NUMERICAL EXPERIMENT ON DIFFERENT VALIDATION CASES OF WATER COOLANT FLOW IN SUPERCRITICAL PRESSURE TEST SECTIONS ASSISTED BY DISCRIMINATED DIMENSIONAL ANALYSIS PART I: THE DIMENSIONAL ANALYSIS

Attila Kiss[1], Attila Aszódi[2]
Budapest University of Technology and Economics, Hungary, European Union.

Abstract

As recent studies prove in contrast to "classical" dimensional analysis, whose application is widely described in heat transfer textbooks despite its poor results, the less well known and used discriminated dimensional analysis approach can provide a deeper insight into the physical problems involved and much better results in all cases where it is applied. As a first step of this ongoing research discriminated dimensional analysis has been performed on supercritical pressure water pipe flow heated through the pipe solid wall to identify the independent dimensionless groups (which play an independent role in the above mentioned thermal hydraulic phenomena) in order to serve a theoretical base to comparison between well known supercritical pressure water pipe heat transfer experiments and results of their validated CFD simulations.

1. Introduction

The Supercritical pressure Water Cooled Reactor [1] is one of the six worldwide developed Generation IV nuclear reactor concepts. The European concept of the SCWR is called as the High-Performance Light-Water Reactor (HPLWR) [2], [3]. The specialty of the SCWR concept is that the pressure of the coolant (light water) is higher (25 MPa) than its critical value (22.1 MPa), and the outlet water temperature of the reactor is well above (500°C) than the critical temperature (374ºC). The SCWR developments are in the preliminary design stage. The concept is based on the design of present Light Water Reactors (LWR) and the commercial supercritical – ultra supercritical boilers. Whereas the two above mentioned technical bases are in use there are unresolved challenges and questions about the SCWR concept: i.e. need of new high temperature resistance structural materials [4], questionable role of the hyper-compressibility at supercritical conditions [5] and the specific heat transfer enhancement, deterioration and regeneration (after deterioration) processes under certain supercritical conditions [6], [7], [8], [9]. The investigation of the thermal hydraulic processes in SCWR fuel assemblies is very important, considering the necessity of accurate prediction of the heat transfer coefficient (htc, hereinafter) and the wall temperature distribution of the fuel pins. In the last decade many researches [10], [11], [12] have been performed on heat transfer under supercritical conditions using CFD. Most of them validated the applied CFD code simulating turbulent heat transfer case in horizontal or vertical pipe experiment [6], [7], [8], [13]. These validations have ended with reasonable results: the simulations have estimated both qualitatively

[1] Corresponding Author: Institute of Nuclear Techniques, Budapest University of Technology and Economics, Muegyetem rkp. 9., R bld. 317/8, H-1111 Budapest, Hungary. Tel.: +36 1 463 4339, Fax: +36 1 463 1954, E-mail: kissa@reak.bme.hu.
[2] Director of Institute of Nuclear Techniques and Head of Department of Nuclear Energy,Budapest University of Technology and Economics.
E-mail: aszodi@reak.bme.hu.

and quantitatively good the experimental data within a certain but more or less acceptable discrepancy. Based on the above mentioned validations their authors have started CFD analysis on more difficult geometries just like a part or a whole fuel assembly cooled by supercritical pressure water (SCW, hereinafter) without clearly knowing the physical causes of the different heat transfer modes in SCW. This ongoing research has aimed to asses the physical processes standing in the background which leads to the different heat transfer modes in SCW (more about the modes see next chapter). In the first step of this attempt a so called discriminated dimensional analysis (DDA, hereinafter) has been performed on SCW pipe flow heated through the pipe solid wall to identify the independent dimensionless groups (which play an independent role in the above mentioned thermal hydraulic phenomena) in order to serve a theoretical base to comparison between well known supercritical pressure water pipe heat transfer experiments and results of their numerical simulations. CFD simulations provide more orders of magnitude of data about the investigated thermal hydraulic process (both locally near the heated wall and in the bulk fluid) than an experiment in same geometry under same conditions without perturbation of the flow due to intrusion measuring tools. On the other hand while CFD does provide locally more detailed data than an experiment, the CFD simulation is only as realistic as the models and physical representation included in the calculation. CFD simulations cannot be used as a total replacement for experimental results and should be viewed as an aid in understanding the behaviour. Additionally, validation of CFD calculations is difficult even under the simplest of conditions. But if a validated CFD calculation has been provided then the relationship between the thermal hydraulic characteristics (for example different heat transfer modes) and the global parameters (heat- and mass flux) and local profiles (near wall velocity, temperature and material properties) of variables can be identified. In one sentence the principal of this research: DDA provides fistful dimensionless groups by theoretical prediction about the thermal hydraulics of SCW which will be verified profusely investigating validated CFD calculations.

2. Heat transfer in supercritical pressure water

The SCW has some special characteristics which differ from the subcritical pressure fluids. First of all there is no phase change in the supercritical fluid range (above the critical pressure and temperature). If the pressure of a fluid is beyond its critical value, then its material properties alter steeply around a certain temperature where the isobaric specific heat has a peak (for SCW and 24 MPa see Figure 1).

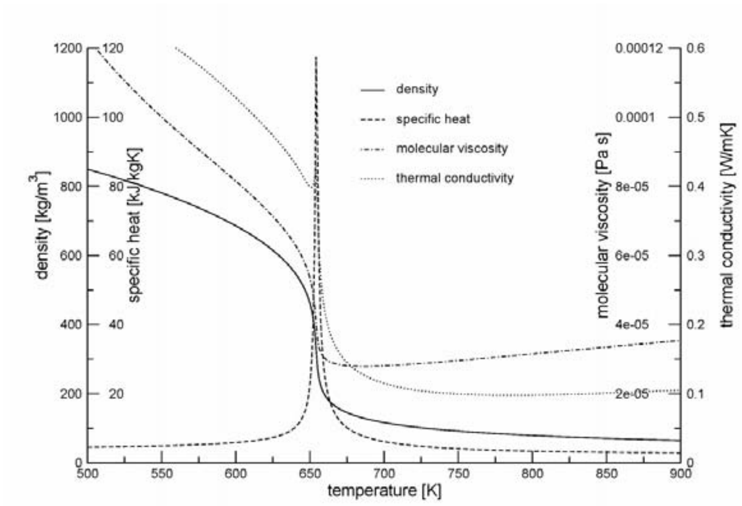

Figure 1 Physical properties of water at a pressure of 24.0 MPa [12].

This above mentioned certain temperature is the so called pseudo-critical temperature which depends on the absolute pressure (see Figure 2 – the peak of specific heat drifts to the higher temperature if pressure increases). The phenomenon when the temperature goes through the thin region around pseudo-critical temperature is the so called pseudo-critical transition.

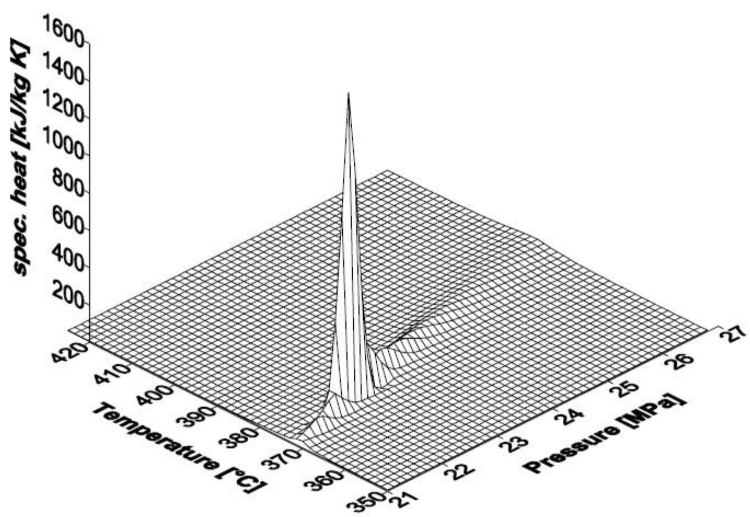

Figure 2 The isobaric specific heat as a function of pressure and temperature [14]. Critical point of water: p_c=22.064 MPa, T_c=373.95°C.

More than 450 experiments have been published from the early 1930s about the heat transfer in SCW. A consistent classification of heat transfer modes has been created based on these experiments. Three different heat transfer modes are identified: the normal heat transfer (NHT), enhanced (improved) heat transfer (EHT) and deteriorated heat transfer (DHT) which can be seen for vertical upward SCW flow in pipe on Figure 3 and Figure 4 [9].

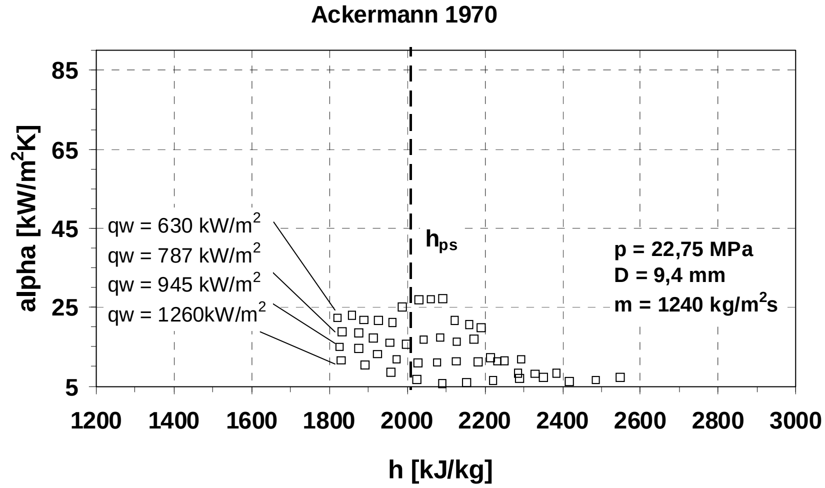

Figure 3 Htc versus bulk fluid enthalpy of NHT (q_w=945 kW/m^2), EHT (q_w=630 and 787 kW/m^2) and DHT (q_w=1260 kW/m^2) [15].

An approximately constant temperature difference can be seen between the wall and bulk fluid temperature (Figure 4) after the developing length of thermal boundary layer in case of normal heat transfer which leads a relatively high htc (Figure 3). In case of lower fraction of heat flux to mass flux the temperature difference between the wall and bulk fluid has been decreased which means the htc has been enhanced.

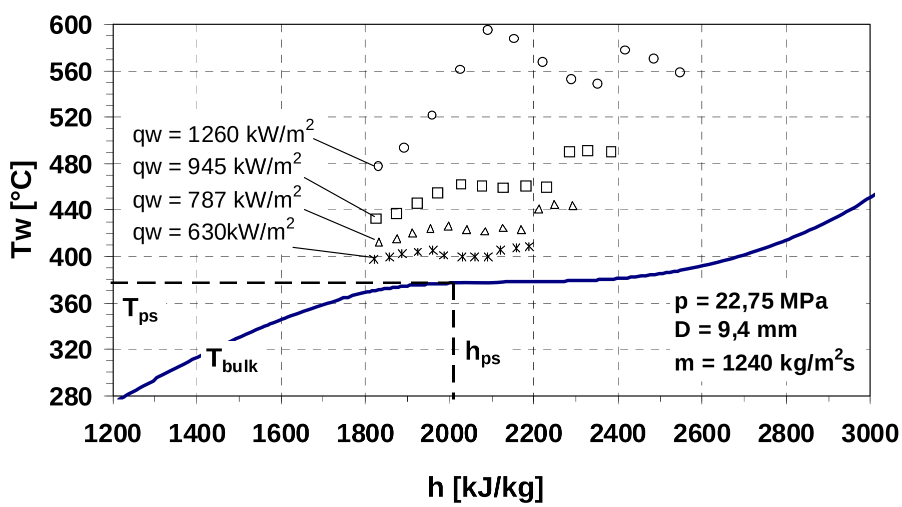

Figure 4 Wall temperature versus bulk fluid enthalpy of NHT (q_w=945 kW/m^2), EHT (q_w=630 and 787 kW/m^2) and DHT (q_w=1260 kW/m^2) [15].

If the fraction of heat flux to mass flux parameters were beyond the DHT criteria (see Equation 1 and 2) then deteriorated heat transfer has appeared which leads relatively low htc and peaks in wall temperature [16]. Htc could be regenerated after a wall temperature peak. This phenomenon called as regeneration of heat transfer (RHT).

$$\frac{q_w}{G} \geq 0.95 \div 1.05 \; kJ/kg \;\; \text{for stable flows} \tag{1}$$

$$\frac{q_w}{G} \geq 0.68 \div 0.9 \; kJ/kg \;\; \text{for oscillatory flows} \tag{2}$$

Physically it has not fully understood how the heat transfer mode change from normal to enhanced, from normal to deteriorated, and why the regeneration occurs after DHT.

So called correlations have been created in force based on experimental data in the interest of estimating the htc at subcritical pressure in turbulent flows. These correlations are not valid in case of estimating heat transfer near and above the thermodynamic critical point without modifications (the change of physical properties across the tube cross section has to be taken into account). Several supercritical correlations were created (for example [6], [7], [8]) but all of them are relatively accurate only within their own parameter ranges. The common feature of the supercritical correlations is that they take into account the variation of the thermo-physical properties across the tube cross section due to certain fractions (for instance the fraction of isobaric specific heat at bulk and wall temperatures in a certain axial level were proposed by the authors of [6] or the fraction of the specific volumes at bulk and wall temperatures in a certain axial level were proposed by the authors of [8]) which is multiplied with the subcritical base correlation (for example the Dittus-Boelter correlation). These so called supercritical pressure correlations have been implemented in many advanced system codes, just like APROS [17] and these codes are considered as they can handle more or less properly the thermal hydraulics of SCW. But the supercritical correlations have a very critical imperfection currently: they can not reproduce DHT and RHT duo to its dependence on localized conditions such as thermal profile, velocity profile, inlet temperature, pressure, mass velocity and heat flux [18]. That means system codes using these current correlations also can not predict universally the heat transfer of SCW (mainly DHT and RHT).

CFD codes seem to be able to reproduce not only NHT and EHT but DHT and RHT with a good qualitative and quantitative agreement [10], [19] due to full three dimensional CFD approaches simulating the previously mentioned local profiles about properly. But there are a lot of scalar and vector variables and their fields in a CFD result. So that is a hard work to identify brief relationships between the many relevant variables and the heat transfer modes mentioned above. That is the reason why DDA have been applied on supercritical pressure water pipe flow heated through the pipe solid wall to reduce the number of independent variables which influence the heat transfer mode of the coolant.

3. Classical and discriminated dimensional analysis

Dimensional analysis has been applied on various physical problems not only in engineering so far. As [20] describes well most text-books on conduction and convection heat transfer, both classical [21] and modern [22], make use of the results obtained by dimensional analysis, which can be named as “classical dimensional analysis” (CDA, hereinafter), to deduce, from the large number of variables that are generally involved in this kind of problem, the dimensionless groups of variables as a function of which the solutions may be expressed. This is, undoubtedly, one of the main advantages of CDA, since the number of dimensionless groups which fully describe the problem is much smaller than the number of non-dimensionless physical quantities that take part in it. The consequence of using dimensional analysis in the classical sense (no spatial discrimination) of Bridgman [23] and Langhaar [24] poses two problems: (1) it may introduce into the solution certain non-dimensionless groups, which are the ratio between purely geometric quantities, such as the ratios between characteristic lengths (the so-called “form factors”), (2) it provides dimensionless groups that do not play an independent role in the problem. To solve this problem Mills [22] established a distinction between what he calls “simple dimensional analysis” (CDA) and “vectorial dimensional analysis” (DDA), mentioning that with the last term the lengths measured in different directions (coordinates) in space can be adopted as independent dimensions. DDA increases the number of equations in the dimensional analysis but it brings about a diminution in the number of dimensionless groups and the solution becomes more precise [25].

4. DDA on supercritical pressure water pipe flow heated through the pipe solid wall

To take consideration that the heat transfer of SCW depends on localized (such as temperature profile and velocity profile near the heated wall) and global conditions (such as inlet temperature, pressure, mass velocity and heat flux) an assumption has been made: the flow field can be divided into two regions. The first region, the so called near wall region consists of the fluid near the heated solid wall wherein the heat transfers mainly due to heat conduction in the viscous and transitional sub-layer and due to turbulent heat convection in the turbulent sub-layer. The velocity and temperature field change steeply near the heated wall (in the boundary layer). The second region, the so called bulk region consists of the bulk of fluid flow wherein the heat transfers mainly with turbulent heat convection. Here the velocity and temperature field change very moderately. Thus the friction force and its relevant dimensional variable (μ_b) have been neglected in list of the relevant variables. The inertia forces have been also neglected (ρ_b excluded from the list of the relevant variables). Because considering the turbulence would complicate the DDA process that is the reason for neglecting turbulence scales in the variables list (see below) which leads a quasi-laminar heat transfer case. Thus the heat transport could be imagined as follows: in the near wall region heat conduction transports heat from the heated wall through the viscous and transitional sub-layer up to the turbulent sub-layer. Here the turbulent heat convection overtakes the dominant role from heat conduction and transport the heat toward the bulk region wherein turbulent convection (considered by $\rho_b c_{pb}$ dimensional variable in the list below) transports heat further into the relatively cooled bulk. Thus heat conduction has neglected as heat transport process beyond the near wall region (k_b - excluded from the list of the relevant variables). The friction dissipation is also neglected so the energy of fluid motion does not transform to internal energy. The relevant list of dimensional variables for heat transfer phenomena of SCW can be seen below (see Figure 5):

- v^* – characteristic velocity within the near wall region, which must be a small fraction of the typical steady velocity far from the wall (v_0) far from the boundary layer: $v^*=c\ v_0$ (where c is a constant) [m/s],
- D_0 – diameter of the straight tube [m],
- l_0 – length needed for developed flow conditions in the axial direction of the tube [m],
- $\Delta\theta$ – temperature difference between two location [K],
- q_w – heat flux [W/m^2],
- $\rho_b c_{pb}$ – specific volumetric heat capacity in the bulk region [J/(m^3 K)],

- ρ_w – local fluid density in the near wall region [kg/m^3],
- μ_w – local dynamic viscosity in the near wall region [Pa s],
- k_w – local heat conductivity in the near wall region [W/(m K)],
- $\rho_w c_{pw}$ – local specific volumetric heat capacity in the near wall region [J/(m^3 K)],
- α – htc (dimensional variable which order of magnitude has to be defined) [W/(m^2 K)].

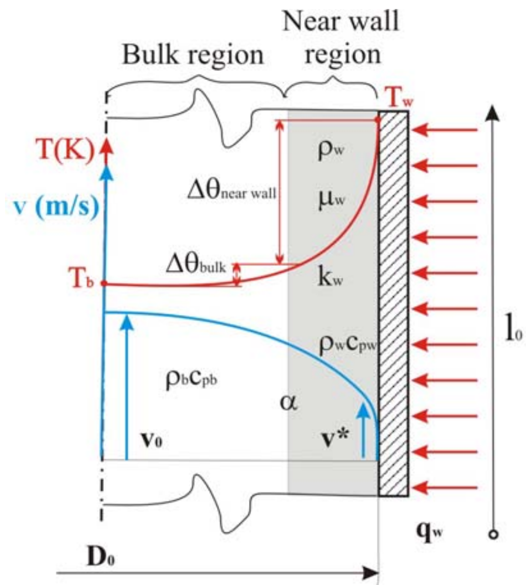

Figure 5 The relevant dimensional variables of heat transfer in SCW.

The Prandtl number (Pr, hereinafter) covers the range from 0.79 to 7.5 in SCW at 250 bar between 280 °C and 500 °C (reference temperature range of HPLWR). Thus the ratio between the thickness of thermal boundary layer and viscous boundary layer is within 0.51 and 1.08 (see Equation 3). It means that the region of high temperature and velocity gradient coincides in the near wall region. That is the reason why the list of relevant dimensional variables above takes into consideration the inertial forces (ρ_w) and viscous forces (μ_w) in the near wall region.

$$\begin{aligned} &\sqrt[3]{\frac{1}{\mathrm{Pr}}} = \frac{\delta_{th}}{\delta_v} \\ &0.79 \le \mathrm{Pr}_{HPLWR} \le 7.5 \\ &0.51 \le \frac{\delta_{th}}{\delta_v} \le 1.08 \end{aligned} \tag{3}$$

In this study to the Descartes coordinate system three perpendicular independent coordinates have been used which means the effect of pipe curvature on SCW heat transfer has been neglected. The applied dimensional base is the following:

- $L_{\parallel}$ - spatial coordinate parallel to the direction of mean flow velocity (v_0),
- $L_{\perp}$ - spatial coordinate perpendicular to the direction of mean flow velocity (the direction in which the momentum is diffused),

- $S\perp$ - the friction surface near the wall (spatial coordinate which normal direction is $L\perp$),
- Q – heat quantity,
- T – time quantity,
- Θ – temperature quantity,
- M – mass quantity.

The relevant list of variables and their dimensional exponents in the above listed dimensional base can be seen in Table 1.

Table 1 The relevant list of dimensional variables and their dimensional exponents.

Base	v^*	D_0	l_0	$\Delta\theta$	q_w	$\rho_b c_{pb}$	ρ_w	μ_w	k_w	$\rho_w c_{pw}$	α
$L_\parallel$	1	0	1	0	0	0	0	0	0	0	0
$L\perp$	0	1	0	0	0	-1	-1	1	1	-1	0
$S\perp$	0	0	0	0	-1	-1	-1	-1	-1	-1	-1
Q	0	0	0	0	1	1	0	0	1	1	1
T	-1	0	0	0	-1	0	0	-1	-1	0	-1
Θ	0	0	0	1	0	-1	0	0	-1	-1	-1
M	0	0	0	0	0	0	1	1	0	0	0

As it is well known from CDA theory, the number of the independent dimensionless groups, i, that may be derived from the dimensional variables of the relevant list, n, is:

$$i = n - H \tag{4}$$

where H is the rank of the matrix of the dimensional exponents [25]. The rank of the dimensional exponent matrix has been calculated using MAPLE 9: H = 6. Knowing that the number of dimensional variables is n = 11 and applying Equation 4 the number of the independent dimensionless groups is i = 5. Solving the linear equation system of dimensional exponents the following dimensionless groups can be derived as a result of DDA on the current thermal hydraulic case. (In the following R is the set of real number thus c_i is a constant.)

In the following if the local or bulk variables form solely a dimensionless group then that dimensionless group should be qualified as a parameter which regards only on the near wall or bulk region. The rearrangement of dimensionless groups below means only an attempt to check the physical validity and to find a picturesque explanation to each dimensionless group.

$$\Pi_1 = \frac{\Delta\theta \cdot \alpha}{q_w} \Rightarrow .: q_w \Rightarrow q_w \propto c_1 \cdot \alpha \cdot \Delta\theta, where\, c_1 \in R \tag{5}$$

The meaning of the first dimensionless group (see Equation 5) which should define the order of magnitude of htc is clear: this is the well known Newton law of heat transfer [22]. The wall heat flux is proportional with the htc and temperature difference. Here the constant (c_1) can be defined: $c_1 = 1$.

$$\Pi_2 = \frac{D_0 \cdot v^* \cdot \Delta\theta \cdot \rho_w \cdot c_{pw}}{l_0 \cdot q_w} \Rightarrow .: \Delta\theta_{near\,wall}$$

$$\Delta\theta_{near\,wall} \propto c_2 \cdot \frac{l_0}{D_0} \cdot q_w \cdot \frac{1}{v^* \cdot \rho_w \cdot c_{pw}}, where\, c_2 \in R \tag{6}$$

$$\Delta\theta_{near\,wall} \propto c_2 \cdot \frac{l_0}{D_0} \cdot \frac{q_w}{v^* \cdot \rho_w} \cdot \frac{1}{c_{pw}} = c_2 \cdot \frac{l_0}{D_0} \cdot \frac{q_w}{G_w} \cdot \frac{1}{c_{pw}}$$

The second dimensionless group specifies the ratio of local linear heat convection rate and the linear heat generation rate from the heated wall to SCW. This ratio concerns on the near wall region only. It is assumed that the local linear heat convection rate has mainly axial direction in the viscous sub-layer (here the heat transports in axial direction due to the moving fluid by advection and diffused in radial direction with heat conduction), has mixed (axial and radial) in the transitional sub-layer and has mainly radial direction in the turbulent sub-layer due to strong turbulent convection effect. Rearranging Equation 6 the relationship can be found between wall heat flux (q_w) and temperature difference ($\Delta\theta_{near\ wall}$) (between the wall and near wall temperature) in sense of heat convection. Wall heat flux is directly proportional to temperature difference so the higher heat flux causes higher temperature difference if the other variables remain constant. If they do not then the local velocity (v^*) and local density (ρ_w) (together the local mass flux, G_w) and the local specific heat (c_{pw}) could counterbalance the effect of high heat flux in case they represent together a high value. Grouping together the wall heat flux and local mass flux a familiar ratio could be found which recall to the criteria of heat transfer deterioration (see Equation 1 and 2). This ratio of wall heat flux per local mass flux seems to be local criteria of heat transfer deterioration. That looks reasonable if one consider that mass flux changes through the cross section of vertical pipe: that should be the highest in the bulk and decreases to near to the heated wall.

$$\Pi_3 = \frac{\Delta\theta \cdot k_w}{D_0 \cdot q_w} \Rightarrow .: \Delta\theta \Rightarrow \Delta\theta \propto c_3 \cdot \frac{D_0}{k_w} \cdot q_w, where\, c_3 \in R \tag{7}$$

The meaning of the third dimensionless group seems to be in close relationship with the meaning of the second but it concerns on the heat conduction. The third dimensionless group shows the ratio between conducted heat amount driven by temperature difference and linear heat generation rate. Rearranging Equation 7 a relationship can be found between wall heat flux and temperature difference in sense of heat conduction. Here also wall heat flux is directly proportional to temperature difference so the higher heat flux causes higher temperature difference if the other variables remain constant. For a concrete geometry the only parameter to the relationship of heat flux and temperature difference is the local heat conduction coefficient (k_w). That is very apparent if local heat conduction coefficient remains high then due to strong heat conduction through the viscous and transitional sub-layer the temperature difference represents a relatively low value.

$$\Pi_4 = \frac{l_0 \cdot \mu_w}{v^* \cdot D_0^2 \cdot \rho_w} \Rightarrow .: \frac{l_0}{D_0} \Rightarrow \frac{l_0}{D_0} \propto \frac{v^* \cdot D_0 \cdot \rho_w}{\mu_w} = \mathrm{Re}_w, where\, c_4 \in R \quad (8)$$

The fourth dimensionless group comes from the quasi-laminar approach: it means that the needed length of fully developed flow conditions is proportional to the local Reynolds number [22]. Here the only specialty that one should recognize is the usage of the local material properties and velocity scale when calculating the local Re instead of the bulk flow values of SCW flow.

$$\begin{aligned}
&\Pi_5 = \frac{D_0 \cdot v^* \cdot \Delta\theta \cdot \rho_b \cdot c_{pb}}{l_0 \cdot q_w} \Rightarrow .: \Delta\theta_{bulk} \\
&\Delta\theta_{bulk} \propto c_5 \cdot \frac{l_0}{D_0} \cdot q_w \cdot \frac{1}{v^* \cdot \rho_b \cdot c_{pb}}, where\, c_5 \in R \\
&v^* = c\, v_0, where\, v_0\, is\, the\, typical\, steady\;\, velocity\;\, far\;\, from\, the\, wall \\
&\Delta\theta_{bulk} \propto c_5 \cdot \frac{l_0}{D_0} \cdot \frac{q_w}{c \cdot v_0 \cdot \rho_b} \cdot \frac{1}{c_{pb}} = c_6 \cdot \frac{l_0}{D_0} \cdot \frac{q_w}{G_b} \cdot \frac{1}{c_{pb}}, where\, c_6 = \frac{c_5}{c} \in R
\end{aligned} \quad (9)$$

The last, fifth dimensionless group specifies the ratio of linear heat convection rate and the linear heat generation rate from the near wall region to the bulk of SCW. Here that is assumed that the linear heat convection rate has both axial and radial direction in the turbulent sub-layer and beyond that towards the bulk due to the advection effect of the main flow and strong radial turbulent convection effect. Rearranging Equation 9 the relationship can also be found between wall heat flux (q_w) and temperature difference ($\Delta\theta_{bulk}$) (between the near wall and bulk fluid temperature) in sense of heat convection. Wall heat flux is directly proportional to temperature difference so the higher heat flux causes higher temperature difference if the other variables remain constant. If they do not then the typical steady velocity (v_0) and bulk density (ρ_b) (together the bulk mass flux, G_b) and the bulk specific heat (c_{pb}) could counterbalance the effect of high heat flux in case they represent together a high value similar to the near wall situation. The grouping of the wall heat flux and bulk mass flux into bulk criteria of the occurrence of DHT could be done here. The meaning of bulk DHT criteria and relationship to the above discussed local criteria is not so clear. This question should be judged by the upcoming CFD analysis.

What is very surprising that the Nusselt number (Nu) does not represent an independent group among the dimensionless groups nor appears in the five groups provided by the above presented DDA either. That indicates that the prediction of heat transfer under supercritical conditions in water seems to be more difficult compared to heat transfer in constant material property fluids.

5. How to check the meanings of dimensionless groups with CFD simulations

DDA has provided two independent dimensionless groups which coincides the experimental experience and well accepted knowledge: the Newton low of heat transfer (first group – Equation 5) and the order of magnitude of needed development length of laminar flow (fourth group – Equation 8). The second and third dimensionless groups (Equation 6 and 7) concern specifically on the near wall region. The more important part of heat transfer occurs in the near wall region wherein the heat goes through the overlapping viscous and thermal boundary layer. Here first conduction dominates in viscous and transitional sub-layer then turbulent heat convection overtakes its dominant role. That is the procedure how heat travels from heated wall to the theoretical border between the bulk of the fluid and near wall layers. In the bulk region turbulent heat convection is the dominant heat transport process. Preliminary explanations of the meanings of second and third dimensionless groups have been written in the chapter before. In the next step well published experiments of vertically installed, straight, smooth bore tubes with upward flow of SCW will be investigated by the CFD code ANSYS CFX to demonstrate the validity of dimensionless group second, third, fifth and to provide a deeper insight into the underlying physics of the heat transfer in SCW.

6. Conclusions

Discriminated dimensional analysis has been performed for supercritical pressure water pipe flow heated through the pipe solid wall to identify the independent dimensionless groups (which play an independent role in the above mentioned thermal hydraulic phenomena) in order to serve a theoretical base to comparison between well known supercritical pressure water pipe heat transfer experiments and results of their CFD numerical simulation.

The above presented discriminated dimensional analysis has provided two independent dimensionless groups which match the experimental experience and well accepted knowledge: the Newton low of heat transfer and the order of magnitude of needed development length of laminar flow. The other three independent dimensionless groups concern the heat convection and conduction in the near wall and bulk region where the local phenomena of heat transfer in SCW occurs. Concerning the heat convection the local velocity and local density (together the local mass flux) and the local specific heat could counterbalance the effect of high heat flux in case they represent together a high value. On the other hand that is very apparent if local heat conduction coefficient remains high then due to strong heat conduction through boundary layer the temperature difference represents a relatively low value.

In the next step well published experiments of vertically installed, straight, smooth bore tubes with upward flow of SCW will be investigated by the CFD code ANSYS CFX to demonstrate the validity of dimensionless groups concerning the heat convection and conduction and to provide a deeper insight into the underlying physics of the heat transfer in SCW.

7. Acknowledgement

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