Research article

Assessment of heat transfer correlations in the sub-channels of proposed rod bundle geometry for supercritical water reactor

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A B S T R A C T

There are heat transfer correlations for heat transfer analysis in single tube geometries after several experimental and theoretical heat transfer studies in these single tube geometries. This is not the case for heat transfer analysis in rod bundle geometry with regard to proposed square fuel assembly of the Supercritical-Water-Cooled Reactor (SCWR) European Atomic Energy (EURATOM) design. Thus limited heat transfer studies exist on rod bundle geometry at supercritical pressures. Heat transfer correlations with accurate prediction capabilities of coolant and wall temperatures will be helpful in carrying out heat transfer studies at supercritical pressures. This paper presents the performance of twelve selected heat transfer correlations assessed on the 1/8th bare square fuel assembly of the SCWR EURATOM design using Simulation of Turbulent Flow in Arbitrary Regions Computational Continuum Mechanics C++ based code (STAR-CCM + CFD code). The obtained numerical results were compared with the results obtained by Wataa numerical experimentation. Overall, the Cheng et al. correlation provided the most satisfying prediction for the wall temperatures in all the sub-channels and captured closely Wataa’s Numerical data. The maximum wall temperature was obtained in sub-channel 9, the hottest sub-channel and exceeded the design limit 620 °C by 60 °C for the Cheng correlation. The difference in temperature between the hottest and coldest sub-channels 9 and 1 respectively was approximately 80 °C. It was found that Cheng correlation is best suited for heat transfer prediction in rod bundle geometry at supercritical pressures with regard to the proposed square fuel assembly of the SCWR EURATOM design. It was also found that the different numerical tools adopted for this study and Wataa study were able to capture the trends of normal, enhanced and deteriorated heat transfer regimes normally observed at supercritical pressures. Nevertheless, experimental investigations involving rod bundles adopted in this study should be conducted to validate the results obtained numerically and address the inconsistency of the conclusions drawn when compared with Wataa data and other similar studies.

1. Introduction

Thorough knowledge and understanding of heat transfer characteristics near and above the critical conditions of Pressure and Temperature are crucial to the successful design of Supercritical-Water-Cooled Reactor (SCWR). Heat transfer correlations with accurate prediction capabilities of coolant and wall temperatures in the three heat transfer regimes; normal heat transfer, enhanced heat transfer and deteriorated heat transfer regimes, is helpful in heat transfer prediction in various heat transfer systems. SCWR is the sixth candidate of the advanced, fourth generation nuclear reactor concepts proposed by the “Generation IV International Forum (GIF)” - a consortium of thirteen member countries that laid the groundwork for the fourth generation of nuclear energy systems (Policy Group, 2016). Operating with water at pressures higher than the thermodynamic critical pressure and temperature (22.064 MPa and 373.95 °C respectively). Thus, SCWRs are expected to have higher thermodynamic efficiency as compared to current Light Water Reactors (LWRs). Because of the unique properties and favorable heat and mass transfer characteristics, supercritical water has attracted great interest in many applications, such as fossil-fired power plants (Pioro et al., 2004; Farah et al., 2016; Schulenberg and Starlinger, 2012). At pressures above temperature-pressure critical point of water, two-phase flow of fluid is not observed at these supercritical pressures. The fluid flow is thus treated as single-phase flow. Issues such as critical heat flux and wall...
burnout observed at two-phase flow regime in the operation of Boiling Water Reactors BWRs are not observed in the operation of SCWRs. However, temperature limitations of fuel meat and cladding become fluid flow and heat transfer concerns at supercritical pressure conditions. Accurate wall temperature and heat transfer coefficient predictions in SCWR fuel assembly are therefore needed to guide the design and operation of SCWRs (Wang et al., 2017a,b).

Wang et al. (2017a,b) performed an experiment at supercritical pressures investigating boiling heat transfer to water in a 2 x 2 sub-channel of SCWR. Wall temperatures observed at sub-critical pressures were compared with that obtained at supercritical pressures. It was found out that subcritical wall temperatures could be less or more than the supercritical wall temperatures. This finding was influenced by the occurrence of departure from nucleate boiling and the value of heat flux to mass flux ratio. Gao and Bai (2017) performed numerical study investigating non-uniform heat transfer at supercritical pressures in a horizontal tube. The adopted governing equations were solved using finite volume method. Renormalization Group k-ε turbulence (RING k-ε) model was used to capture turbulence in the numerical simulation. The numerical results obtained compared well with the experimental data used for the validation, and based on this, the RING k-ε turbulence model was recommended for similar numerical studies. The results of the numerical study show that there exist a non-uniform heat transfer in a horizontal circular tube, and pressure and heat flux variations could influence heat transfer significantly in the tube at supercritical conditions. Shen et al. (2017) performed experimental and numerical study investigating heat transfer to water at supercritical pressure in a vertical tube. The dimensionless specific heat ratio, buoyancy and acceleration parameters were calculated. The variation of heat transfer coefficient with the dimensionless parameters was found to be significant. However, the Jackson buoyancy parameter does not show dependence on the heat transfer coefficient. Mockry et al. and Bishop et al. correlations performed well in predicting experimental heat transfer data among the six heat transfer correlation examined. It was found out that the mechanisms causing development of heat transfer enhancement and deterioration were due to combined effects of specific heat and buoyancy.

Gschmidtner et al. (2018) carried out assessment of 11 heat transfer correlations at supercritical pressures. 12,000 experimental data points were used to evaluate these 11 heat transfer correlations. It was indicated that complex and implicit heat transfer correlations did not improve the prediction accuracy significantly, and it was recommended that simple and explicit heat transfer correlations like Cheng et al. correlation should be adopted in heat transfer prediction at supercritical pressures considering thermo-physical properties, flow acceleration and buoyancy were studied. It was observed that flow acceleration caused by thermal expansion impairs turbulence but the presence of thermal boundary layer reduces the effects of flow acceleration on heat transfer at supercritical pressures. Heat transfer enhancement and deterioration are caused by buoyancy effects as a result of growth and decay of turbulence. It was also observed that inaccurate prediction of heat transfer is caused by the failure of the adopted turbulence models to capture production of turbulence kinetic energy and turbulent Prandtl number. Du et al. (2019) carried out numerical study adopting SST turbulent model in a vertical pipe at supercritical pressures. Effects of tube diameter on convective heat transfer were investigated. The findings obtained are 1) decreasing tube diameter improves heat transfer in the enhanced heat transfer region, 2) rising wall temperature in the deteriorated heat transfer region reduces by decreasing the tube diameter, and 3) there is close relationship between peak heat transfer coefficient and pseudo-critical temperature. It was also observed that significant variations in density and thermal acceleration caused by effect of inertia contribute to phenomenon of heat transfer deterioration at supercritical pressures. Kong et al. (2019) developed a new criterion for predicting heat transfer at the onset of heat transfer deterioration at supercritical pressures in vertical tubes with inner diameters varying from 3 to 38 mm. The new criterion valid for system pressures in the range of 22.5–31 MPa, mass fluxes in the range of 200–2150 kg/(m²s), and heat fluxes in the range of 148–1810 kW/m² with prediction accuracy of 94.25%. This prediction accuracy is higher than that of the existing criteria for predicting heat transfer at the onset of heat transfer deterioration. Pioro (2019) performed heat transfer study at supercritical pressures considering flow geometries (tubes, annulus, 3- and 7-rod bundles) and supercritical fluids (SCW, SC carbon dioxide and SC R-12). Pioro stated that the two (2) correlations Mokry et al., (2011) and Gupta et al. (2013) valid for only the normal and improved/enhanced heat transfer regimes. Pioro found out that the minimum onset of deteriorated heat flux that is observed in annulus, and 3- and
7-rod bundles is 1.6–1.8 times that of the bare tubes. Wang et al. (2019) performed an experimental study investigating heat transfer of water at supercritical pressure in a double pipe heat exchanger. It was found that total HTC increases with the mass flow rate, and the variation of the HTC of the outer tube with the increase of the mass flow rate is insignificant. The peak HTC decreases with the pressure increase. The temperature at which the peak HTC occurs is not the same as the PCT, and the difference between the two temperatures increases with pressure. And the difference between the two temperatures was attributed to the temperature variation at the heat transfer section and the variation of the physical properties (especially density) of the coolant. It was also found out that the effect of buoyancy at different pressures is significant in the PCT region. Chen et al. (2019) performed an experimental study investigating the spacer grid effects on transfer of heat to Freon R134a at supercritical pressure in a 19-rod bundle geometry. Enhanced heat transfer was maximum and reached its peak near the PCT region, and sub-critical heat transfer correlations were not able to capture this observation. Heat transfer enhancement effect by the spacer grid at supercritical conditions was similar to that at subcritical conditions. A new heat transfer correlation was developed to predict heat transfer in the PCT region. Lei et al. (2019) performed an experimental study investigating heat transfer to CO2 at supercritical conditions in a small tube. A new heat transfer correlation for heat transfer of supercritical CO2 using a deep learning method. It was found that different characteristics of heat transfer were observed for various heat fluxes at low mass flux. The enhanced heat transfer regime and the peak of heat transfer coefficient occurred in the low enthalpy region. The heat transfer coefficient decreases with pressure under low heat flux conditions, and heat transfer at low mass flux conditions is significantly influenced by buoyancy effect.

The supercritical fluid flow and heat transfer predictions using numerical tools is attracting a lot of attention recently because of the high pressure and temperature working conditions that limit the number of experimental studies carried out at these supercritical pressure conditions. Correlations on fluid flow and heat transfer are implemented in these numerical tools to obtain fluid flow and heat transfer data to complement similar limited experimental data (Shitsi et al., 2018). From the above literature review, there are few studies on 4-rod bundle geometry, and there is one study in literature on 7-rod bundle geometry by Dyadyakin and Popov (1977). Therefore, this paper seeks to present the performance of the twelve selected heat transfer correlations assessed on the 1/8th bare square fuel assembly (7-rod bundle geometry) of the SCWR EURATOM design using STAR-CCM + CFD code. The numerical results obtained were compared with the results obtained by Waata numerical experimentation.

2. Methodology

2.1. STAR-CCM + CAD and the system model descriptions

3D-CAD is a feature-based parametric modeler within STAR-CCM+ was used to generate the one-eighth geometry. Extruding and cutting operations were then executed on the created geometry. Parts and regions were subsequently assigned to the geometry for integration with meshing and simulation process. In this analysis, dimensions used for the model (in mm) were obtained from the square fuel assembly configuration design proposed by Hofmeister et al. (2005, 2007), as illustrated in Figure 1. Figure 1 shows the mesh scene of the computational geometry (Figure 1a) and a representation of Fuel rod and sub-channels in “1/8 assembly” (Figure 1b) created using STAR CCM + CAD. Optimum mesh size of 1, 177, 342 cells was obtained using meshing specifications including base size of 0.2 mm, prism layer thickness of 0.1 mm, near wall prism layer thickness of 0.1 mm and surface growth rate of 1.3 mm. Physics models and boundary specifications adopted are presented in Table 1.

Table 1. Physics models and Boundary Specifications.

| S/No | Physics Model                   | Specification          |
|------|---------------------------------|------------------------|
| 1    | Space Model                     | 3-Dimensional          |
| 2    | Time Model                      | Steady State           |
| 3    | Material                        | Water                  |
| 4    | Energy of State Model           | Polynomial Density     |
| 5    | Flow Model                      | Segregated Flow        |
| 6    | Energy Model                    | Segregated Fluid       |
| 7    | Viscous Regime Model            | Turbulent              |
| 8    | Turbulence Model                | K-Omega                |
| 9    | Wall Function                   | Low γ’ Treatment       |
| 10   | Convection Scheme               | 2nd Order Upwind       |
| 11   | Inlet                           | Mass Flow              |
| 12   | Outlet                          | Pressure               |
| 13   | Wall Surface                    | Heat flux              |

Figure 1. Mesh Scene of the Computational Geometry (a), and a representation of Fuel rod and sub-channels in “1/8 assembly” (b) created using STAR CCM + CAD.
one-eighth (1/8th) the computational domain was considered and of the FA to converge, symmetrical design advantage was utilized. Thus 4 Standard Lien’s Low-Re κ

2 Standard Wilcox

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650 kW/m² in the fuel rods was implemented in the STAR-CCM temperature of 500 the sub-channels, the distribution was aimed at an average outlet tem-

2.3. Physical Models

The Physical Models adopted in this study includes Continuity equation, Momentum equations and Energy equation. The detailed treatments or descriptions of these Physical Models are given in the litera-

2.2. Initial conditions

The numerical data used by Wataa (Waata, 2006) was implemented as input data for modelling 1/8th Fuel Assembly (FA) in the STAR-CCM code. The fuel rod diameter of 8 mm, P/D ratio of 1.15 and 4.2 m as the active height of the heated section of the fuel assembly. The detailed dimensions of the FA is found in Waata (2006). A uniform heat flux of 650 kW/m² in the fuel rods was implemented in the STAR-CCM code. The feed water temperature to the reactor pressure vessel was set at 280 °C and a total mass flow rate of 0.167 kg/s (601.2 kg/h). The operating pressure was 25 MPa with pseudo-critical temperature PCT of 384.9 °C. Inlet coolant temperature to the fuel assembly was set at 300 °C and in the sub-channels, the distribution was aimed at an average outlet temperature of 500–550 °C of this assembly. The water properties from National Institute of Standards and Technology (NIST) software Table was used to calculate physical properties of water applied for the SCW used in this analysis as a coolant (Lemmon et al., 2002).

Table 3. Turbulence models.

| No. | Turbulence model | Type | Wall Treatment |
|-----|------------------|------|----------------|
| 1   | Shear-Stress Transport (SST) Menter’s | κ-ω | Low y + |
| 2   | Standard Wilcox  | κ-ω | Low y + |
| 3   | Abe-Kondoh-Nagano (AKN) Low-Re | κ-ε | Low y + |
| 4   | Standard Lien’s Low-Re | κ-ε | Low y + |

2.4. Heat transfer correlation for supercritical conditions

Twelve different heat transfer correlations were considered and implemented in this study. This was to analyze their effects on the prediction of wall temperature in the proposed fuel assembly using STAR-CCM + code. The heat transfer correlations applied in this study are shown in Tables 4, 5, and 6.

In recent decades, many researchers have proposed heat transfer correlations at supercritical pressures. The most widely used heat transfer correlation for forced convection is the Dittus-Boelter correlation. Correlation of Bishop et al. which made use of Prandtl number was proposed to account for the effect of entrance region. In order to develop an accurate heat transfer correlation, experimental data covering a wide range of operating conditions was analyzed by Mokry et al., (2011). In order to improve heat transfer prediction at supercritical pressures compared with heat transfer prediction at subcritical pressures with constant fluid properties, acceleration parameter was proposed and implemented in Cheng et al. correlation.

As reported by Wang et al. (2017a,b), heat transfer correlations can be categorized into three types for supercritical fluids. The first category which performs well in the prediction of heat transfer in single phase fluids at subcritical conditions and is derived from the expression based on the Dittus and Boelter correlation (Dittus and Boelter, 1930). For the second category, a frictional factor has been added to the developed correlation equations for heat transfer in supercritical fluids that have been developed by Russian researchers. Most of the heat transfer correlations in the last category have been developed in recent years based on the “mechanisms of heat transfer at supercritical pressures”. With a view to increasing an in-depth knowledge on the mechanisms of heat transfer enhancement and deterioration phenomena, some researchers have stated that buoyancy and thermal acceleration play dominant and significant roles in the prediction of wall temperatures (Cheng et al., 2009; Chen and Fang, 2014; Shitsi et al., 2017). The HTC in the supercritical water must be addressed prior to, and during the formulation and development of new empirical correlations. In addition, the integral effect of specific heat and buoyancy effect are the main reasons resulting in the abnormal heat transfer.

As can be seen in the Tables 4, 5, and 6, amid the 12 selected heat transfer correlations, only the Dyadyakin and Popov (1977) correlation was developed for rod bundle while the remaining 11 correlations were principally proposed and recommended for tubes.

3. Results and discussion

From the assessment results of the turbulence model results obtained, it can be inferred that the most suitable turbulence models capturing the coolant temperature obtained by Waata in this analysis were found to be SST κ-ω (Menter’s) and standard (Wilcox) κ-ω as displayed in Figures 2, 3, 4, and 5. Nevertheless, SST κ-ω (Menter’s) turbulence model was selected due to its widely used and recommendations are given by several re-

Table 1. The Detailed dimensions of the 1/8th fuel assembly implemented in STAR-CCM + CAD are presented in Table 2.

Table 2. Dimensions used for creating a 1/8th FA geometry.

| Square | “2.1” Assembly type | Values |
|--------|---------------------|--------|
| Number of moderator boxes per assembly (–) | 1 |
| Cladding outer diameter | 8 mm |
| P/D | 9.2 |
| Number of fuel rods (–) | 40 |
| Active axial heated height | 4.2 m |
| Fuel assembly box | |
| Length of the inner side | 65.2 mm |
| Thickness of wall | 1 mm |
| Length of the outer side | 67.2 mm |
| Moderator box | |
| Length of the outer side | 26.8 mm |
| Thickness of wall | 0.3 mm |
| Length of the inner side | 26.2 mm |
| References | Correlations | Flow Geometry | Applicability Range |
|------------|--------------|---------------|---------------------|
| Dittus and Boelter (1930) | \( Nu_b = 0.023Re_b^{0.8}Pr_b^{0.4} \) | Tubes | Subcritical pressures |
| Griem (1996) | \( Nu_b = 0.0169Re_b^{0.833}Pr_b^{0.432} \) | Tubes | \( P = 0.4-27.4 \) MPa; \( G = 170-3000 \) kg/m²s; \( q = 420-8400 \) kW/m²; \( t_b = 2.5-420 \) °C |
| Shitsman (1974) | \( Nu_b = 0.023Re_b^{0.8}Pr_b^{0.4} \) | Tubes (D = 7.8, 8.2 mm) | \( P = 22.8-27.6 \) MPa; \( G = 651-3662 \) kg/m²s; \( q = 310-3460 \) kW/m²; \( t_b = 282-527 \) °C |
| Bishop et al. (1964) | \( Nu_b = 0.006Re_b^{0.8}Pr_b^{0.4} \) | Tubes (D = 2.5, 5.1 mm) | \( P = 22.6-29.4 \) MPa; \( G = 450-3000 \) kg/m²s; \( q = 280-1200 \) kW/m²; \( H_b = 420-1400 \) kJ/kg |
| McAdams et al. (1950) | \( Nu_b = 0.023Re_b^{0.8}Pr_b^{0.4} \) | Tubes | \( P = 23-25 \) MPa; \( q = 0.3-0.6 \) MW/m²; and \( G = 500-2500 \) kg/m²s |
| Ornatsky et al. (1970) | \( Nu_b = 0.023Re_b^{0.8}Pr_b^{0.4} \) | Tube (D = 3 mm) | \( P = 0.8-24 \) MPa; \( t_b = 221 \) °C; \( G = 538 \) kg/m²s; \( q = 0.035-0.336 \) MW/m² and \( G = 75-224 \) kg/m²s |
| Dyadyakin and Popov (1977) | \( Nu_b = 0.021Re_b^{0.8}Pr_b^{0.4} \) | Bundles (D_2b = 2.15-2.77 mm) | \( P = 24.5 \) MPa; \( G = 500-4000 \) kg/m²s; \( q < 4700 \) kW/m²; \( t_b = 90-570 \) °C |
| Mokry et al. (2011) | \( Nu_b = 0.061Re_b^{0.8}Pr_b^{0.4} \) | Tube (D = 10 mm) | \( P = 24 \) MPa; \( G = 200-1500 \) kg/m²s; \( t_b = 70-1250 \) kW/m²; \( t_b = 320-350 \) °C |
| Gupta et al. (2013) | \( Nu_b = 0.061Re_b^{0.8}Pr_b^{0.4} \) | Tube (D = 10 mm) | \( P = 24 \) MPa; \( G = 200-1500 \) kg/m²s; \( t_b = 70-1250 \) kW/m²; \( t_b = 320-350 \) °C |

| References | Correlation | Flow Geometry | Applicability Range |
|------------|--------------|---------------|---------------------|
| Petukhov et al. (1983) | \( St = Nu_b Re_b^{0.2} - \frac{(\zeta)}{(Re)^{0.2}} \) | Tubes, upwards, downwards and horizontal (D = 8 mm, L = 1.67 m) | \( P = 7.7-8.9 \) MPa; \( G = 1000-4100 \) kg/m²s; \( q = 384-1053 \) kW/m²; \( t_b = 0-80 \) °C |
| Kranshchekov et al. (1967) | \( Nu_b = Nu_b \left( \frac{\mu_b}{\mu} \right)^{0.11} \left( \frac{\lambda_b}{\lambda} \right)^{0.3} \left( \frac{C_p}{C_p} \right)^{0.25} \) | Tubes (D = 1.6-20 mm) | \( 2 \times 10^3 < Re_b < 8.6 \times 10^7, 0.85 < Pr_b < 65, 0.90 < \frac{\mu_b}{\mu} < 3.60, 1.00 < k_b/k_w < 0.60 \) and \( 0.07 < C_p/C_p < 4.50 \) |

| References | Correlation | Flow Geometry | Applicability Range |
|------------|--------------|---------------|---------------------|
| Cheng et al. (2009) | \( Nu_b = 0.023Re_b^{0.8}Pr_b^{0.4}F_2^{0.4} \) | Tubes (D = 10, 20 mm) | \( P = 22.5-25 \) MPa; \( G = 700-3500 \) kg/m²s; \( q = 300-2000 \) kW/m²; \( t_b = 300-450 \) °C |
| Chen and Fang (2014) | \( Nu_b = 0.46Re_b^{0.4}Pr_b^{0.4} \) | Tubes (D = 6-26 mm) | \( P = 22-34.3 \) MPa; \( G = 201-2500 \) kg/m²s; \( q = 129-1735 \) kW/m²; \( H_b = 278-3169 \) kJ/kg |
Waata, this was followed by the Shitsman and Ornatsky correlations in the HTD region.

In the case of HTCs observed in Figure 7, most of the correlations closely captured the HTC computed by Waata at the entrance part of the sub-channel. However, there was a shift in the location of the maximum peaks (between 1.68 m and 2 m) for the twelve-correlation compared to the HTC computed by Waata (1.3 m) along the active length of the sub-channel. Beyond 2.0 m, the Cheng et al. correlation closely captured the Waata HTC, followed by the McAdams, Dittus Boelter, Griem, and Dyadyakin and Popov correlations. The Gupta correlation over-estimated the HTC as observed in Figure 7. The NHT region is observed at the inlet section where all the correlations closely predicted the Waata HTC data (from 0.0 m to 0.8 m of the active length of the sub-channel). This NHT region is followed by HTE where the HTC values start to increase up to the point where the peak of each heat transfer correlation is located. The region after the HTE region is the HTD region.

The following set of graphical results presents the rest of comparisons of the wall temperature profiles computed by the 12 selected correlations with the wall temperatures obtained by Waata in sub-channels 2, 4, 7 and 9.

Accordingly, it was observed that in all the 5 sub-channels analyzed, the wall temperatures computed by the Cheng et al. correlation consistently and closely captured Waata’s obtained wall temperatures in the HTD region from 2.0 m to about 3.8 m along the active length. In sub-channel 2, the Cheng et al. correlation was followed by the Dyadyakin and Popov, McAdam’s, and Petukhov correlations (Figure 8). A similar trend of the estimation of the wall temperatures obtained by the correlations and compared with the Waata data was shown in Figure 9 (results of sub-channel 4), however towards the outlet of the sub-channel only the wall temperatures computed by the Cheng et al., and Dyadyakin and Popov correlations were more than that of Waata’s in both sub-channels 2 and 4 (Figures 8 and 9). In addition, it was also observed that the Cheng et al. correlation overestimated the wall temperature obtained by Waata in the HTE region, in sub-channels 2 and 4. The Gupta, Shitsman, Mokry, Krasnoshchekov and Protopopov correlations under-estimated the wall temperature obtained by Waata in the HTD region in sub-channel 2 (Figure 8). A similar trend was observed in sub-channel 4, except for the
Gupta correlation which closely estimated the wall temperatures obtained by Waata (Figure 9).

In sub-channels 7, as observed in the other sub-channels, the Petukhov and Cheng et al. correlations slightly overestimated the wall temperature obtained by Waata in the HTE region. In the HTD region, the result of Cheng et al. correlation agreed with the Waata’s data, from 1.68 m to 3.78 m in sub-channel 7 (see Figure 10). However, in sub-channel 9, both the results of Cheng et al. and Kranoshchekov and Protopopov were very close to the results of the Waata in the HTD region (see Figure 11). Moreover, in the upper part of the sub-channel 9, all the wall temperatures computed by the 12 selected correlations in the sub-channel were more than the wall temperature obtained by Waata. Nevertheless, in sub-channel 7 only the Petukhov, Cheng et al. and Dyadyakin and Popov wall temperatures were more than the Waata’s wall temperature in the upper part of the channel.

Furthermore, for all the five (5) sub-channels in the NHT region, it was observed that the twelve correlations did not favorably estimate the wall temperature obtained by Waata. In the HTE region of sub-channel 9, almost all the correlations captured the wall temperature trend obtained by Waata, except the Gupta correlation which slightly underestimated it. It was observed also that almost all the twelve correlations closely predicted the Waata numerical wall temperature at the PCT region of 384.9 °C. The trends of the wall temperatures observed at the PCT region flattened around 384.9 °C indicating maximum enhanced heat transfer in this PCT region. This observation was also made in other experimental and numerical studies including Xi et al. (2014a); Gu et al. (2015a, b); Wang et al. (2014); Gu et al. (2016); Shi et al. (2017); Li et al. (2018); and Kong et al. (2019). It is interesting observing that both the coolant and wall temperatures tend to flatten at the PCT region around the PCT value with the coolant temperatures below the wall temperatures as shown in the figures. The maximum deviations of the wall temperatures estimated by the 12 twelve correlations from the Waata wall temperature were observed at the HTD region towards the upper part of the sub-channels (or the outlet of the sub-channels). Thus most of the 12 heat transfer

Figure 4. Temperature profiles in SC 4 of a square fuel assembly.

Figure 5. Temperature profiles in SC 9 of a square fuel assembly.
correlations predicted the Waata data quite well in the enhanced heat transfer region compared to the prediction in the deteriorated heat transfer region.

In general, based on Cheng et al. correlation, it was observed that the maximum wall temperature computed slightly exceeds the design allowable limit of 620 °C by an average of 10 °C in SC (1) (the coldest SC), SC (2) and SC (4), as captured in Figures 6, 8, and 9 respectively. In sub-channels 7, the allowable limit temperature was exceeded by 35 °C (Figure 10), while in sub-channel 9 (the hottest SC) the deviation from the design limit was a little more than 80 °C as observed in Figure 11. The difference in temperature between the hottest and coldest sub-channels 9 and 1 respectively was approximately 80 °C. The maximum wall temperature was obtained in sub-channel 9, the hottest sub-channel and exceeded the design limit 620 °C by 60 °C for the Cheng correlation while for the other correlations it was more. It was also observed that the different numerical tools adopted in the current study and in the study of Waata are able to predict the Normal, Enhanced and Deteriorated heat transfer regimes normally observed in the heat transfer systems at supercritical pressures.

The results for the HTCs in sub-channel 2, 4, 7, and 9 are presented in Figures 12, 13, 14, and 15.

In sub-channel 2 (see Figure 12), most of the correlations estimated closely the HTC data obtained by Waata at the inlet part of the sub-channel except the Krasnoshchekov and Protopopov, and Cheng et al. correlations' results. In the half part of the subchannel towards the outlet, the Cheng et al., McAdams, and Dyadyakin and Popov correlations closely estimated the HTC obtained by Waata. It was observed that there was a shift in the location of the maximum peak (between 1.7 m and 2.0 m) for HTCs computed by the twelve different correlations, compared to that of Waata's (1.2 m). The Cheng et al. correlation had the lowest peak while the Shitsman, Bishop and Gupta correlations had the highest peak in sub-channel 2. The peak of the Dyadyakin and Popov, as well as that of Krasnoshchekov and Protopopov correlations, was close the HTC's peak obtained by Waata.

Figure 13 also shows a similar trend of HTC profile observed in sub-channel 4, except that the Cheng et al. and McAdams correlations showed a good agreement with Waata's computed HTCs at the entrance of the sub-channel and from 2.0 m to 4.2 m. Similarly, only the Gupta correlation had the highest peak while the Bishop, and Krasnoshchekov and Protopopov correlations had the similar peak with the Waata's computed HTC result.

Figure 14 shows HTC profiles observed in sub-channel 7. The twelve correlations predicted HTC values close to that of the Waata in the NHT
region observed at the inlet section of the sub-channel. Maximum de-
viations in the HTC values observed in the HTE region where the HTC
peak for each heat transfer correlation was located. The HTC peaks of
Gupta et al., Mokry et al., Bishop et al., Shitsman, Ornatsky, and Dyad-
yakin and Popov correlations were above that HTC peak of the Waata
data. The remaining heat transfer correlations have their HTC peaks below
that of the Waata data. Heat transfer from the fuel rods to the coolant is at
its maximum in this HTE region. This HTE region is followed by HTD
region where heat transfer from the fuel rods to the coolant started to
reduce to its minimum towards the end of the sub-channels for all the
twelve heat transfer correlations.

A similar trend of HTC results was also observed in sub-channel 9 (see
Figure 15) computed using the twelve different correlations and
compared with the HTC result obtained by Waata. The peaks obtained by
Bishop, Dyadyakin and Popov, and Mokry correlations were close to the
peak of the Waata data. However, it was observed that the Gupta cor-
relation significantly overestimated the HTC result obtained by Waata.
Gupta correlation had the highest peak followed by Shitsman, Ornatsky
and McAdams correlations, while the peaks of Kranoshchev and Pro-
topopov, Petukhov, Griem, Cheng et al. and Dittus Boelter correlations
were below the peak obtained by Waata but at different locations.

It was also observed that there was a shift in the location of the peak
for HTCs computed by the twelve different correlations, compared to the
Waata’s HTCs. In all the five sub-channels, the Gupta correlation had the
highest peak, this was followed by the Shitsman correlation except in SC
(4) (see Figure 9). The maximum value of the HTC was approximately
146 kW/m² in sub-channel 9 and the minimum HTC value was approx-
imately 102 kW/m² in sub-channel 2, obtained by the Gupta correlation.
For Cheng et al. correlation, the value of the HTC was approximately 41
kW/m² in sub-channel 9 and approximately 32 kW/m² in sub-channel 2.
It was also observed that the peak location varied between 1.0 m and 2.0
m for the 12 selected heat transfer correlations in all the individual sub-
channels. Studies such as Gu et al. (2015a, b); Wang et al. (2014); Gu
et al. (2016), Gao and Bai (2017); Shen et al. (2017); Li et al. (2018);
Figure 10. Simulation results for selected heat transfer correlations showing the wall temperature profiles in SC 7.

Figure 11. Simulation results for selected heat transfer correlations showing the wall temperature profiles in SC 9.

Figure 12. Simulation results for selected heat transfer correlations showing the HTC profiles in SC (2).
Figure 13. Simulation results for selected heat transfer correlations showing the HTC profiles in SC (4).

Figure 14. Simulation results for selected heat transfer correlations showing the HTC profiles in SC (7).

Figure 15. Simulation results for selected heat transfer correlations showing the HTC profiles in SC (9).
Kong et al. (2019); Du et al. (2019); and Lei et al. (2019) obtained similar shape of the HTC profile obtained in this study. It can be observed that both the coolant and wall temperature results of this study, and that of the Waata study flattened at the PCT region with a temperature value of 384.9 °C (PCT value at 25 MPa). Thus the coolant and wall temperature values of the two numerical studies are close or of this study, and that of the Waata study significantly from the experimental results yet to be obtained. For most of good experimental and numerical studies on heat transfer to water at supercritical pressures, the trend of the wall temperatures obtained flattened at this PCT region with the values of the coolant and wall temperatures close or equal to the PCT value. Heat transfer coefficient prediction of SCW is challenging due to the steep and non-linear variations in its thermo-physical properties. Near the pseudo-critical point, the density, thermal conductivity, and viscosity fall drastically whereas the specific heat experiences a sharp peak. It can be observed that none of the correlations tested in this analysis is most reliable heat transfer correlation providing favorable prediction in all the sub-channels, hence there is still no consistent conclusion on the best performing heat transfer correlation. This leaves room for improvement and modification on the best performing correlations in this analysis.

4. Conclusions

This study seeks to present the performance of twelve selected heat transfer correlations assessed on the 1/8th bare square fuel assembly of the SCWR EURATOM design. The STAR-CCM + CFD Code was used for this study. SST κ-ε turbulence model was selected among other turbulence models implemented in the code. The obtained results from this work were compared with the results obtained by Waata numerically. Overall, the Cheng et al. correlation provided the most satisfying prediction for the wall temperatures in all the sub-channels and captured closely Waata’s Numerical data. This was followed by the McAdams correlation, but the Dyadyakin and Popov, and the Petukhov correlations also yielded results close to Waata data. The maximum wall temperature was obtained in sub-channel 9, the hottest sub-channel and exceeded the design limit 620 °C by 60 °C for the Cheng correlation while for the other correlations it was more. The difference in temperature between the hottest and coldest sub-channels 9 and 1 respectively was approximately 80 °C. It was also found that the different numerical tools adopted for this study and Waata study were able to capture the trends of normal, enhanced and deteriorated heat transfer regimes normally observed at supercritical pressures.

Declarations

Author contribution statement

Seth Kofi Debrah: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.
Edward Shitsi, Silas Chabi & Neda Sahebi: Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data.

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Competing interest statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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