variety of operating conditions and fluids**
  4. **to conveniently plan for experiments in downscaled facilities, representing as far as possible the conditions to be expected in full scale apparatuses**

- **In summary, establishing dynamic similarity is a powerful technique for achieving that reasonable degree of universality from system-specific conclusions that is one of the main goals in proposing physically based theories**

Reminder about the available methodologies for establishing similarity principles and scaling laws

- **The Buckingham π theorem is perhaps the most basic technique to identify dimensionless groups used in establishing similarity and scaling principles:**
  - **It allows to identify the number of relevant dimensionless groups by subtracting the number of basic dimensions to the number of all the necessary and sufficient variables required to describe a problem**
  - **Its application is advisable when the governing equations of the system are unknown, but the understanding of the basic physics is very well established**
  - **Determining the dimensionless groups requires careful algebraic developments in assigning exponents to each variable**
- **A classical example is found for convective heat transfer:**

$$\Pi_i = w^a h_{conv}^b D^c \rho^d c_p^e \mu^f k^g \qquad \Pi_1 = \frac{h_{conv} D}{k} \qquad \Pi_2 = \frac{\rho w D}{\mu} \qquad \Pi_3 = \frac{c_p \mu}{k}$$

Reminder about the available methodologies for establishing similarity principles and scaling laws

- **Whenever governing equations are available for describing a phenomenon, putting the equations in dimensionless form is very effective**
- **Two relevant examples from fluid mechanics and heat transfer:**
  - **Navier-Stokes equations**

$$\boxed{\frac{D\vec{w}^*}{Dt^*} = \frac{1}{Re}\nabla^{*2}\vec{w}^* - \nabla^* p^* + \frac{1}{Fr}\vec{k}} \qquad Re = \frac{\rho w_0 L}{\mu} \qquad Fr = \frac{w_0^{\ 2}}{gL}$$

  - **Energy balance equations with viscous dissipation**

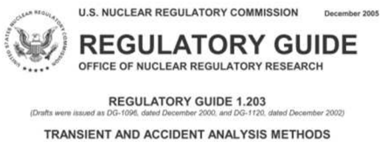
$$\boxed{\frac{DT^*}{Dt^*} = \frac{1}{RePr}\nabla^{*2}T^* + \frac{Br}{RePr}\varphi^*} \qquad Pr = \frac{c_p\mu}{k} \qquad Br = \frac{\mu w_0^{\ 2}}{k\Delta T}$$

- **This route has the advantage that the relevance of each term (phenomenon) in the balance equations can be evaluated**

Reminder about the available methodologies for establishing similarity principles and scaling laws

- **It must be reminded that an appropriate scaling procedure is nowadays required in the frame of the Evaluation Model Development and Assessment Procedure (EMDAP)**

- **This is a basic ingredient in the evaluation of code "uncertainty" on the basis of the code "accuracy" observed in analysing downscaled tests (Integral and Separate Effect tests)**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REGULATORY GUIDE

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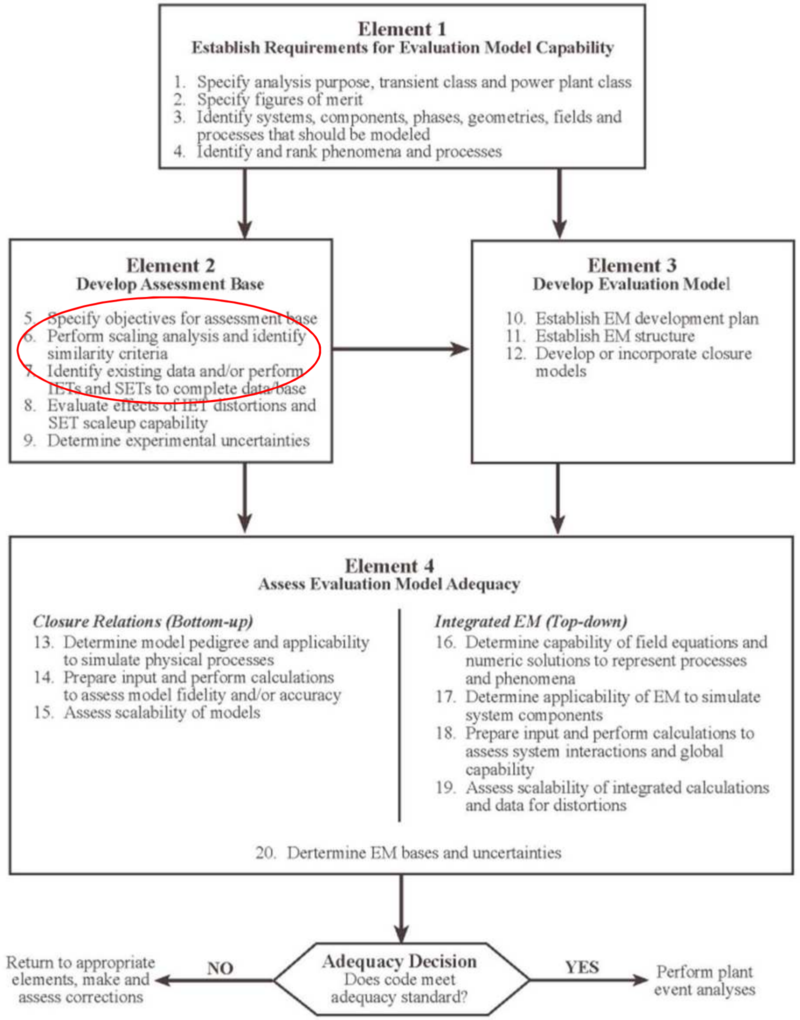
(Drafts were issued as DG-1096, dated December 2000, and DG-1120, dated December 2002)

TRANSIENT AND ACCIDENT ANALYSIS METHODS



EMDAP Procedure (from RG 1.203)

Reminder about the available methodologies for establishing similarity principles and scaling laws

- In this frame it must be mentioned that works have been published in the last decades in order to set up a coherent approach for relevant scaling phenomena in NPPs
- In one of these works (Zuber et al., 1998), a two-tiered scaling methodology was proposed:
  - "The top-down or system approach is used to derive scaling groups which are expressed in terms of characteristic time ratios that combine the process and system points of view"
  - "The bottom-up or process approach focuses on the important processes" and "assures that all important processes are fully addressed and, thereby, ensures the prototypicality of test data"
- The dimensionless groups identified in these analyses can be compared in different systems to identify possible distortions between test and prototypical conditions
- A "ranking" of phenomena must be made to consider the acceptability of distortions (e.g., PIRT)

Reminder about the available methodologies for establishing similarity principles and scaling laws

- **Whatever the adopted approach, it is necessary to recognise that a perfect scaling is often impossible for complex systems characterised by several interacting phenomena:**
  - **Experimental facilities based on scaling principles will be necessarily more suitable for representing some phenomena and less suitable for representing others**
  - **The ranking of phenomena is needed to consider their relevance on the target result to be addressed and to judge about the quality of the obtained scaling**
  - **This ranking may be more or less objective (based on engineering skill or quantified by an objective hierarchy)**

Dimensionless Parameters involved in Heat Transfer at Supercritical Pressures

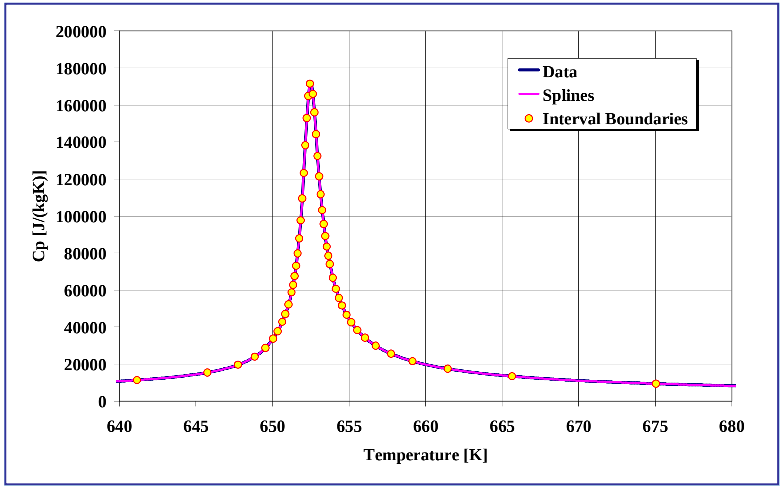
- **Heat transfer at supercritical pressure is more complex than in subcritical conditions, because of the complications brought about by the changes in fluid properties**

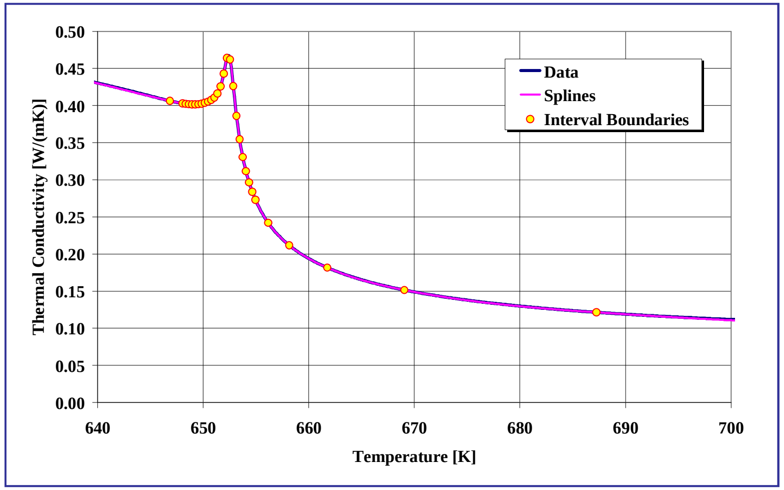
- **In particular, heat transfer enhancement and deterioration may take place as a consequence of the following effects:**
  - **sharp increase of the specific heat at the pseudocritical temperature**
  - **effects of buoyancy forces that affect turbulence production, sometimes leading to heat transfer deterioration in heated channels with upward flow**
  - **transition from a liquid-like to a gas-like fluid across the pseudo-critical threshold**

Dimensionless Parameters involved in Heat Transfer at Supercritical Pressures

- **The remarkable change in fluid thermodynamic and transport properties at the pseudocritical temperature is in fact a major feature to be taken into account in developing correlations**

Water at 23.5 MPa





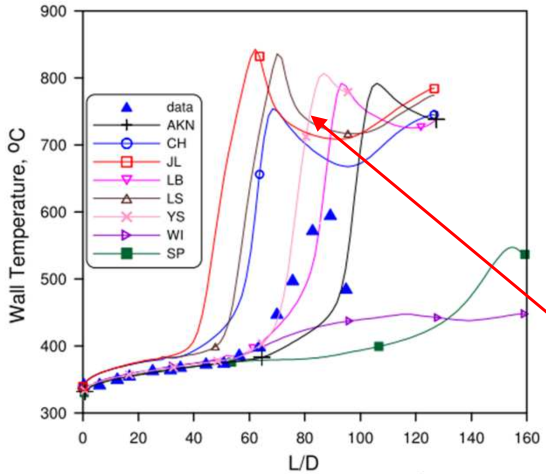
Dimensionless Parameters involved in Heat Transfer at Supercritical Pressures

- **Heat transfer enhancement is mainly attributed to the sharp increase in the specific heat at the pseudocritical temperature, that makes the temperature difference between wall and bulk fluid to decrease at a given heat flux**

- **Heat transfer deterioration, on the other hand, is a combined effect of buoyancy and/or acceleration that occurs as a consequence of property changes and often is interpreted assuming the "laminarisation" of the flow, due to decreased turbulent production**

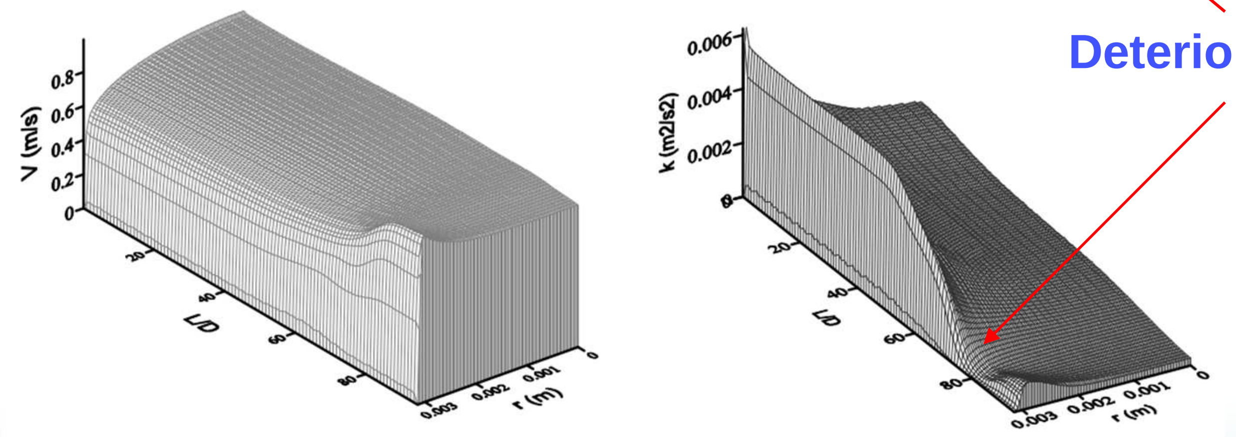
Dimensionless Parameters involved in Heat Transfer at Supercritical Pressures

Water data for upward flow by Pis'menny et al. (2006) predicted by CFD codes



e) upward flow, G=509 kg/(m^{2}s), q=390 kW/m^2, T_{in} =300 °C

Deterioration



a) axial velocity *b) turbulence kinetic energy*

Dimensionless Parameters involved in Heat Transfer at Supercritical Pressures

- **A review of available literature correlations, e.g. as presented in the textbook by Pioro and Duffey (2007), is interesting to highlight the main dimensionless parameters proposed in this frame (the reader is referred to the textbook for details)**

- **Many correlations for the Nusselt number in forced convection conditions are cast in the classical power law form as a function of the Reynolds and the Prandtl numbers**

$$Nu = const \times Re^{n_1} Pr^{n_2} \times (property\ correction\ factors)$$

where n_1 and n_2 are appropriate exponents

- **In the case of free convection, the adopted form is changed to**

$$Nu = const \times Gr^{n_1} Pr^{n_2} \times (property\ correction\ factors)$$

Dimensionless Parameters involved in Heat Transfer at Supercritical Pressures

- **More complex formulations for forced convection in "normal" heat transfer, used for calculating the Nusselt number to be then corrected, are based on classical relationships by Russian scientists, having the general form**

$$Nu_0 = f\left(\frac{\xi}{8}, \mathrm{Re}, \mathrm{Pr}\right)$$

requiring the evaluation of friction factors by an appropriate correlation; property group correction factors are applied to both Nu and ξ

- **Entrance effects are also taken into account by appropriate multipliers, in similarity with classical relationships for thermal and/or combined entry length problems, e.g.:**

$$\left(1 + C\frac{D}{x}\right)^m$$

Dimensionless Parameters involved in Heat Transfer at Supercritical Pressures

- **The thermodynamic and thermophysical properties entering the dimensionless numbers may be calculated in bulk or at the wall**
- **There are instances in which averages or different mixes of bulk and average values are adopted.**
- **In particular, the adopted Prandtl number is often averaged between the bulk and the wall conditions, mainly referring to an averaged specific heat, while the values of viscosity and thermal conductivity are generally taken either at the bulk or at the wall depending on the correlation**

$$\overline{Pr}_b = \frac{h_w - h_b}{T_w - T_b}\frac{\mu_b}{k_b} \qquad \overline{Pr}_w = \frac{h_w - h_b}{T_w - T_b}\frac{\mu_w}{k_w}$$

- **Averaging the specific heat across the boundary layer is considered an important feature, probably owing to its sharp peak when pressure is not too far from the critical one**

Dimensionless Parameters involved in Heat Transfer at Supercritical Pressures

- **The averaged specific heat appears also in property ratios adopted to correct the Nusselt number calculated with reference formulations for additionally taking into account the differences of properties in bulk and at the wall**

$$Nu = Nu_0 \left(\frac{\mu_b}{\mu_w} \right)^{n_1} \left(\frac{k_b}{k_w} \right)^{n_2} \left(\frac{\overline{C}_p}{C_{p,b}} \right)^{n_3}$$

- **In some cases, the ratios of densities in bulk and at the wall is also introduced to account for property variations across the boundary layer; e.g.:**

$$Nu = Nu_0 \left(\frac{\overline{C}_p}{C_{p,b}} \right)^{n_1} \left(\frac{\rho_b}{\rho_w} \right)^{n_2}$$

Dimensionless Parameters involved in Heat Transfer at Supercritical Pressures

- **Another form in which density in bulk and at the wall play a role in correlations is related to their difference. This is the case of the factor introduced by Kirillov et al. (1990) accounting for the role of free convection**

$$k^* = \left(1 - \frac{\rho_w}{\rho_b}\right)\frac{Gr}{Re^2}$$

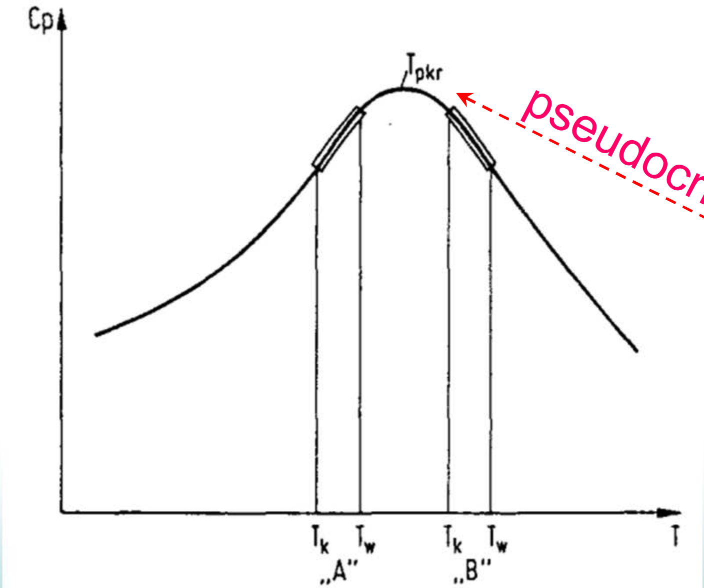
- **A further example is the definition of the Grashof number by relationships of the kind:**

$$Gr = \left(\frac{gD^3\rho_b^2}{\mu_b^2}\right)\left(\frac{\rho_b - \rho_w}{\rho_w}\right)$$

- **The relative values of the wall, the bulk and the pseudo-critical temperature are also considered for discriminating among the types of correlations to be used.**

Dimensionless Parameters involved in Heat Transfer at Supercritical Pressures

- **In particular, the exponents in the correlations may depend on the relative value of the pseudocritical temperature and the bulk and wall temperatures**
- **In this respect, it is interesting to consider a work by Mayinger and Scheidt (1984) in which a "rough and simple deliberation criterion" is taken, suggesting that heat transfer enhancement may occur in conditions like the "A" and impairment in conditions like "B" in the following figure**



pseudocritical

- **Though it is recognised that other properties in addition to the specific heat have a role, an "Eckert number" is suggested as having a role in determining heat transfer**

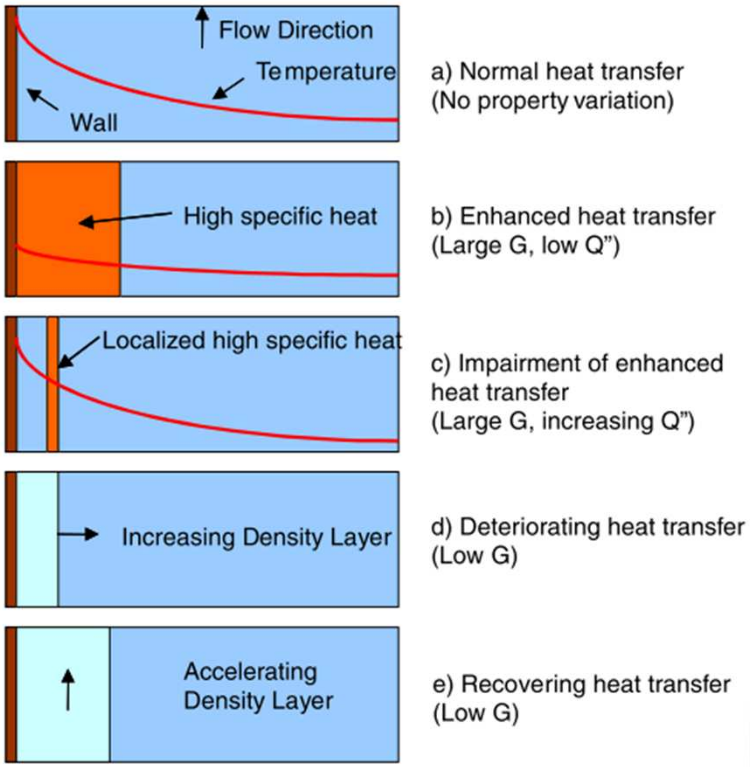
bulk

$$Ec = \frac{T_{pkr} - T_K}{T_W - T_K}$$

wall

Dimensionless Parameters involved in Heat Transfer at Supercritical Pressures

- **Similar arguments are proposed in a more recent paper by Licht et al. (2008), that makes use of the following figure for illustrating the explanation of heat transfer enhancement and deterioration provided by Jackson and Hall in 1979.**



- **As it can be noted, also the relative value of the heat and the mass fluxes have a role in determining deterioration**
- **This is accounted for in literature by various parameters related to the ratio**

$$q''_w / G$$

that, being dimensional, must be somehow recast into dimensionless form

Very rich description: read the paper !!!

Dimensionless Parameters involved in Heat Transfer at Supercritical Pressures

- **The form proposed in the paper by Mayinger and Scheidt (and previously by Polyakov) is**

$$\bar{\beta} = \frac{1}{\varrho\,(T_F)} \cdot \frac{\varrho_K - \varrho_W}{T_W - T_K} \qquad \Pi_2 = \frac{\bar{\beta}}{c_{p_K}} \cdot \frac{\dot{q}}{\dot{m}}$$

heating power

mass flow rate

bulk C_p

This formulation has the interesting feature to account for fluid expansion as a consequence of temperature increase

- **A similar formulation is suggested by McEligot and Jackson (2004) for gases**

heating flux

$$q^+ = \frac{\beta q''_{\mathrm{wall}}}{G c_{\mathrm{p}}}$$

mass flux

- **A further similar formulation is adopted also by Cheng et al. (2009) to account for acceleration effects, also proposing a criterion for the onset of deteriorated heat transfer in the form**

heating flux

$$\frac{q}{G} = 1.354 \cdot 10^{-3} \frac{C_{P,PC}}{\beta_{PC}}$$

Pseudocritical values

mass flux

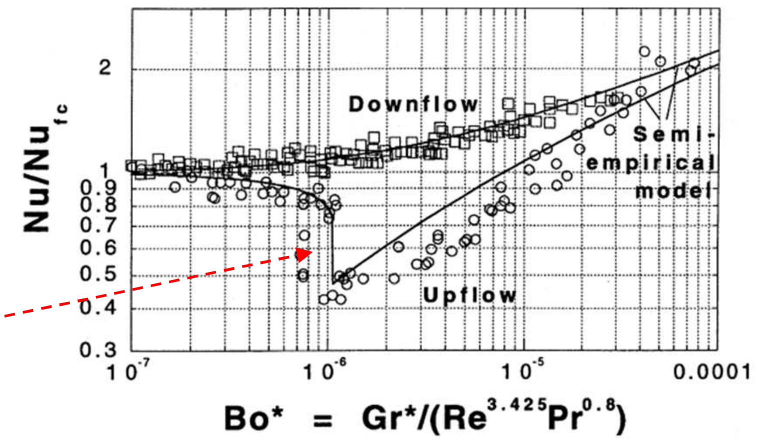
Dimensionless Parameters involved in Heat Transfer at Supercritical Pressures

- **Buoyancy parameters are also introduced following previous work by Jackson, allowing for establishing the extent at which this phenomenon may influence heat transfer**
- **In a recent proposal, Jackson (2011) suggests the use of the buoyancy number**

$$Bo_b^* = Gr_b^* / (Re_b^{3.425} Pr_b^{0.8})$$

where $Gr_b^* = g\beta_b q_w d^4 / (k_b \nu_b^2)$ **, that is expected to provide as good results as those obtained in predicting buoyancy affected data for gases**

Deterioration in upward flow



Dimensionless Parameters involved in Flow Stability Analyses

- **This subject has been partly covered in a previous lecture; here it is just highlighted that the different adopted sets of dimensionless numbers have considerable similarities**
- **Let us consider firstly the case of boiling channels. A classical set of parameters includes**

$$N_{sub} = \frac{h_{l,sat} - h_{in}}{h_{lv,sat}} \frac{v_{lv,sat}}{v_{l,sat}}$$

Subcooling number

$$N_{pch} = \frac{\dot{Q}}{W\, h_{lv,sat}} \frac{v_{lv,sat}}{v_{l,sat}}$$

Phase-change number

$$Fr = \frac{w_0^2}{g\,L}$$

Froude number

$$\Lambda = \frac{f\,L}{2\,D_h} \quad K_{in}, \quad K_{ex}$$

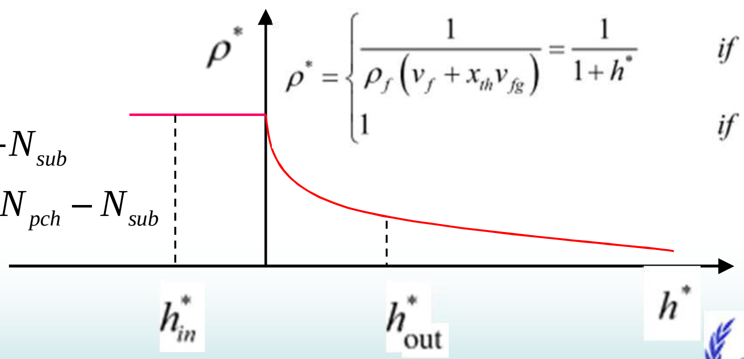
Distributed and localised friction

These two numbers determine the change in dimensionless enthalpy across the channel, linked to fluid expansion through the unique trend of dimensionless density vs. dimensionless enthalpy

$$h_{in}^* = -N_{sub}$$

$$h_{out}^* = N_{pch} - N_{sub}$$

$$\rho^* = \begin{cases} \dfrac{1}{\rho_f \left(v_f + x_{th} v_{fg}\right)} = \dfrac{1}{1+h^*} & if \quad h^* \geq 0 \\ 1 & if \quad h^* < 0 \end{cases}$$



Dimensionless Parameters involved in Flow Stability Analyses

- **The dimensionless number for supercritical fluids rephrase these concepts**
- **In the formulations by Zhao et al. (2005) and Ortega Gòmez et al. (2006) it is easy to recognise that an expansion number has the role of N_{pch} and also a subcooling number appears**
- **In the compact formulations by Yeylaghi et al. (2011) the effect of fluid expansion is also built-in**

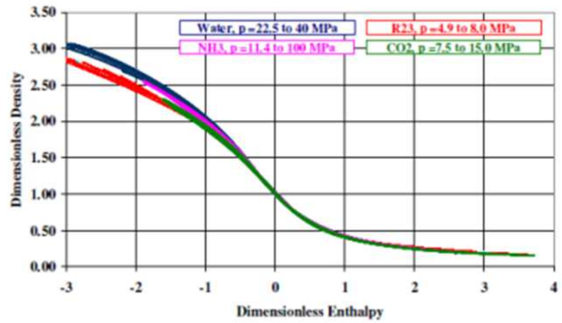
$$\hat{Q} = 2\xi \qquad \hat{Q} = \frac{Q\theta_e}{GA} \qquad \theta_e = -\frac{1}{\rho_e}\frac{\partial \rho_e}{\partial h_e} \qquad \xi = \left(1 - \frac{\rho_e}{\rho_i}\right) + \frac{\rho_e}{2}\left(\frac{1}{G}\frac{\partial p_e}{\partial G}\right)$$

- **The formulations by Ambrosini and Sharabi (2006) are formally very close to those for the boiling channel, obtained just by a change in the expansion characteristics**

$$N_{\mathrm{sub}} = \frac{h_{\mathrm{f}} - h_{\mathrm{in}}}{h_{\mathrm{fg}}}\frac{v_{\mathrm{fg}}}{v_{\mathrm{f}}} \rightarrow N_{\mathrm{SPC}} = \frac{\beta_{\mathrm{pc}}}{C_{p,\mathrm{pc}}}(h_{\mathrm{pc}} - h_{\mathrm{in}})$$

$$N_{\mathrm{pch}} = \frac{q_0'' \Pi_{\mathrm{h}} L}{\rho_{\mathrm{f}} w_{\mathrm{in}} h_{\mathrm{fg}} A}\frac{v_{\mathrm{fg}}}{v_{\mathrm{f}}} \rightarrow N'_{\mathrm{TPC}} = \frac{q_0'' \Pi_{\mathrm{h}} L}{\rho_{\mathrm{pc}} w_{\mathrm{in}} A}\frac{\beta_{\mathrm{pc}}}{C_{p,\mathrm{pc}}}$$

The definition of dimensionless enthalpy and the uinque relation with dimensionless density achieve a similar generality as in boiling channels



Dimensionless Parameters involved in Flow Stability Analyses

- **Additional definitions for the expansion parameter are presented later in the lecture**

  – **Marcel et al. (2009)**

$$N_{PCH} = \frac{q' L_C}{G_0 h_0 A}$$

  – **Rohde et al. (2011)**

$$N_{\Delta h} \equiv \frac{Q}{G_C A_C h_{pc}}$$

Dimensionless Parameters involved in Flow Stability Analyses

- **In summary, also in stability analysis, fluid expansion, that is seen to have relevance in heat transfer, has a key role**

- **The overall change in density along the channel is mainly responsible for the predicted unstable behaviour**

- **In the formulations adopted by Ambrosini and Sharabi (2006) there is the explicit appearance of the dimensionless power to flow rate ratio in the form**

$$N_{TPC} = \frac{\dot{Q}_{heating}}{W_{in}} \frac{\beta_{pc}}{C_{p,pc}}$$

similar to groups proposed in correlating heat transfer to quantify the effect of acceleration

Application of Dimensionless Parameters in Fluid-to-Fluid Scaling

- **Fluid-to-fluid comparison is necessary especially in designing facilities with fluids aimed at simulating a prototypic fluid behaviour**
- **Few examples of such applications are referred to in the following, showing that the techniques to be adopted are different, depending on the phenomena to be scaled (e.g., heat transfer or flow stability)**
- **Pioro and Duffey (2007) mention a previous work by Jackson and Hall (1979) suggesting the following choices**

Geometric similarity $$\left(\frac{x}{D}\right)_A = \left(\frac{x}{D}\right)_B$$ *Pressure* $$\left(\frac{p}{p_{cr}}\right)_A = \left(\frac{p}{p_{cr}}\right)_B$$

Bulk Fluid Temperature $$\left(\frac{T_b}{T_{cr}}\right)_A = \left(\frac{T_b}{T_{cr}}\right)_B$$ *Mass Flux* $$\left(\frac{GD}{\mu_b}\right)_A = \left(\frac{GD}{\mu_b}\right)_B$$

Heat Flux or Wall Superheat $$\left(\frac{qD}{k_b T_b}\right)_A = \left(\frac{qD}{k_b T_b}\right)_B \quad or \quad \left(\frac{T_w - T_b}{T_{cr}}\right)_A = \left(\frac{T_w - T_b}{T_{cr}}\right)_B$$

Heat Transfer $$Nu_A = Nu_B$$

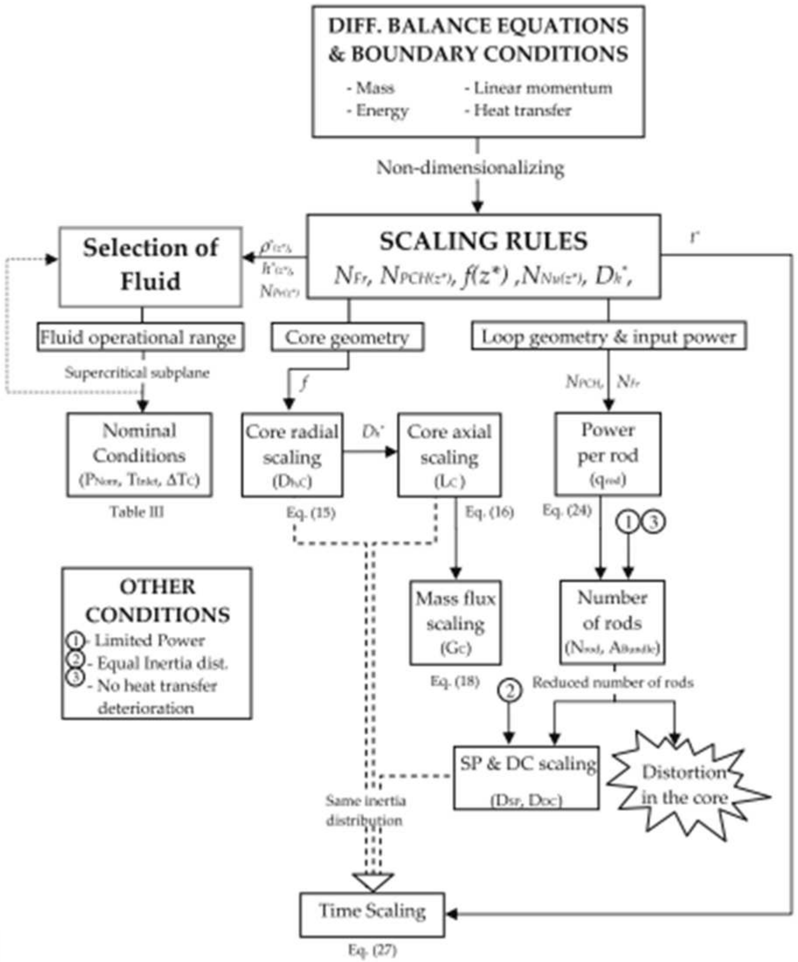
Application of Dimensionless Parameters in Fluid-to-Fluid Scaling

- **Recently Marcel et al. (2009) proposed a methodology for scaling an experimental facility devoted to the analysis of stability of the HPLWR**
- **The diagram of the methodology shows the different steps requested in the process**
- **The work is based on balance equations cast in dimensionless form by the definitions**

$$t^* = \frac{t}{\frac{L_C \rho_0}{G_0}}, \quad \rho^* = \frac{\rho}{\rho_0}, \quad h^* = \frac{h}{h_0}, \quad G^* = \frac{G}{G_0}, \quad N_{Fr} = \left(\frac{G_0}{\rho_0}\right)^2 \frac{1}{L_C g},$$

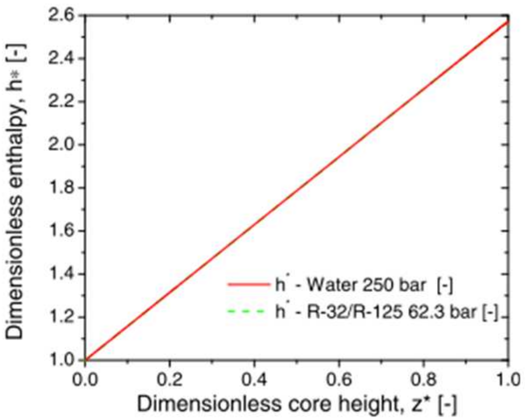
$$p^* = \frac{p}{\frac{G_0^2}{\rho_0}}, \quad A^* = \frac{A}{L_C^2}, \quad z^* = \frac{z}{L_C} \quad \text{and} \quad D_h^* = \frac{D_h}{L_C} \quad N_{PCH} = \frac{q' L_C}{G_0 h_0 A}$$

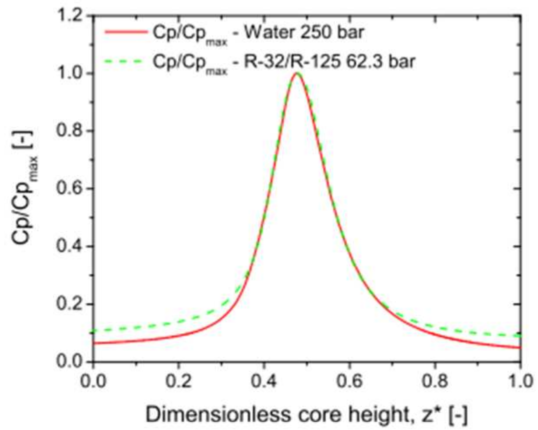
which take as reference parameters the core length and the core inlet conditions of an HPLWR

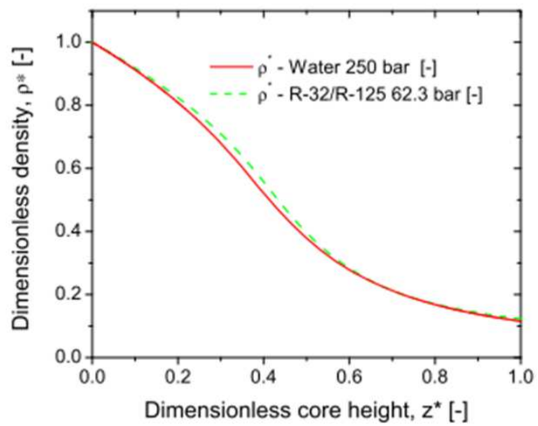


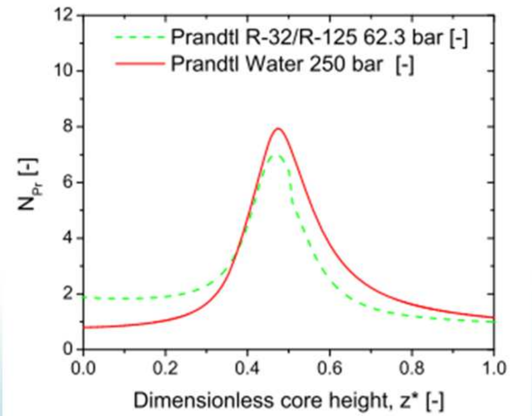
Application of Dimensionless Parameters in Fluid-to-Fluid Scaling

- **The fluid was selected in order to have a similar behaviour with respect to water in dimensionless form. A mixture of R-32 and R-125 refrigerants turned out to be appropriate for preserving the pseudo-N_{pch}**









Preserving the Froude number and the dimensionless frictional pressure drop results in determining the size of the test loop

The adopted solutions are found good in general, though compromises have been accepted in representing some parameters

Application of Dimensionless Parameters in Fluid-to-Fluid Scaling

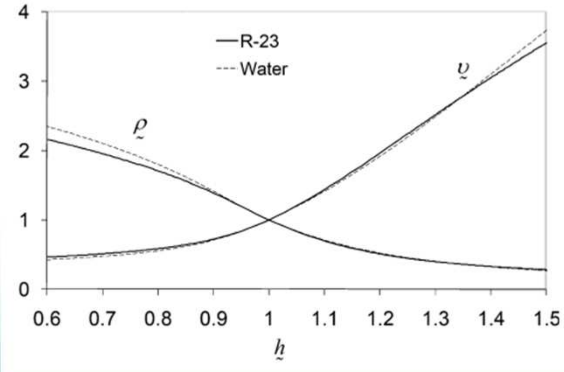
- **In a further development, the same research group produced a further attempt to identify a safer operating fluid (Rohde et al., 2011) in refrigerant R23**
- **The dimensionless variables are defined in this case with reference to the pseudo-critical point**

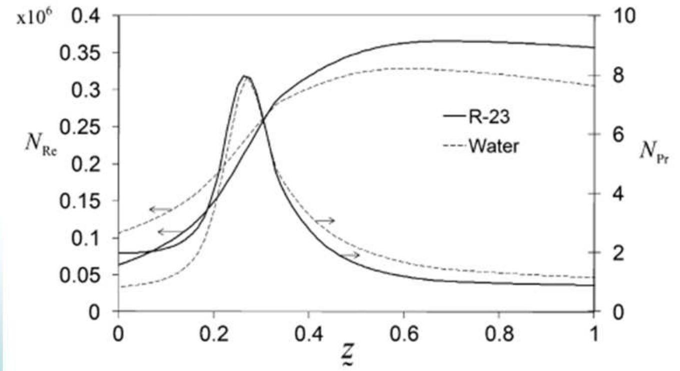
$$\underset{\sim}{t} \equiv \frac{t}{\frac{L_C \rho_{pc}}{G_C}}, \quad \underset{\sim}{G_j} \equiv \frac{G_j}{G_C}, \quad \underset{\sim}{A_j} \equiv \frac{A_j}{L_C^2}, \quad \underset{\sim}{z} \equiv \frac{z}{L_C}, \quad \underset{\sim}{\rho} \equiv \frac{\rho}{\rho_{pc}},$$

$$\underset{\sim}{D_{h,j}} \equiv \frac{D_{h,j}}{L_C}, \quad \underset{\sim}{p} \equiv \frac{p}{\frac{G_C^2}{\rho_{pc}}}, \quad \underset{\sim}{h} \equiv \frac{h}{h_{pc}}, \quad \underset{\sim}{q''} \equiv \frac{S L_C q''}{Q}$$

$$N_{Fr} \equiv \frac{\left(\frac{G_C}{\rho_{pc}}\right)^2}{L_C g}, \quad N_{\Delta h} \equiv \frac{Q}{G_C A_C h_{pc}}$$

- **Similarity is achieved by imposing that the dimensionless parameters are the same in the reference reactor and in the facility**





Application of Dimensionless Parameters in Fluid-to-Fluid Scaling

- **In the aim to modify an experimental test facility working with supercritical water in order to make heat transfer experiments with supercritical CO2, Zwolinski et al. (2011) adopted a scaling analysis**
- **While waiting for experimental data to validate the adopted theory, CFD calculations were made**
- **The adopted criteria were obtained from a work by Jackson (2008)**

$$\left(\frac{x}{D_h}\right)_1=\left(\frac{x}{D_h}\right)_2 \quad \left(\frac{P_o}{P_c}\right)_1=\left(\frac{P_o}{P_c}\right)_2 \quad \left(\frac{q_w D_h}{k_o T_o}\right)_1=\left(\frac{q_w D_h}{k_o T_o}\right)_2 \quad \left(\frac{G D_h}{\mu_o}\right)_1=\left(\frac{G D_h}{\mu_o}\right)_2 \quad \left(\frac{h D_h}{k_o}\right)_1=\left(\frac{h D_h}{k_o}\right)_2$$

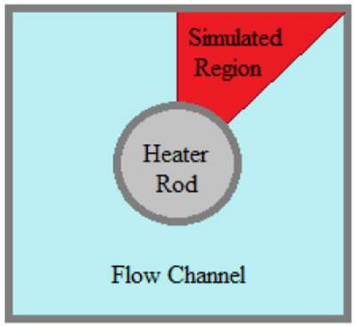
- **Instead of imposing the classical relationship** $\left(\frac{T_o}{T_c}\right)_1=\left(\frac{T_o}{T_c}\right)_2$

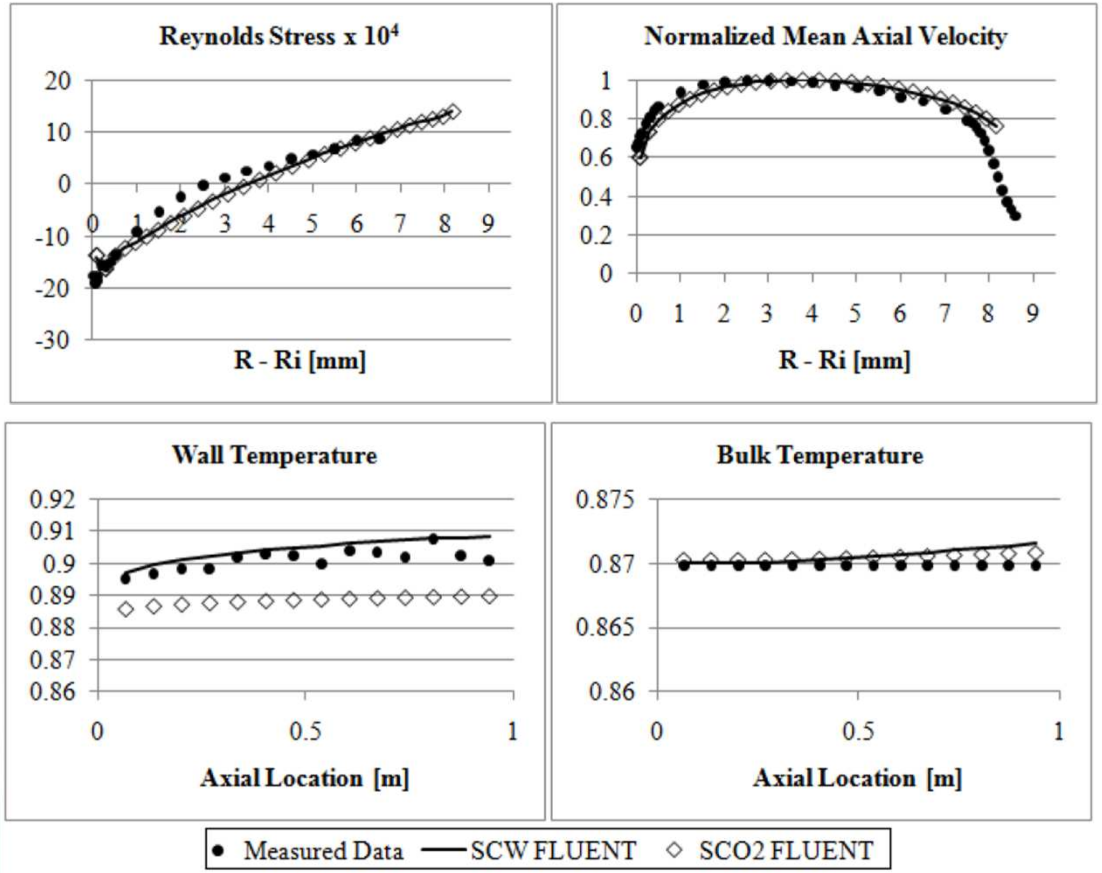
  the proposal by Cheng et al. (2010) $\theta=\left(\frac{T_o-T_{pc}}{T_{pc}-T_c}\right)$

  was adapted in the form $\left(\frac{T_o}{T_{pc}}\right)_1=\left(\frac{T_o}{T_{pc}}\right)_2$

Application of Dimensionless Parameters in Fluid-to-Fluid Scaling

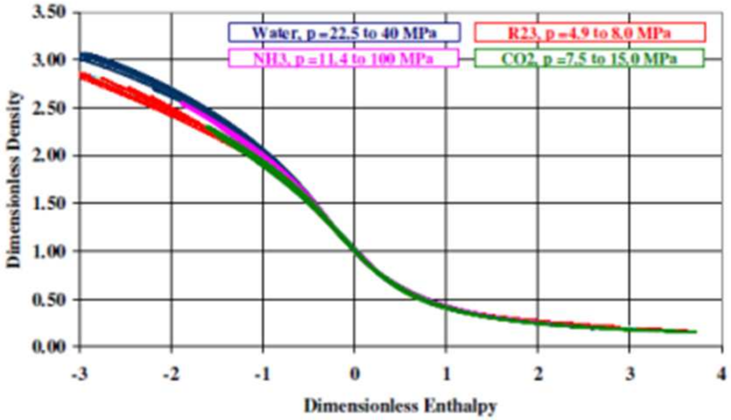
- **The performed CFD calculations (Reynolds Stress model with wall functions or enhanced wall treatment) for water at 25 MPa and carbon dioxide at 8.4 MPa, for the test channel slice shown in the figure, showed very similar behaviour with some discrepancy on wall temperature**





An attempt to merge different approaches

- **The definitions adopted by Ambrosini and Sharabi (2006) for stability analysis have the feature that the dimensionless density is for different fluids a nearly unique function of dimensionless enthalpy irrespective of the supercritical pressure**



- **This is at the root of the suitability of these definitions to correlate stability thresholds for different fluids**
- **Moreover, the expansion parameter, N_{TPC} is similar to dimensionless groups introduced for defining acceleration in bulk fluid**

- **On this basis an attempt was made to set up a coherent set of dimensionless numbers for scaling both heat transfer and stability in a fluid-to-fluid perspective (Ambrosini and De Rosa, 2011)**
- **The attempt is based on 3D mass, momentum and energy balance equations put in dimensionless form to make appearing relevant dimensionless groups**

An attempt to merge different approaches

- **Classical definitions for dimensionless groups are rephrased**

$$\boxed{Pe_{loc,pc} = \frac{\rho_{pc} C_p w_{in} L}{k}}$$

$$\boxed{Re_{loc,pc} = \frac{\rho_{pc} w_{in} L}{\mu}}$$

- **They both contain the group** $w_{in} L$
- **Their ratio is obviously a local Prandtl number that should have a similar trend with respect to dimensionless enthalpy in the different fluids for having a proper similarity**

$$\boxed{Pr_{loc} = \frac{Pe_{loc,pc}}{Re_{loc,pc}} = \frac{C_p \mu}{k}}$$

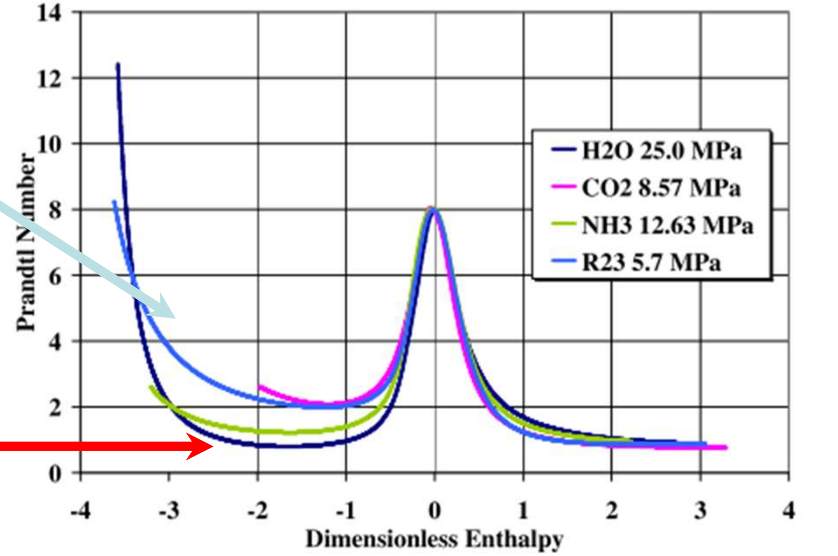
- **The dimensionless enthalpy at the wall and in bulk represent also and index of the location of the pseudocritical temperature in the radial direction**

$$h^* = \frac{1}{v_{pc}} \left(\frac{\partial v}{\partial h} \right)_{p,pc} (h - h_{pc}) = \frac{\beta_{pc}}{C_{p,pc}} (h - h_{pc})$$

An attempt to merge different approaches

- **Three different operating pressures were selected for carbon dioxide, ammonia and refrigerant R23 in order to have a similar maximum value of the Prandtl number as water at 25 MPa (first choice criterion)**
- **There are anyway evident deviations in the trends of this parameter in the liquid-like region**

Large differences between water and CO2 and R23



Better similarity between water and ammonia

An attempt to merge different approaches

- **First analyses were made by CFD in order to highlight predicted discrepancies when applying similarity criteria used for stability analyses (equality of N_{PCH}, N_{SPC}, Fr) to heat transfer**

- **CFD is obviously only a preliminary help for a study that should be made considering experimental data, since:**
  - **The turbulence models are not yet enough validated**
  - **There is no guarantee that the models are coherent with the previously described dimensionless numbers**

- **Results for dimensionless enthalpy at the wall in corresponding conditions were calculated**

- **The analyses showed discrepancies clearly linked to the different values of the Prandtl number of the fluids**

An attempt to merge different approaches

- **In fact, the anticipation in deterioration shown by fluids other than water is coherent with <u>the different values of the Prandtl number at the wall</u>**
- **In this respect a similar behaviour is observed for R23 and CO_2**

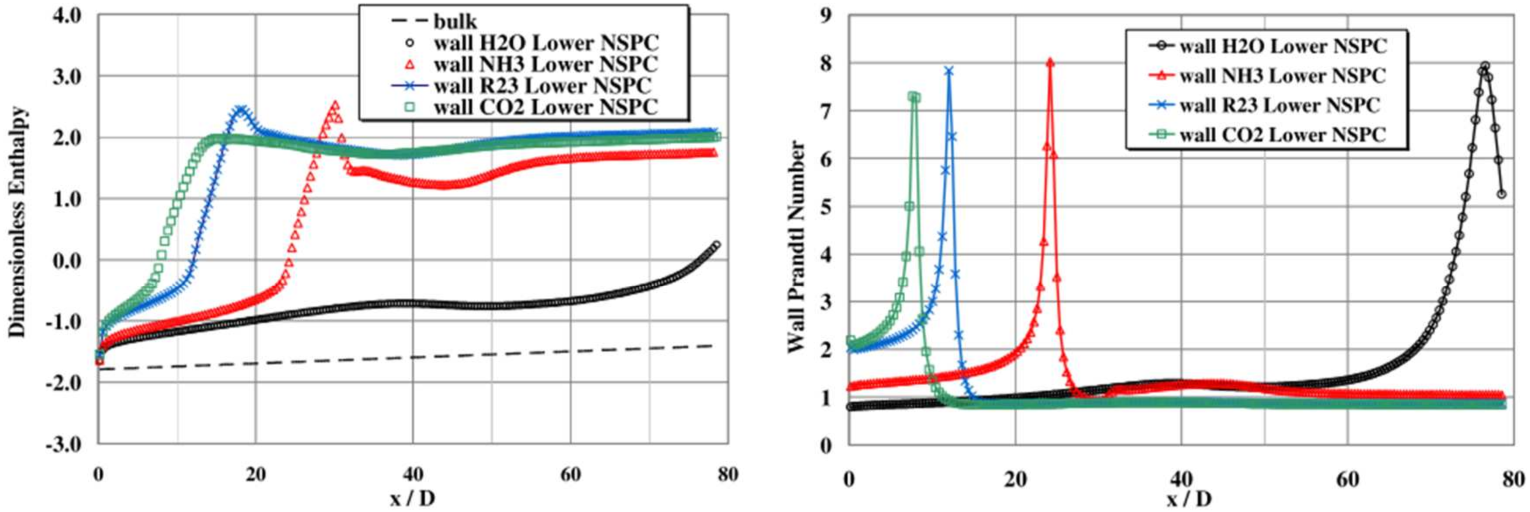


Figure 6. Bulk and wall dimensionless enthalpy and wall Prandtl number for the case with lower N_{SPC}

- **Work is underway to further exploit this approach, trying to highlight its possible capabilities**

Conclusions

- **Similarity principles can be established for supercritical fluids in relation to different phenomena**
- **Depending on the purpose of the scaling analysis different approaches have been used in the past**
- **For stability analysis and heat transfer different dimensionless groups and scaling strategies have been proposed**
- **The field is still open for research, aimed at validating coherent similarity theories against experimental data**

Thank you for your attention,

Walter Ambrosini

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