# DEVELOPMENT OF A HEAT TRANSFER CORRELATION FOR THE HPLWR FUEL ASSEMBLY BY MEANS OF CFD ANALYSES

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## Abstract

The High Performance Light Water Reactor (HPLWR) has been under development in the HPLWR phase-2 project funded by the European Union. The HPLWR project started September 2006 and ended February 2010. Work package 5 within this project involves the improved understanding of heat transfer, CFD model development and validation, and the prediction of the heat transfer rate in a HPLWR fuel assembly. USTUTT, KTH, NRG and FZK contributed to this work package. The overall objective of work package 5 was the development of a heat transfer correlation for the prediction of the heat transfer rate in the HPLWR fuel assembly by means of CFD analyses. In the HPLWR fuel assembly, a helical wire has been selected as spacer and mixing device. This wire-wrap imposed a significant challenge in the development of the geometrical models for the CFD analyses. Due to the wire-wrap it was not possible to model a full fuel assembly consisting of 40 rods. Therefore, an alternative procedure has been adopted to develop a heat transfer correlation for the HPLWR fuel assembly. This procedure involved the definition of correction factors accounting for the effect of the rod bundle geometry and the wire-wrap spacer with respect to a smooth circular tube with super-critical water.

The present paper describes the procedure followed in work package 5 of the HPLWR phase-2 project for the development of a heat transfer correlation for the HPLWR fuel assembly design and presents the derivation of the applied correction factors from a large set of CFD analyses for different representative geometries like an annulus, a single sub-channel and a 4 rod-bundle, all with and without inclusion of the wire wrap.

Keywords: Thermal hydraulics, CFD analyses, heat transfer, super critical water, wire wrap.

## 1. Introduction

The High Performance Light Water Reactor (HPLWR) has been under development in the HPLWR phase-2 project funded by the European Union. The HPLWR project started September 2006 and ended February 2010. Work package 5 (WP5) within this project provides an improved understanding of heat transfer, CFD model development and validation, and the prediction of the heat transfer rate in a HPLWR fuel assembly.

The objectives of WP5 of the HPLWR phase-2 project are to reduce the large uncertainty in heat transfer correlations used at supercritical pressures and to understand basic heat transfer phenomena with super-critical water, such as heat transfer deterioration. A heat transfer correlation suitable for the HPLWR design including the wire wrap as a spacer has been derived from an extensive set of CFD analyses performed by USTUTT, KTH, and NRG. A single heated pin both in an annulus and in a square channel, a sub channel and an assembly of 4 heated pins have been studied. All geometries have been modeled separately with and without the presence of a wire wrap. The CFD results have been used to derive correction factors to update a base correlation from literature to account for the effect of the wire-wrap and the effect of the geometry of the HPLWR fuel assembly.

The outline of the paper is as follows. Chapter 2 presents a literature review on heat transfer correlations for rod bundles, giving the required background information for constructing a heat transfer correlation for the HPLWR fuel assembly. In chapter 3 the base heat transfer correlation and the correction factors for geometry and wire are defined. Chapter 4 presents the CFD analyses with the calculated wire and geometry factors. The proposed heat transfer correlation is given in chapter 5.

## 2. Heat transfer in rod bundles

The structure of turbulent flow in channels with non-circular geometry is much more complex than that in circular tubes. The reasons for the difference stem from the fact that the flow, even in the time-averaged sense, is inherently three-dimensional in the former case. This means that there exists a net convective heat transfer in the direction perpendicular to the main flow due to so called secondary flows. Rod bundles show also different characteristics as far as the transition from the laminar to the turbulent flow is concerned. Furthermore, transition to the fully-developed turbulent flow in rod bundles takes place at higher Reynolds numbers in comparison to that of a tube with an equivalent diameter. The fully developed turbulent flow in rod bundles with pitch-to-diameter ratio $p/d$ larger than 1.1 takes place at a Reynolds numbers higher than $1\sim1.5\cdot10^4$. Due to the above-mentioned differences heat transfer correlations developed for tubes are not applicable, and correlations for rod bundles are developed from experimental data obtained in such geometries.

Analysis of a broad experimental database with heat transfer measurements in rod bundles indicates that [if the equivalent hydraulic diameter of a bundle is expressed in the traditional way as $d_h = 4\ A/P$, where $A$ is the bundle flow cross-section area and $P$ is the wetted perimeter, and the heat transfer coefficient is correlated in the usual way as Nu = $f$(Re, Pr, ...)] the Nusselt number is a non-linear function of the pitch-to-diameter ratio $p/d$. This dependence is particularly strong for low values of the $p/d$ ratio, but disappears with increasing value of the ratio. For a $p/d$ value of around 1.2 the heat transfer in rod bundles is effectively the same as circular pipes with an equivalent hydraulic diameter.

## 2.1 Overview of heat transfer correlations for rod bundles

There are several heat transfer correlations available in the open literature that have been developed for rod bundles under sub-critical conditions. Not all of them, however, are accurate enough to be recommended for general applications. In addition, only the correlations for rod-bundles arranged in a square lattice are relevant here, since this type of arrangement is employed in the proposed HPLWR reactor core design. Three widely used correlations for rod bundles arranged in a square lattice under sub-critical conditions are given below:

*Weisman [1]:*

$$\mathrm{Nu} = A \cdot \mathrm{Re}^{0.8}\,\mathrm{Pr}^{1/3}, \quad \text{where } A = 0.042\,p/d - 0.024 \tag{1}$$

The correlation of Weisman is valid in the range: $1.1 < p/d < 1.3$.

*Markoczy [2]:*

$$\mathrm{Nu} = A \cdot \mathrm{Re}^{0.8}\,\mathrm{Pr}^{0.4}, \tag{2}$$

$$\text{where } A = 0.023\left[1 + 0.91 \cdot \mathrm{Re}^{-0.1}\,\mathrm{Pr}^{0.4}\left(1 - 2e^{-B}\right)\right]$$

$$\text{and } B = \frac{4}{\pi}\left(\frac{p}{d}\right)^2 - 1$$

The validity range for the correlation of Markoczy is: $1.02 < p/d < 2.5$, $0.66 < \mathrm{Pr} < 5$ and $3 \cdot 10^3 < \mathrm{Re} < 10^6$.

*Ajn and Putjkov [3]:*

$$\mathrm{Nu} = A \cdot \mathrm{Re}^{0.8}\,\mathrm{Pr}^{0.4}, \tag{3}$$

$$\text{where } A = 0.023\left[1.184 + 0.351 \cdot \lg\left(p/d - 1\right)\right]$$

The correlation of Ajn and Putjkov is applicable to gas flow in tight rod bundles and is valid in the range: $1.03 < p/d < 2.4$.

There are very few correlations that have been developed for heat transfer to super-critical water flowing in rod bundles. Dyadyaki and Popov [4] used 504 experimental points obtained in a tight seven-rod bundle and propose the following correlation:

*Dyadyaki and Popov [4]:*

$$\mathrm{Nu} = 0.021 \cdot \mathrm{Re}_b^{0.8}\,\overline{\mathrm{Pr}}_b^{0.7}\left(\frac{\rho_w}{\rho_b}\right)^{0.45}\left(\frac{\mu_b}{\mu_{in}}\right)^{0.2}\left(\frac{\rho_b}{\rho_{in}}\right)^{0.1}\left(1 + \frac{2.5 d_h}{x}\right), \tag{4}$$

$$\text{where } \overline{\mathrm{Pr}}_b = \frac{\bar{c}_p \mu_b}{\lambda_b} \text{ and } \bar{c}_p = \frac{i_w - i_b}{T_w - T_b}.$$

Here subscripts *w, b* and *in* refer to wall, bulk and inlet, respectively; $d_h$ is the hydraulic diameter and $x$ is the distance from the inlet. The correlation of Dyadyaki and Popov is valid only for the rod bundle geometry as used in the experiments and cannot be applied for HPLWR geometry. In particular, the correlation is independent of the pitch-to-diameter ratio *p/d*, which limits its applicability.

## 2.2 Effect of pitch-to-diameter ratio

The general form of the heat transfer correlations listed in the previous section is as follows:

$$\mathrm{Nu}_{bundle} = F_{geo}\left(p/d, \mathrm{Pr}, \mathrm{Re}\right) \cdot \mathrm{Nu}_{base}\left(\mathrm{Re}, \mathrm{Pr}\right) \tag{5}$$

where $\mathrm{Nu}_{bundle}$ is the Nusselt number in the rod bundle, $F_{geo}$ a geometry factor accounting for the effect of the rod bundle geometry and $\mathrm{Nu}_{base}$ the base correlation. Selecting, for instance, Dittus-Boelter ($\mathrm{Nu}=0.023\cdot\mathrm{Re}^{0.8}\cdot\mathrm{Pr}^{0.4}$) as the base correlation, the corresponding geometry factors can be deduced for Eq. (1) through (3). The Weisman correlation contains $\mathrm{Pr}^{1/3}$, whereas the Dittus-Boelter correlation contains $\mathrm{Pr}^{0.4}$, giving a geometry factor of $(A/0.023)\cdot\mathrm{Pr}^{1/15}$. The geometry factor deduced from the Markoczy and the Ajn and Putjkov correlation is equal to $A/0.023$.

The geometry factor for the correlations given in Eq. (1) to (3) is shown in Figure 1. Each of the factors has been plotted in the range of their applicability. Since *p/d* for the HPLWR is equal to 1.18, all correlations can be applied for this particular geometry.

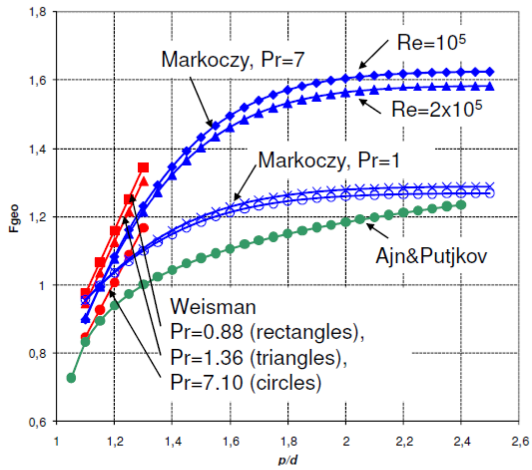



Figure 1 Rod bundle geometry factor $F_{geo}$ as a function of pitch-to-diameter ratio *p/d* deduced from three common heat transfer correlations for rod-bundles in a square lattice arrangement.

## 2.3 Effect of wire

Wires influence heat transfer in two ways: (1) by increasing turbulence, and (2) by increasing the heat transfer area. The combined effect of the wire is that the heat transfer coefficient is higher in bundles with wires as compared to bare bundles. According to measurements reported by Fenech [5], the heat transfer coefficient in a rod bundle with *p/d* = 1.05 and wire wrap was 75% higher than predicted from the Weisman correlation. This conclusion, however, should be taken with caution since the Weisman correlation is not valid for such low values of the pitch-to-diameter ratio. The same author observed also that the ratio of the mean heat transfer coefficient to the heat transfer coefficient in hot spots varied from 1.4 (for low Reynolds numbers) to 1.08 (for high Reynolds numbers).

## 3. Heat transfer correlation for the HPLWR fuel assembly

The heat transfer correlation proposed here for the HPLWR fuel assembly has the following form:

$$\mathrm{Nu}_{HPLWR} = F_{geo} \cdot F_{wire} \cdot \mathrm{Nu}_{base}, \tag{6}$$

where $\mathrm{Nu}_{base}$ is the base heat transfer correlation for a reference geometry, $F_{geo}$ the correction factor accounting for the effect of the rod bundle geometry and $F_{wire}$ the correction factor accounting for the effect of the wire wrap spacer applied in the HPLWR fuel assembly. The base heat transfer correlation $\mathrm{Nu}_{base}$ and the expressions for the correction factors $F_{geo}$ and $F_{wire}$ will be defined in the next subsections. The base heat transfer correlation is taken from literature. The geometry and wire factor for the HPLWR fuel assembly will be derived from CFD analyses of several representative geometries in chapter 4.

### 3.1 Base heat transfer correlation

The heat transfer correlation of Jackson [6] derived for the heat transfer to super-critical water in circular tubes is selected as the base correlation $\mathrm{Nu}_{base}$ in Eq. (6). Jackson's correlation is defined as follows:

$$\mathrm{Nu}_{base} = 0.0183 \cdot \mathrm{Re}_b^{0.82}\, \mathrm{Pr}_b^{0.5} \left(\frac{\rho_w}{\rho_b}\right)^{0.3} \left(\frac{\overline{c_p}}{c_{pb}}\right)^{n}, \tag{7}$$

where the exponent $n$ is given as:

$n = 0.4$ for $T_b < T_w < T_{pc}$ and $1.2T_{pc} < T_b < T_w$,

$n = 0.4 + 0.2\left(\dfrac{T_w}{T_{pc}} - 1\right)$ for $T_b < T_{pc} < T_w$,

$n = 0.4 + 0.2\left(\dfrac{T_w}{T_{pc}} - 1\right)\left[1 - 5\left(\dfrac{T_b}{T_{pc}} - 1\right)\right]$ for $T_{pc} < T_b < 1.2T_{pc}$ and $T_b < T_w$,

here $T$ is the temperature in Kelvin, $\rho$ the density and $c_p$ the specific heat. Indices $b$, $pc$ and $w$ in the above equations refer to the bulk, pseudo-critical and wall temperature, respectively. Eq. (7) contains a modified specific heat calculated that is defined as $\overline{c_p} = \dfrac{i_w - i}{T_w - T_b}$.

### 3.2 Geometry factor

Using Eq. (5), the geometry factor is defined as:

$$F_{geo} = \frac{\mathrm{Nu}_{bare\,bundle}}{\mathrm{Nu}_{base}} , \tag{8}$$

where $\mathrm{Nu}_{bare\ bundle}$ is the average Nusselt number for a bare rod bundle. According to Figure 1 the geometry factor for the HPLWR fuel assembly is in a range from 0.9 to 1.15 for sub-critical conditions, where the lowest value is given by the Ajn & Putjkov correlation and the highest value by the Weisman correlation.

### 3.3 Wire factor

The wire factor is defined as follows:

$$F_{wire} = \frac{\mathrm{Nu}_{wired\ bundle}}{\mathrm{Nu}_{bare\,bundle}} , \tag{9}$$

This factor is a ratio of the average Nusselt number for a rod bundle with wire-wrap spacers to the average Nusselt number for a bare rod bundle. This factor varies with geometry and Reynolds number, and can be in a range from 1 to 1.6 according to experimental data (*e.g.* Fenech [5]).

## 4. CFD analyses

In this paper, a base correlation for heat transfer to super-critical water in a smooth circular tube is adapted for heat transfer in a HPLWR fuel assembly. As explained above, the adopted strategy involves the definition of correction factors accounting for the effect of the rod bundle geometry and the wire wrap spacer. The derivation of these correction factors by means of CFD analyses is presented in this chapter. It should be emphasized, here, that the derived heat transfer correlation will be employed in safety or system codes to calculate average fuel rod surface temperatures. For this purpose, average flow features and related heat transfer rates suffice.

### 4.1 HPLWR Evaporator Conditions

The HPLWR core is an innovative three-pass design. This core consists of 52 fuel assemblies in the evaporator, 52 fuel assemblies in the super-heater 1 and 52 fuel assemblies in the super-heater 2 (see *e.g.* Schulenberg [7] for details). The HPLWR fuel assembly consists of 40 fuel rods arranged in a square lattice. The present work considers an upward flow of super-critical water in the evaporator. Super-critical water enters the HPLWR evaporator at a bulk temperature of about 310 °C and exits at a bulk temperature of about 390 °C at an operating pressure of 25 MPa. The pseudo-critical temperature of super-critical water at this pressure is about 385 °C. Thus, the coolant crosses its pseudo-critical point in the HPLWR evaporator. Therefore, the evaporator is considered within WP5 for analyzing the different heat transfer phenomena with super-critical water.

In the HPLWR evaporator a nominal sub-channel has a super-critical water mass flux of 1665 kg/m$^2$s and a heat flux up to 859 kW/m$^2$ applied at the fuel rods surface. Whereas a hot sub-channel has a mass flux of 1332 kg/m$^2$s and a heat flux up to 1375 kW/m$^2$ applied at the fuel rods surface. Both these conditions are employed for CFD analyses and are summarized in Table 1.

| **Conditions** | **Mass flux (kg/m$^2$s)** | **Heat flux (kW/m$^2$)** |
|---|---|---|
| Nominal | 1665 | 859 |
| Hot-channel | 1332 | 1375 |

Table 1 Nominal and hot sub-channel conditions in the HPLWR evaporator.

## 4.2 HPLWR representative geometries

The different representative geometries, considered for analyzing the effect of the geometry and the wire-wrap spacer on the heat transfer in the HPLWR fuel assembly, are presented in Table 2 by means of simple drawings. All these geometries are modelled with and without helical wire-wrap around the fuel rod(s). The annulus is even considered with two wire-wrap spacers, one around the fuel rod and one along the inside of the outer tube wall.

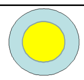
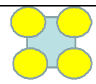
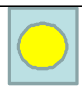
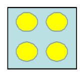
| **Geometry name** | **Schematic representation** | **Geometry name** | **Schematic representation** |
|---|---|---|---|
| Annulus |  | Sub-channel |  |
| Square annulus |  | Four rod-bundle |  |

Table 2 Overview of the considered geometries for heat transfer analyses with super-critical water at HPLWR evaporator conditions. The yellow region represents the fuel rods and the blue region the flow area for the super-critical water coolant.

Although the full fuel assembly could not be modeled, all the selected geometries have a level of relevance to the design of the HPLWR fuel assembly. In fact, it is attempted to imitate the flow characteristics and related heat transfer in different parts of the HPLWR fuel assembly by using these simplified geometries. The selected four rod-bundle, for instance, comprises of three different types of sub-channels found in the HPLWR fuel assembly: the central (A), wall (B) and outer corner sub-channel (C), as shown in Figure 2a. These cover some of the HPLWR sub-channels with different hydraulic diameters as discussed in *e.g.* Waata [8] and Kiss et al. [9]. In this way, the four rod-bundle geometry without and with wire-wraps aims at capturing more realistic flow details around the fuel rods and along the square outer periphery of the HPLWR fuel assembly. The double wired annulus aims to understand the influence of multiple wires on the heat transfer. The fuel rod in the square annulus geometry even includes a cladding to investigate its effect on the heat transfer and the fuel rods surface temperature, see Figure 2c.

Consequently, it can be stated that analyses of these geometries will provide some fundamental understanding of the flow features and related heat transfer in the HPLWR fuel assembly. Moreover, analyses of these geometries will make it possible to determine the correction factors for the proposed HPLWR heat transfer correlation in Eq. (6).

## 4.3 CFD model

The analyses presented in this chapter are performed with the CFD codes ANSYS-CFX 11.0 (USTUTT, KTH) and FLUENT 6.3 (NRG). In general, each institute applied the same guidelines for setting up the computational grid and model [10]. Super-critical water is modelled as an incompressible, single-phase fluid under steady, isobaric, turbulent flow conditions. Temperature dependent properties of super-critical water at an operating pressure of 25 MPa are implemented in the different CFD codes for viscosity, density, thermal conductivity and specific heat. These temperature dependent properties are adopted from the NIST database as in Lemmon et al. [11].

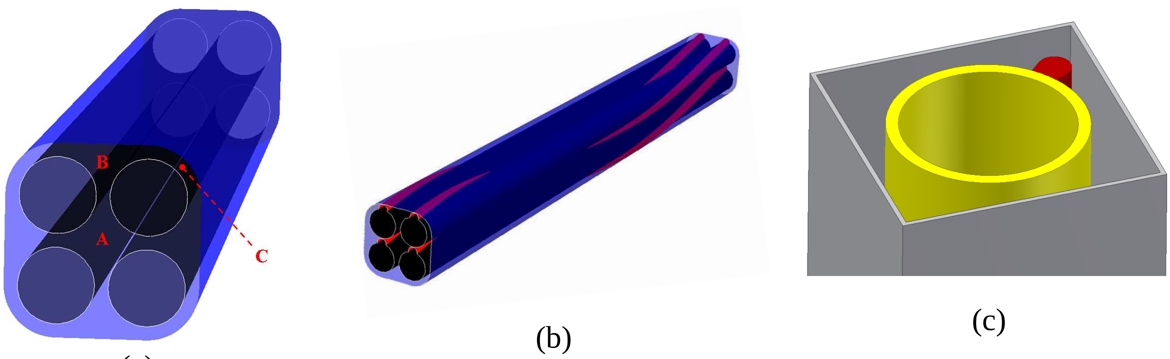
Based on the code validation exercises by Palko and Anglart [12] and Visser et al. [13], the SST k-ω turbulence model with enhanced wall treatment is applied. Buoyancy is included in the transport equations of the model to account for the effect of gravity. An important weakness of this isotropic two-equation RANS (Reynolds Averaged Navier Stokes) based approach is its incapability in predicting secondary flows that appear in rod-bundles. However, the secondary flow in bare rod-bundles with a *p/d* ratio around 1.2 is less than 1% of the axial flow (see e.g. [14]) and the secondary flow cannot develop in wired rod-bundles where the flow is guided by the helical wires [15, 16]. Therefore, it is assumed that the effects of secondary flow on the heat transfer from the fuel rods can be neglected in the present study, which is focused on average flow features of a HPLWR fuel assembly.

The geometries that are analyzed with CFD are listed in Table 2. The hydraulic diameters ($d_h = 4\,A/P$) of these selected geometries are in the range of 4-5 mm. The general features of the modeled geometries correspond to those of the HPLWR fuel assembly and are listed in Table 3. Examples of the geometrical models used in the CFD analyses are shown in Figure 2 for the four rod-bundle without wire, the four rod-bundle with wire and the square annulus with wire and cladding. CFD analyses are performed for the nominal and hot sub-channel HPLWR conditions listed in Table 1. Fully developed flow conditions are imposed at the inlet of the modeled geometries to minimize/avoid inlet effects. These fully developed flow conditions are obtained from a series of isothermal pre-computations with the geometry under consideration.

| **Fuel rods** | **Dimensions** |
|---|---|
| diameter | 8 mm |
| pitch-to-diameter ratio | 1.18 |
| cladding thickness | 0.5 mm |

| **Helical wire-wraps** | **Dimensions** |
|---|---|
| axial pitch | 200 mm |
| diameter | 1.34 mm |

Table 3 General features of the modeled geometries.




(a) (b) (c)

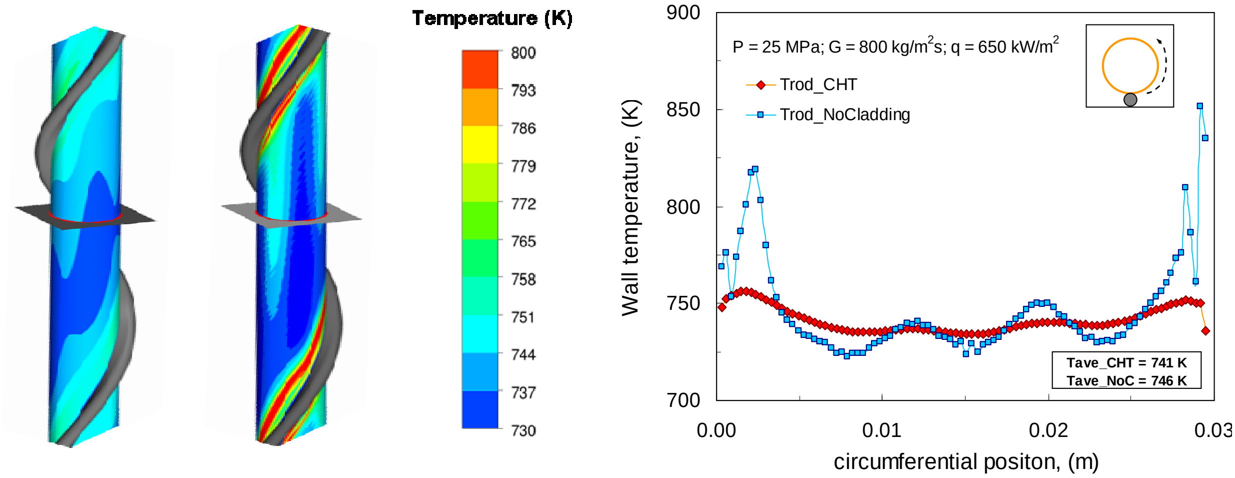
Figure 2 Three examples of geometries employed for the CFD analyses on heat transfer to super-critical water: (a) a four rod-bundle without wire-wrap, (b) a four rod-bundle with wire-wrap and (c) a square annulus with wire-wrap and cladding (c).

Following the recommendations from literature and guidelines from [10], the generated computational grids satisfy the y+ < 1 requirement in order to resolve, both, the thermal and viscous boundary layer near the fuel rod(s). Modelling a wired geometry complicates the model and further increases the grid requirements, resulting in about 16 Million unstructured computational cells for a wired 4 rod-bundle with an axial length of one wire-pitch (*i.e.* 200 mm). This means that resolving a complete HPLWR fuel-assembly with 40 pins will require more than 100 Million computational cells per wire-pitch, which poses a too large computational effort at the moment for most organizations.

## 4.4 CFD results

In this subsection some important results of the RANS CFD analyses are presented in order to explain the heat transfer characteristics observed in the HPLWR relevant geometries.

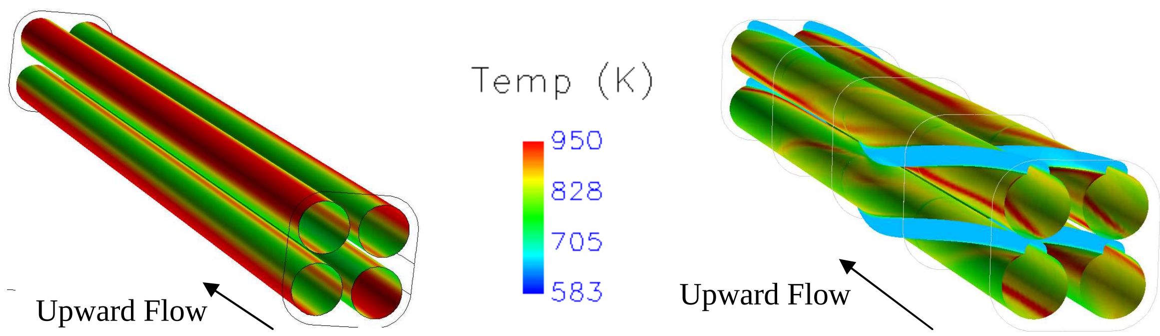
Figure 3 shows the calculated temperature contour over the fuel rod surface for the wired square annulus with and without cladding. High temperature regions close to the wire are observed on the surface of the fuel rod without cladding. Conduction through the cladding effectively reduces these local hot regions near the wire-wrap, making the temperature distribution over the fuel rod more uniform. Although the temperature peaks near the wire are strongly mitigated, the average cladding temperature is only slightly lowered (from 746 K to 741 K) by the effect of conduction through the cladding, as shown in Figure 3c. Since average flow features suffice for the derivation of the HPLWR heat transfer correlation, it is not necessary to take the effect of cladding into account.




(a) (b) (c)

Figure 3 The effect of cladding for the wired square annulus. The calculated temperature contours over the fuel rod surface with and without cladding is shown in (a) and (b), respectively. The calculated temperature profiles over the fuel rod surface at a certain axial position are compared in (c).

Figure 4 shows the calculated temperature contours over the fuel rods of the unwired and wired four rod-bundle assembly under hot-channel conditions. Large regions of high temperature are found on the fuel rods at the corners of the assembly for the unwired rod-bundle. This is attributed to a lower velocity in these regions in the case without wire, see *e.g.* Chandra et al. [14]. With wire present the temperature on the fuel rod surface is more uniform and only shows some streaks of high temperature.




(a) (b)

Figure 4 Calculated surface temperature contours on the fuel rods for an unwired (a) and wired (b) four rod-bundle assembly. Shown are the sections with an axial position between 1.6 and 1.8 m.

The average surface temperatures for the unwired and wired rod-bundle sections shown are about 863 K and 834 K, respectively. Clearly, the presence of the wire-wrap globally reduces the surface temperatures of the fuel rods and results in an improved heat transfer from the rods to the super-critical water coolant. This effect of the wire-wrap is attributed to its impact on the flow. The flow is guided around the fuel rods by the presence of the wire-wrap, generating a strong swirl flow and effective inter sub channel mixing. The average heat transfer rate is improved by about 10% by the presence of wire-wrap.

## 4.5 Derivation of the geometry and the wire factor

Chapters 2 and 3 described a way to estimate two correction factors for adapting a preferred heat transfer correlations to estimate the fuel rods average surface temperature in the HPLWR fuel assembly. These factors are derived mainly to use this modified correlation in a system or a safety code. The calculated average geometry factor and average wire factor for the different considered geometries and conditions are displayed in Table 4. Both these factors are based on a mean value of the Nusselt number. This mean Nusselt number is taken for each geometry as the average in flow direction over a temperature range of 310 ~ 390 °C of the bulk, *i.e.* typical temperatures in the HPLWR evaporator.

The geometry factor for each geometry shown in Table 4 is derived from CFD analyses of these geometries without wire-wrap and by relating the calculated average Nusselt numbers to the calculated Nusselt numbers for a smooth tube with similar hydraulic diameter. The average geometry factor for the annulus and square annulus are in the range of 0.9 to 1.2 for the nominal and hot-channel conditions. This means that the heat transfer coefficients in these geometries are about the same as for a smooth circular tube with an equivalent hydraulic diameter. This finding agrees with experiments using supercritical fluids that also revealed that an annulus has a comparable or higher heat transfer coefficient than a tube with an equivalent hydraulic diameter (see *e.g.* Mori et al. [17]). The average geometry factor for a sub-channel and a 4 rod-bundle is smaller than 1 for nominal and hot-channel conditions. Thus, these geometries have a lower heat transfer coefficient than a smooth circular tube with an equivalent hydraulic diameter.

The wire factors are derived by comparing the unwired with the wired CFD analysis for each geometry. For all the considered geometries the wire factors are generally close to 1.1. This means that the presence of the wire-wrap spacer improves the heat transfer coefficient with about 10 %. The observed heat transfer deterioration in the considered unwired sub-channel under the hot channel condition is mitigated by the presence of the wire-wrap. A similar mitigating influence of the wire-wrap is observed for the square annulus as well by Zhu and Laurien [18].

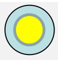
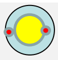
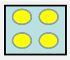
| | Geometry | Geometry factor | Wire factor | Conditions | Owner |
|---|---|---|---|---|---|
|  | Annulus | 1.2 | 1.0-1.1 | Hot | NRG |
| | | (-) | 1.1 | Nom. | KTH |
|  | Multi-wired annulus | | | | |
| | | (-) | 1.0 | Nom. | KTH |
|  | Square annulus | 0.9-1.1 | 1.1-1.3 | Hot | USTUTT |
| | | 0.9 | 1.0 | Nom. | USTUTT |
|  | Sub-channel | **HTD (<1)** | **No HTD (>1)** | Hot | NRG |
| | | 0.6 | 1.05 | Nom. | NRG |
|  | Four rod bundle | 0.7 | 1.1 | Hot | NRG |
| | | 0.6 | (-) | Nom. | NRG |

Table 4 RANS CFD analyzed geometry and wire factors.

Based on the RANS CFD analyses of the sub-channel and 4 rod-bundle a geometry factor of 0.6 is recommended for use in the proposed HPLWR heat transfer correlation defined in Eq. (6). From a literature review of rod bundle experiments under sub-critical conditions geometry factors between 0.9 and 1.15 are typically found. In this respect, the calculated value of 0.6 seems a conservative value. A wire factor of 1.1 is recommended based on the results in Table 4.

## 5. Conclusion

The heat transfer correlation proposed in this paper for the current design of the HPLWR fuel assembly has the following form:

$$\mathrm{Nu}_{HPLWR} = F_{geo} \cdot F_{wire} \cdot \mathrm{Nu}_{base} \qquad (10)$$

The correlation by Jackson [6] valid for super-critical water in a circular tube is selected as base correlation $\mathrm{Nu}_{base}$. In this HPLWR heat transfer correlation the correction factor $F_{geo}$ accounts for the effect of the rod bundle geometry and $F_{wire}$ for the effect of the wire wrap spacer that is applied in the HPLWR fuel assembly. The geometry and wire factors have been calculated using CFD analyses of several representative geometries. Based on these CFD analyses the following factors are recommended: $F_{geo} = 0.6$ and $F_{wire} = 1.1$.

The proposed heat transfer correlation is based on RANS CFD calculations only. The correlation could not be validated due to the lack of experimental data for rod bundles under super-critical conditions and a wire-wrap as spacer. Only a limited range of enthalpy and heat fluxes, representative for the evaporator of the three pass core design, have been considered in the CFD analyses. Thus, further CFD analyses and CFD code validation are required in the coming years.

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