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Theoretical and Numerical Study of Heat Transfer Deterioration in HPLWR

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ABSTRACT

A numerical investigation of the Heat Transfer Deterioration (HTD) phenomena is performed using the low-Re $k - \omega$ turbulence model. Steady state Reynolds-averaged Navier-Stokes equations are solved together with equations for the transport of enthalpy and turbulence. Equations are solved for the supercritical water flow at different pressures, using water properties from the standard IAPWS tables. All cases are extensively validated against experimental data. The influence of buoyancy on the HTD is demonstrated for different mass flow rates in the heated pipes.

Numerical results prove that the RANS low-Re turbulence modeling approach is fully capable to simulate the heat transfer in pipes with the water flow at supercritical pressures. A study of buoyancy influence shows that for the low mass flow rates of coolant, the influence of buoyancy forces on the heat transfer in heated pipes is significant. For the high flow rates, buoyancy influence could be neglected and there are clearly other mechanisms causing the decrease in heat transfer at high coolant flow rates.

1 INTRODUCTION

High Performance Light Water Reactor (HPLWR) is one of the six Gen-IV reactor concepts, based on the existing boiling and pressurized water reactors. Water at high pressures ($p>22.1$MPa), used as a cooling medium, allows significant increase of the system thermal efficiency. As the reactor is designed to operate at pressure higher than the supercritical one, there is no phase change between liquid and vapour phase and therefore the boiling crisis is inherently avoided. However, close to the pseudo-critical point, where the thermo-physical properties vary significantly, the heat transfer shows unusual behaviour. Enhanced, normal or deteriorated heat transfer regime may exist depending on the flow parameters and the applied heat flux.

In the deteriorated region, the heat transfer coefficient decreases causing the increase in wall temperature. As shown by several experiments (Shitsman [1], Kirillov et. al. [2] or Ornatskij et. al. [3]), the increase in wall temperature is not so rapid as in case of boiling crisis in classical light water reactors. Due to the relatively mild increase in wall temperature, the onset of HTD (Heat Transfer Deterioration) is not well defined. Many different definitions are used in the literature. For example Koshizuka et. al. [4] defined the onset of HTD as the following ratio:

$$D_r = \frac{\alpha}{\alpha_0} < 0.3 \quad (1)$$

where α_0 is the heat transfer coefficient calculated numerically by Jones-Launder's k-ε model using constant properties at bulk liquid temperature. Heat transfer is considered to be deteriorated when $D_r<0.3$.
The modified Koshizuka's criterion for the onset of the HTD is frequently used. Here, α_0 is calculated using the Dittus-Boelter [5] correlation:

$$Nu = 0.023\,\mathrm{Re}^{0.8}\,\mathrm{Pr}^{0.4} \quad (2)$$

with thermo-physical properties evaluated at the bulk liquid temperature. Differences in the definition of the onset of the HTD could lead to the relevant differences in its prediction. However, for the present study the exact definition is not relevant, as all simulations are performed in the highly deteriorated region.

2 NUMERICAL MODELING ISSUES

The effect of buoyancy and its influence on the heat transfer is simulated numerically, using the Ansys-CFX 11.0 computational code, for steady state flow within heated pipes. All simulations which include heat transfer require proper resolution of the boundary layer. The standard k-ε turbulence model offers very robust and reliable modeling of turbulence for the bulk flow. However, for the near wall region ($y^+<30$), the flow is approximated by wall functions. This means, the whole viscous sublayer and part of the buffer layer is not resolved numerically with the k-ε model.

The standard k-ω turbulence model, as developed by Wilcox [6], allows resolving the viscous sublayer. However this model is known to be sensitive to the free stream conditions. Strong variations of final results could occur depending on the value of the turbulent frequency specified at the inlet.

The Shear Stress Transport (SST) model, as developed by Menter [7] combines the robustness of the k-ε model for the bulk flow and the low-Re treatment of the boundary layer using the modified Wilcox k-ω model.

As the validation of different cases against the experimental data proves, the low-Re SST model is fully capable to model the heat transfer to supercritical water (including the deteriorated region) and the calculated results are in a very good agreement with the experimental data. This is demonstrated in Figure 1, where the comparison of SST and k-ε turbulence models is shown for the experiment by Ornatskij et. al. [3] (described later). The heat transfer coefficient is plotted against the bulk fluid temperature.

The k-ε model fails to calculate the heat transfer to supercritical fluid in deteriorated region. The SST model predicts the heat transfer coefficient in a very good agreement with the experimental results. The main reason for the substantial difference in results for these two turbulence models is the near wall treatment. SST model allows resolving the boundary layer numerically. Standard k-ε turbulence model approximates the boundary layer by wall functions (for coarse grid, $y^+>5$), which are not suitable for the flows where the thermo-physical properties changes rapidly close to the wall. For the very fine grids ($y^+<1$) the non-linear damping functions, required for the k-ε model, cause the loss of accuracy and so the final results differ substantially from the experimental values.

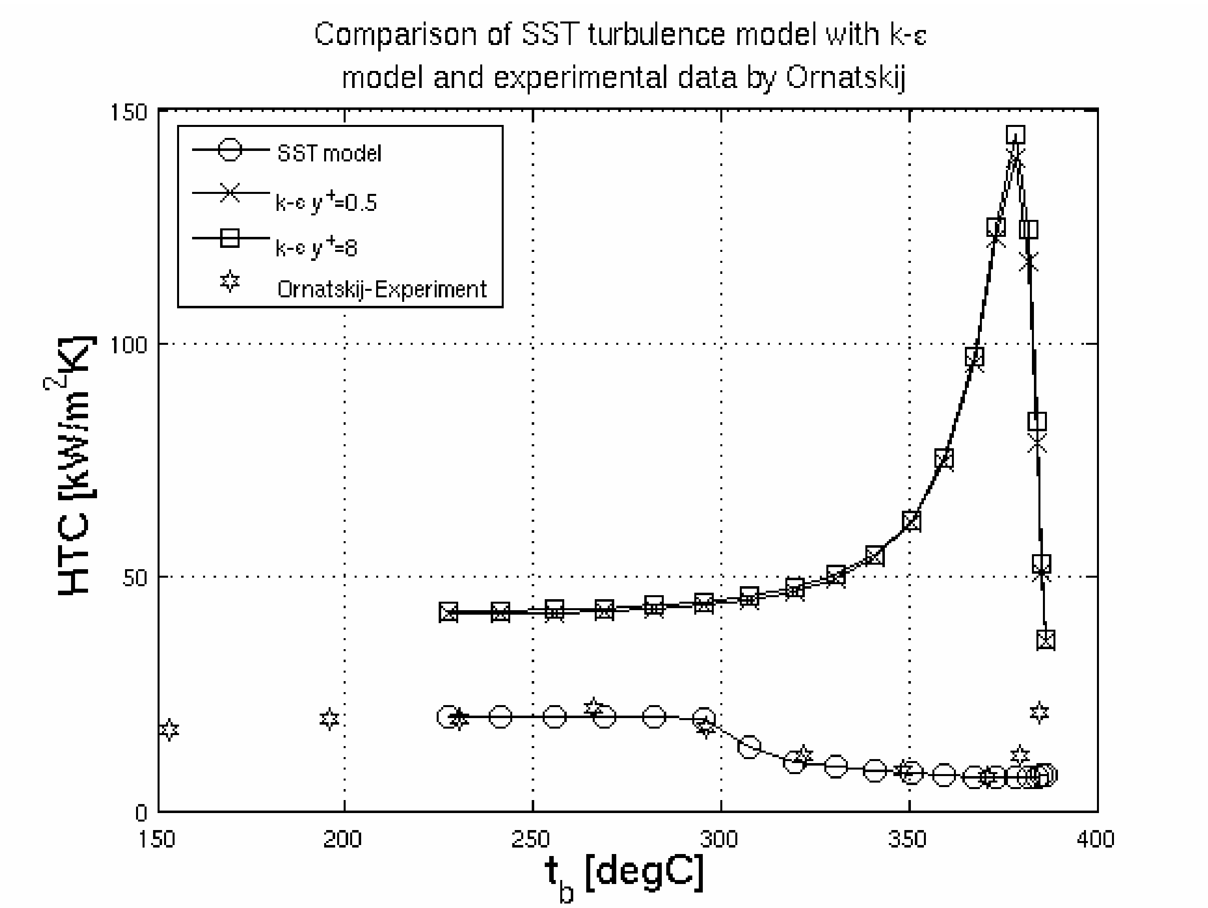

Figure 1**:** Comparison of SST turbulence model, k-ε model and experiment by Ornatskij et. al. [3]. Flow conditions: p=25.5MPa, d=3mm, G=1500kg/m^2s and q=1810kW/m^2.

Sensitivity analysis for the grid size is also made for the SST model. In order to resolve the boundary layer, the non-dimensional distance of the first computational cell from the wall (y^+) should be kept below 1. Figure 2 proves that if this condition is fulfilled, the results are insensitive to the grid size. This behavior results from the implementation of the wall treatment by SST turbulence model in Ansys CFX-11.0 computational software. Here, if the non-dimensional distance of the first computational cell y^+ is bigger than 1, the near wall region is approximated by wall functions, which leads to the similar behavior of results as in the case of k-ε model. If the distance is smaller than y^+=1, boundary layer is resolved numerically leading to the correct solution.

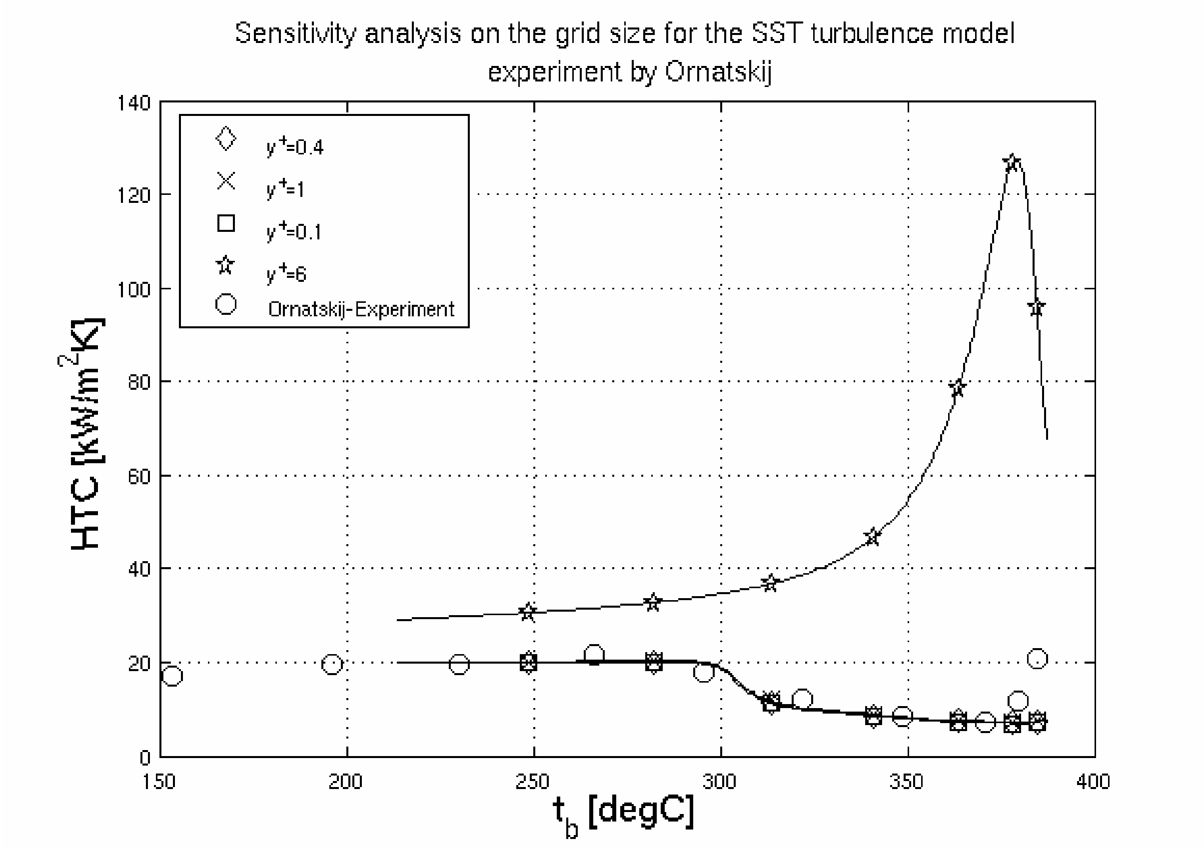

Figure 2: Sensitivity analysis on the grid size for the SST turbulence model, comparison with the experiment by Ornatskij et. al. [3]. Flow conditions: p=25.5MPa, d=3mm, G=1500kg/m^{2}s and q=1810kW/m^2.

3 INFLUENCE OF BUOYANCY ON HEAT TRANSFER

Once the correct numerical results are obtained, the influence of buoyancy on heat transfer could be studied by the comparison of the solution obtained with and without the buoyancy terms in the governing equations. The expected influence of buoyancy can be examined by the ratio of Grashof and Reynolds numbers.

$$\frac{Gr}{\mathrm{Re}^2} = \frac{g\beta L\Delta T}{U^2} \tag{3}$$

where g is the gravitational constant, β is the thermal expansion coefficient, L is the characteristic length, ΔT is the temperature change and U is the velocity of coolant. For the normal operating conditions in the pressurized water reactors (PWR), this ratio is small due to the very high flow velocities, relatively small change in temperature and the low value of the thermal expansion coefficient. Therefore the buoyancy influence on heat transfer could be neglected in conditions typical for PWRs.

However, for the HPLWR conditions, even though the flow velocity is relatively high, there is a strong change in thermo-physical properties, namely density and thermal expansion coefficient, thus the ratio of Grashof and Reynolds numbers may be relevant. It should be pointed out that the buoyancy is not the only phenomenon causing the HTD. Its influence strongly depends on the flow conditions. Several resources show that other effects, such as the streamwise acceleration (McEligot et. al. [8]) or the direct change of the thermo-physical properties (Koshizuka et. al. [4]), could cause the heat transfer to deteriorate.

In the vertical pipes with upward flow, the buoyancy accelerates the flow close to the wall, where there is the highest density difference. The increase of velocity causes the decrease of the velocity gradient and thus the decrease of the turbulent kinetic energy. Loss of the turbulence close to the wall then decreases the heat transfer coefficient. In order to examine this effect, Mikielewicz et. al. [9] proposed the following non-dimensional number:

$$Bo = \frac{Gr^{*}\delta_{M+}(v_w / v_b)(\rho_w / \rho_b)^{0.5}}{2Nu_{Dh}\,\mathrm{Re}_{Dh}^{3}(f_\tau /2)^{1.5}\,\mathrm{Pr}^{0.4}} \tag{4}$$

which applies for arbitrary heated surfaces in a vertical duct (δ_{M+} is a distance near the edge of the viscous layer, Jackson [10] proposed 26). Gr^* is defined as:

$$Gr^{*} = g\beta q_{wall}'' D_h^4 / kv^2 \tag{5}$$

According to Mikielewicz et. al. [9], Bo>0.1 corresponds to the onset of significant buoyancy effects. When applying the Dittus-Boelter correlation (equation 2) and Blasius correlation for the friction factor, a modified Bo number can be defined:

$$Bo^{*} = \frac{Gr^{*}}{\mathrm{Re}_{Dh}^{3.425}\,\mathrm{Pr}^{0.8}} \tag{6}$$

Then the onset of significant buoyancy influence is expressed as:

$$Bo^{*} > 6.10^{-7} \tag{7}$$

4 NUMERICAL RESULTS AND DISCUSSION

Two different experiments are numerically simulated with Ansys CFX-11.0 computational software, using the SST turbulence model in order to examine the influence of buoyancy on the heat transfer. Experiments by Shitsman [1] and Ornatskij et. al. [3] were chosen due to the following reasons.

Both experiments measure the heat transfer in the highly deteriorated region. On the one hand, the experiment by Ornatskij at. al. [3] is performed for very high coolant flow rate, where the buoyancy force should have no effect on the heat transfer according to equation 7. On the other hand, experimental data by Shitsman [1] are in the region of high buoyancy influence.

4.1 Heat Transfer at Low Coolant Flow Rates

Flow simulation at low coolant flow rate is demonstrated in the experiment by Shitsman [1]. This experiment is performed with supercritical water at p=233bar in a pipe with inner diameter d=8mm. The pipe is uniformly heated with a heat flux of 319.87kW/m^2 and the coolant flow rate is G=430kg/m^{2}s. For these flow parameters, Mikielewicz condition for the influence of buoyancy is fulfilled.

Comparison of the numerical results with the experimental data is shown in Figure 3 where the wall temperature is plotted against the bulk enthalpy. There is a very good agreement between CFX-11.0 results and experimental data. The solver is capable to capture also the deteriorated region represented by the two peaks in the wall temperature.

Solving the same equations on an identical numerical grid without the buoyancy terms in the NS equations leads to substantial under-prediction of the wall temperature. This means that the buoyancy terms in Navier-Stokes equations are responsible for the increase in the wall temperature and hence the heat transfer deterioration is caused by the buoyancy force, as was predicted by equation 7. A possible explanation of this phenomenon is that the buoyancy accelerates the flow close to the wall leading to the more flat velocity profile, decrease in the velocity gradient and decrease of turbulence. Decrease in turbulence then leads to the decrease of the heat transfer coefficient, and thus to the increase in wall temperature.

The Dittus-Boelter correlation (equation 2) prediction of the wall temperature is plotted to visualize, how the heat transfer regime differs from the normal regime.

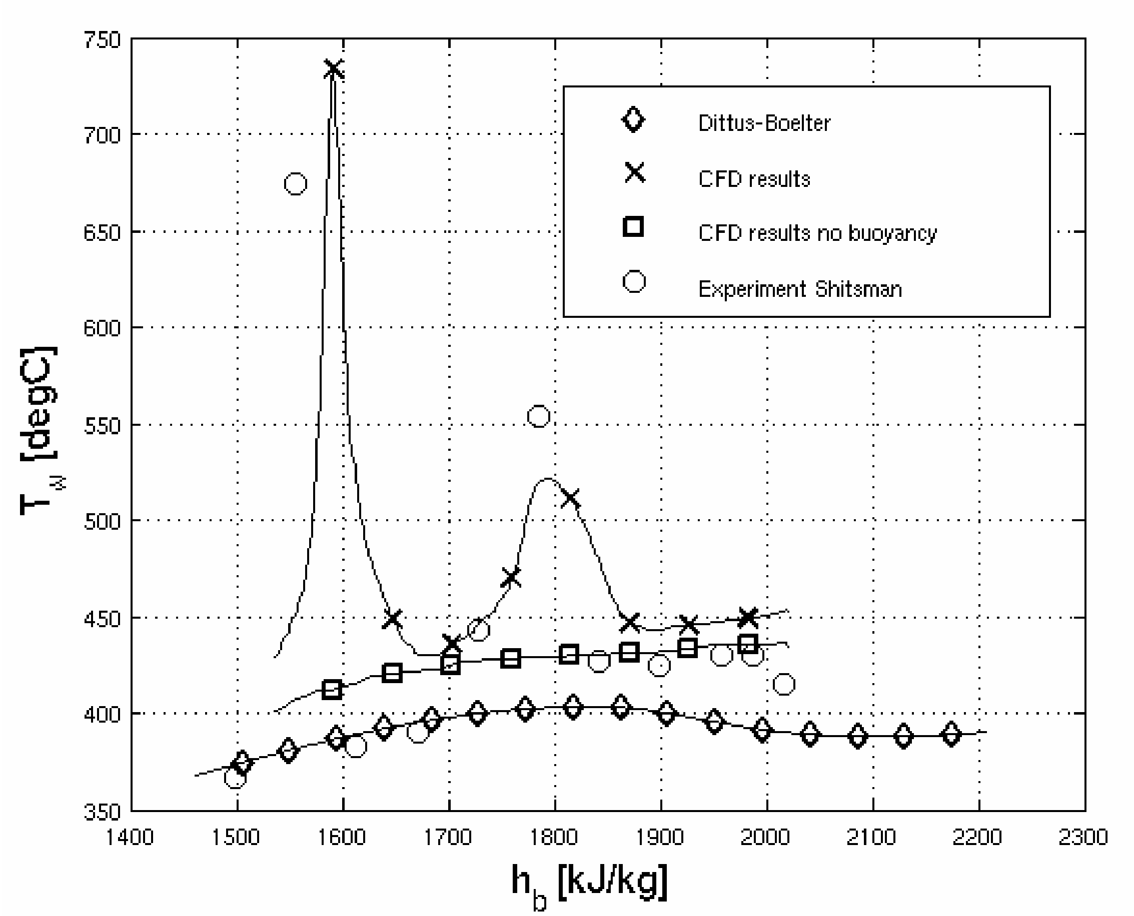

Figure 3: Comparison of the numerical results with the experiment by Shitsman [1] and the correlation by Dittus-Boelter. Flow conditions: p=23.3MPa, d=8mm, G=430kg/m^{2}s and q=319.87kW/m^2.

4.2 Heat Transfer at High Coolant Flow Rates

For the high flow rates, when the condition Bo*>6.10^{-7} is not fulfilled, the buoyancy could be neglected according to Mikielewicz [9]. Such a flow is demonstrated by the experiment of Ornatskij et al. [3]. Here the flow parameters of supercritical water at p=255 bar are measured in a pipe with inner diameter d=3mm. The pipe is uniformly heated with heat flux of 1810kW/m^2 and the coolant flow rate is G=1500kg/m^{2}s.

Even though the buoyancy should not be relevant, heat transfer is still deteriorated (as measured by Ornatskij et.al. [3]) according to the definition:

$$D_r = \frac{\alpha}{\alpha_0} < 0.3 \tag{8}$$

where α_0 is an ideal heat transfer coefficient calculated with the Dittus-Boelter correlation (equation 2) with the properties evaluated at the bulk temperature.

Numerical results and the comparison with the experiment and Dittus-Boelter correlation are shown in Figure 4. The influence of buoyancy is small and there are clearly other mechanisms which cause the decrease in heat transfer. According to Koshizuka et. al [4], change in the thermo-physical properties, such as viscosity and thermal conductivity may lead to the decrease in heat transfer coefficient. The influence of these phenomena could be demonstrated in the same way as the influence of buoyancy, if numerical simulations with constant and variable properties are compared.

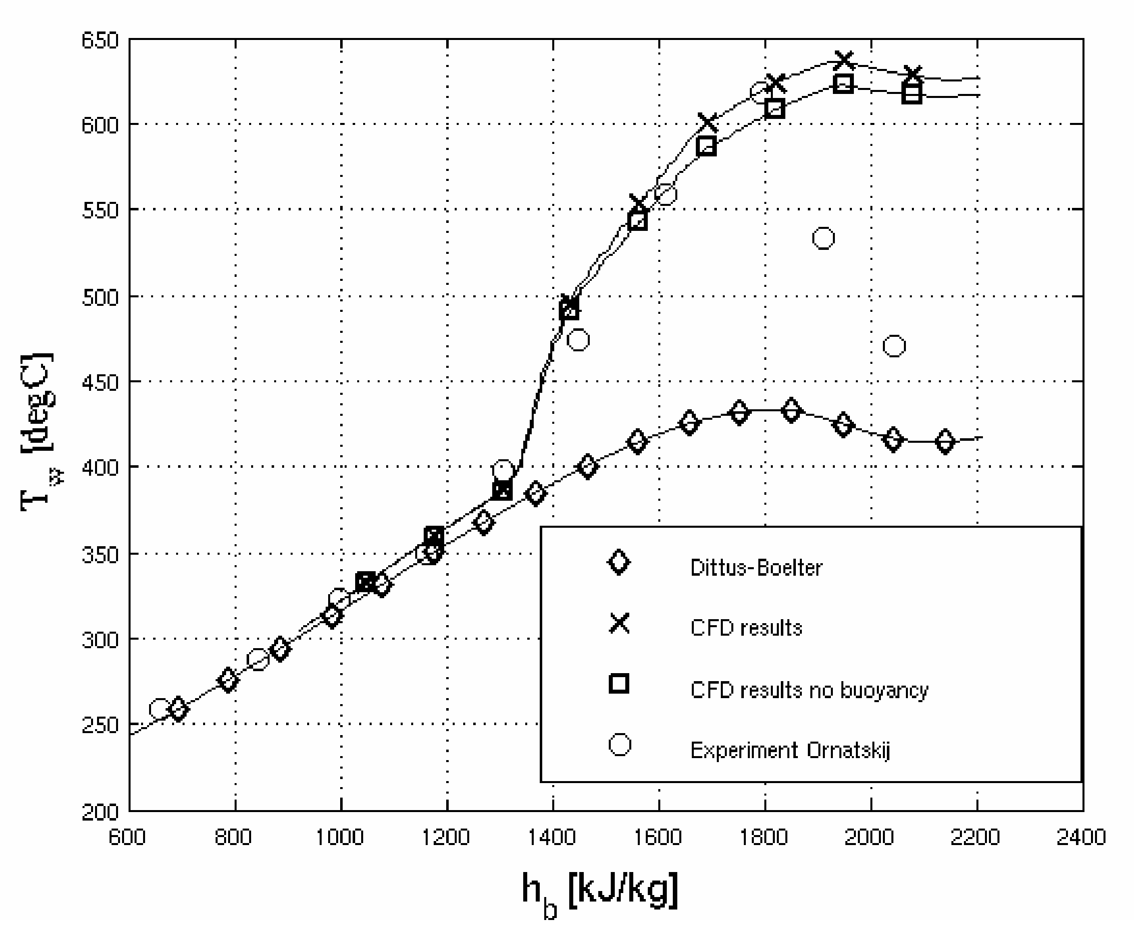

Figure 4**:** Comparison of the numerical results with the experiment by Ornatskij [3] and the correlation by Dittus-Boelter. Flow conditions: p=25.5MPa, d=3mm, G=1500kg/m^{2}s and q=1810kW/m^2.

5 CONCLUSIONS

The present work demonstrates the ability of the low-Re RANS turbulence treatment to model the heat transfer under supercritical pressure. Proper grid resolution of the boundary layer and the accuracy in thermo-physical properties show very high influence on final results.

Buoyancy influence on the heat transfer deterioration was demonstrated. The results proved that under some conditions, buoyancy is the phenomenon that governs the heat transfer deterioration, mainly for relatively low coolant flow rates and high heat fluxes. However, for high coolant flow rates there exist clearly other mechanisms which have to be identified and examined in order to be able to successfully predict the onset of HTD.

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