Computational Fluid Dynamic Simulations of Heat Transfer From a 2 × 2 Wire-Wrapped Fuel Rod Bundle to Supercritical Pressure Water

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Within the Generation-IV International Forum, Canadian Nuclear Laboratories (CNL) led the conceptual fuel bundle design effort for the Canadian supercritical water cooled reactor (SCWR). The proposed fuel rod assembly for the Canadian SCWR design comprised of 64-elements with spacing between elements maintained using the wire-wrap spacers. Experimental data and correlations are not available for the fuel-assembly concept of the Canadian SCWR. To analyze the thermalhydraulic performance of the new bundle design, CNL is using computational fluid dynamics (CFD) as well as the subchannel approach. Simulations of wire-wrapped bundles can benefit from the increased fidelity and resolution of a CFD approach due to its ability to resolve the boundary layer phenomena. Prior to the application, the CFD tool has been assessed against experimental heat transfer data obtained with bundle subassemblies to identify the appropriate turbulence model to use in the analyses. In the present paper, assessment of CFD predictions was made with the wire-wrapped bundle experiments performed at Xi'an Jiaotong University (XJTU) in China. A three-dimensional CFD study of the fluid flow and heat transfer at supercritical pressures for the rod-bundle geometries was performed with the key parameter being the fuel rod wall temperature. This investigation used Reynolds-averaged Navier–Stokes turbulence models with wall functions to investigate the behavior of flow through the wire-wrapped fuel rod bundles with water subjected to a supercritical pressure of 25 MPa. Along with the selection of turbulence models, CFD results were found to be dependent on the value of turbulent Prandtl number used in simulating the experimental test conditions for the wire-wrapped fuel rod configuration. It was found that the CFD simulation tends to overpredict the fuel wall temperature, and the predicted location of peak temperature differs from the measurement by up to 65 deg.
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1 Introduction

Under the Generation-IV International Forum framework [1], Canadian Nuclear Laboratories (CNL) has established the fuel rod assembly concept for the Canadian supercritical water reactor (SCWR). The proposed fuel rod assembly for the Canadian SCWR design comprised of vertically oriented 64-elements with spacing between elements maintained using the wire-wrap spacers (Fig. 1, see Ref. [2] for more details on the SCWR design). Besides maintaining the geometric configuration of the rod bundle, the wire-wrap spacers affect the heat transfer and promote mixing in the flow domain. The enhanced mixing is of importance as it reduces the temperature hot spots that are detrimental to the fuel cladding and thus increases the safety margin. Therefore, the effect of spacers on fluid flow and heat transfer must be well understood for the design of the fuel assembly and its optimization.

To better understand the role of spacers in the conventional pressurized water reactors, several investigations have been undertaken to study the effect of grid spacers on the heat transfer in the fuel rod bundle. However, experiments dealing with the effect of spacers, in particular the wire-wraps, on the heat transfer to supercritical water are limited. Unlike the spacer-grids that result in generation of localized turbulence at the spacer location and the immediate downstream region, wire-wraps aid in development of strong secondary flow patterns due to the helical wires wound on the surface of fuel rods. However, the wire-wraps could result in additional source of pressure drop compared to the bare fuel rod assemblies or those with spacer-grids [3]. Although this could not be substantiated due to lack of experiments for tight lattice geometries (e.g., SCWR), for pressurized water reactor cores, Diller et al. [4] reported that wire-wrap spacers resulted in significant reduction in pressure drop compared to the spacer-grids.

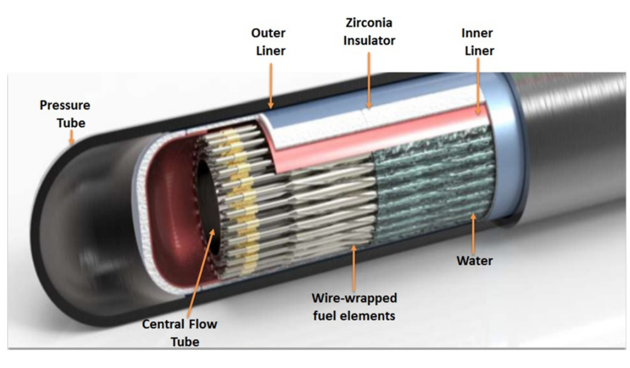

Fig. 1 Cut-out view of the Canadian SCWR fuel assembly with wire-wraps [2]

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Therefore, the pressure drop aspect of the wire-wrapped bundles is currently not well understood and is largely design dependent which varies case-by-case and cannot be generalized.

For heat transfer enhancement, on the other hand, the effectiveness of the wire-wraps has been demonstrated through experiments using tubes, annuli, and bundles [5]. For a wire-wrapped rod inside a vertical square channel [6], it was found that the wire-wrap spacer did not result in significant enhancement of the heat transfer under normal heat transfer conditions. However, the wire-wrap spacer contributed to the improvement of heat transfer in the pseudocritical region, delaying the onset of heat transfer deterioration under low mass flux and high heat flux conditions. On the other hand, for a 2×2 rod bundle, Gu et al. [7] observed significant heat transfer enhancement at high mass-flux test conditions for a similar test geometry at Shanghai Jiaotong University in China. Clearly, more experiments are needed for a complete understanding of the effect of wire-wraps on heat transfer at supercritical pressures. However, as pointed out earlier in Ref. [8], experimental investigations devoted to the heat transfer in rod bundles cooled with coolant at supercritical pressures are limited. The major problems associated with conducting such experiments arise from high operational costs and limited availability of experimental loops that can operate at supercritical flow conditions.

To enhance the understanding gained through the experimental investigations of the wire-wraps effect on flow and heat transfer, computational fluid dynamics (CFD) has also been applied along with system and subchannel codes. The traditional approaches using system or subchannel codes cannot predict the vortices and separated flow phenomena that have significant effects on the boundary layer as well as on the secondary flow. On the other hand, CFD has the potential to resolve the boundary layers, to account for secondary flows and to handle geometries of almost arbitrary complexity. Hence, CFD has been applied by several investigators in the past to model the flow through wire-wrapped bundles, which is a challenging task due to the wire-wrapped bundle's tightly packed configuration. These investigations were primarily based on the Reynolds-averaged Navier–Stokes simulations. It should be noted that the majority of the studies were performed under the context of sodium fast reactors, except for a few performed for SCWR or high-performance light water reactor in Europe [9,10] and in Canada [11].

The meshing aspect of the wire-wrapped bundle, particularly the representation of the rod–wire contact, was studied in detail by investigators at Idaho [12] and Argonne [13] national labs in U.S. For the supercritical water flow through bundles, work performed at Nuclear Research Consultancy Group, The Netherlands [14] found that the presence of wire-wraps enhances intersubchannel mixing by generating a strong peripheral flow. Comparison of turbulence models for the wire-wrapped bundles was made at University of Stuttgart, Germany [9]. They concluded that the shear stress transport (SST) k–ω model was able to predict heat transfer at normal and deteriorated heat transfer conditions. For the Canadian SCWR, during the conceptual stage, limited analyses were made by Podila and Rao [11] to evaluate the suitability of the turbulence models. The results obtained were in line with the conclusions of the work performed by Zhu [9]. However, neither of these two CFD simulations of supercritical bundle flows was assessed against measurements. This was primarily due to the lack of experiments in rod bundles that can be used for assessment of the CFD predictions.

Recently, measurements of wall temperature were carried out by Xi'an Jiaotong University (XJTU) on a vertically oriented heated test section comprising of 2×2 wire-wrapped bundle geometries with water at 25 MPa as coolant (see Ref. [15]). These experiments were conducted under varied operating conditions covering subcritical, pseudocritical, and supercritical regions. The tests provided measurements of circumferential wall-temperature distribution around the heated rods. The power was generated through joule heating in each rod. Wall temperatures were measured using both fixed and moveable thermocouples inside the heated rod at measuring locations along the length of the heated test section. This provided a unique data set that could be used to assess the suitability of the existing models for the CFD modeling of wire-wrapped bundles.

The objective of this study is to perform an assessment of CFD simulations of the 2×2 wire-wrapped rod bundle using experiments from XJTU, China [15]. The STAR-CCM+ CFD code was used in the analysis. This work is an extension of a previously published study focussing mainly on bare bundles [16]. In the present study, the CFD simulations focus on wire-wrapped bundles. Evaluation of turbulence models was performed, and the turbulent Prandtl number (Pr_t) was used as an adjustable parameter to predict experiments. The key parameter used in the assessment is the fuel rod wall temperature.

2 Meshing and Computational Model

2.1 Mesh Generation. The computational domain was simulated using the CFD code STAR-CCM+ v 9.02 utilizing its advanced mesh generation capabilities for nuclear fuel rod bundles. The computer aided design model was developed using the ANSYS DESIGN MODELLER software and the dimensions listed in Table 1 (see Figs. 2 and 3(*a*)). To include the effect of conjugated heat transfer (heat conduction in fuel rods), the computational domain is comprised of fuel rod-related solid model (fuel cladding) and fluid regions. To facilitate meshing of the computational domain, the shape of the wire was approximated using an approach similar to the one discussed by Podila and Rao [11]. The computer aided design model was imported into STAR-CCM+ to mesh the fluid and solid domains.

The entire bundle geometry including wire-wraps was modeled to avoid errors in predicting the redistribution of flow due to the wire-wrap spacers. Prism layer cells were used at the heated walls to correctly predict the near-wall fluid temperature distributions. The first prism cell height at the wall was set at $y^+ \leq 1$ to adequately capture the heat transfer in the boundary layer. Conformal mesh between solid and fluid regions was generated using the polyhedral cells that enable smooth transition from near-wall prism layer cells. In order to avoid disfeaturing of the mesh on the surface of wires, an independent meshing control was applied to the surface of the wires. The adopted meshing approach allowed for precise placement of sufficient number of computational points even in the tight spot near the rod–wire contact. It should be noted that $y^+ \leq 1$ was not applied at unheated boundaries such as pressure tube walls and surface of wire-wraps. The computational domain had a total of 6.6×10^6 cells. The mesh on a cross section is shown in Fig. 3(*b*) for the wire-wrapped configuration. Other pertinent meshing parameters are summarized in Table 2.

2.2 Solution Procedure. In all simulations, the entrance and exit of the flow channel were modeled, respectively, with mass flux and pressure outlet boundary conditions. The experimental test conditions are presented in Table 3. Uniform volumetric heat

Table 1 Dimensions of 2×2 wire-wrapped rod bundle (from Ref. [15])

Geometry	Value
Outer diameter of heated rod (d)	8.0 mm
Wall thickness of heated rod	1.5 mm
Center distance between two rods	9.44 mm
Pitch to diameter ratio (p/d)	1.18
Flow area (A)	186.43 mm^2
Effective heated length (L)	0.6 m
Pitch of wrapped wire	200 mm
Diameter of wrapped wire	1.2 mm
Rod-to-wall gap (including the corner region)	1.44 mm

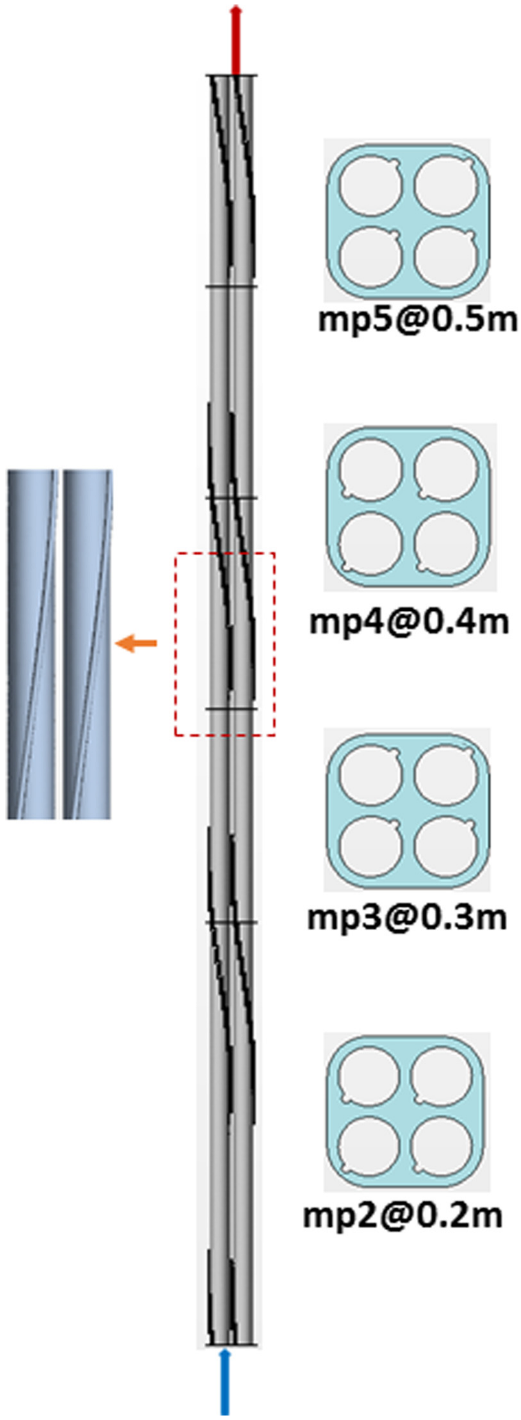
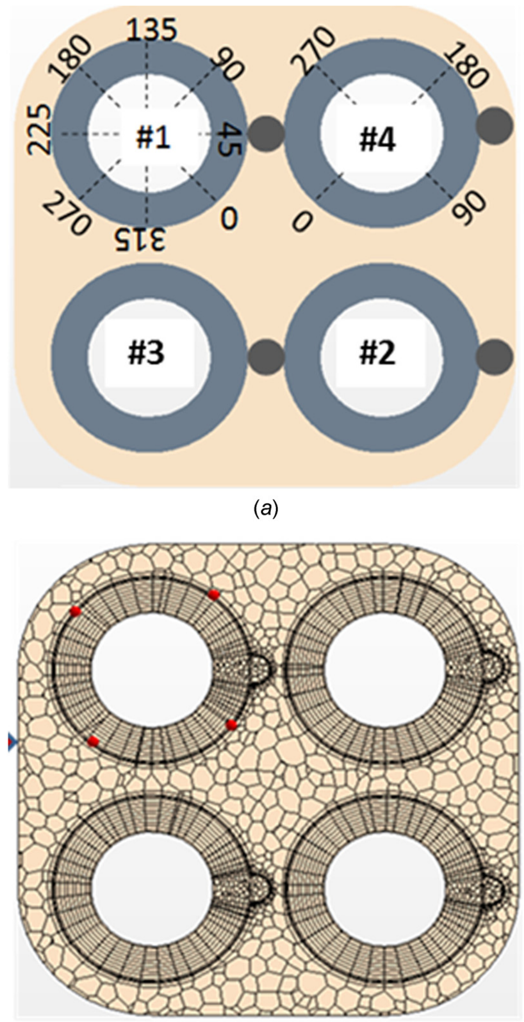


Fig. 2 Fluid domain of 2 × 2 wire-wrapped rod bundle (picture not to scale, pressure tube and fuel rod-related solid domain (cladding) not shown, mp@ represents measurement point and the corresponding location along the heated length)

source was applied in the solid domain of the heated rod (fuel cladding). The inner surface and the two ends of the rod were set adiabatic, while the outer surface of the rod was set as the interface with the fluid domain facilitating conjugated heat transfer. The gravity (buoyancy force) was included in all the simulations to correctly capture the heat transfer characteristics under the test conditions considered in the current investigation. The supercritical water properties at 25 MPa, obtained from the National Institute of Standards and Technology online database [17], were implemented in STAR-CCM+. The implementation details are discussed in Ref. [11].



(a)

(b)

Fig. 3 (a) A cross-sectional view of wire-wrapped rod bundles and (b) a cross-sectional view of mesh (bisque and gray shaded regions represent the fluid and solid domains, respectively)

Table 2 Meshing model options and parameters

Model/parameter	Option/value
Meshing models for fluid domain	Polyhedral, prism, surface remesher
Meshing model for solid domain	Embedded thin layer
Number of prism cells within fluid boundary layer	5
Number of thin layer cells in the solid domain	10
Thickness of the boundary layer (mm)	0.254
Topology of cells	Fluid: polyhedral in the core and prisms at near-wall regions; solid: prisms
First node point value (μm)	2.96
Wall y^+ range	$0.5 \leq y^+ \leq 5$

The governing equations for the three-dimensional geometry were solved using a steady-state segregated solver with Rhie-and-Chow-type pressure velocity coupling combined with a semi-implicit method for pressure linked equations type algorithm. The segregated solver was chosen over the coupled solver because it uses less memory, and it improves solution convergence for some

Table 3 Test conditions used for CFD simulations

Parameter	Case 1	Case 2	Case 3
Pressure (MPa)	25	25	25
Mass flux (kg/m^2 s)	1000	1000	1000
Heat flux (kW/m^2)	400	400	400
Inlet temperature (°C)	266.7	378.2	419.3
Volumetric heat power (MW/m^3)	328.2	328.2	328.2

cases. All equations were solved using the second-order differential schemes. Convergence was monitored for each run, and the solution was iterated till the residuals dropped at least by 3 orders of magnitude or less at completion and fluctuated in a steady manner. In addition, fluid temperature was monitored in the plane sections created near the outlet and in the middle part of the bundle geometries.

3 Evaluation of Turbulence Models

For the case of the 2×2 bare rod bundle, detailed evaluation of two turbulence models, SST k–ω and normal-velocity relaxation turbulence (v2f), was performed earlier in Refs. [16] and [18]. Based on these analyses, the SST k-ω turbulence model was recommended for the supercritical and pseudocritical conditions, whereas the v2f model was found to predict the flow physics better at the subcritical test conditions. However, the turbulence in the bare rod bundle differs significantly from that in the wire-wrapped bundle which has much stronger mixing due to the wire-wrap enhancement. Hence, the applicability of the conclusions derived in the earlier work, including that on the value of turbulent Prandtl number, is re-evaluated in this section for the wire-wrapped rod bundle. The two turbulence models were tested and assessed along with a suitable value of turbulent Prandtl number (Pr_t) for each of the subcritical, pseudocritical, and supercritical cases (cases 1–3 in Table 3). Since the wire-wrapped bundle experiments used a lower heat flux compared to bare bundles, lower values of Pr_t were found to be suitable for simulating the current test conditions. The criterion for the suitability of the models was mainly based on the correct prediction of the location of the peak wall temperature. Note that discussion of the results uses the rod # and circumferential locations (in degrees) that are presented in Fig. 3(*a*).

In this study, the near-wall region was modeled using the all y^+ treatment approach along with the SST k–ω and v2f turbulence models. The all y^+ treatment is a hybrid near-wall modeling approach that utilizes both the high y^+ as well as low y^+ wall treatments for the coarse and fine meshes. Thus, this kind of advanced wall treatment approach facilitates a consistent, y^+ insensitive mesh refinement from a coarse mesh to a fine mesh with mesh points placed inside the viscous sublayer. Note that the terms of k–ω and SST k–ω are used interchangeably hereinafter for simplicity.

At subcritical test conditions, the wall temperatures predicted by the two models are different from each other as seen in Fig. 4(*a*). Two temperature peaks and a valley were predicted by both models. The predicted location of the first peak (at rod-to-rod gap, 45 deg) and that of the valley (at 90 deg) were the same for the two models. However, the predicted location of the second peak was different between the two models. The k–ω model predicted the peak temperature in the rod-to-wall gap region at 225 deg, which is closer, compared to that by the v2f model at near 270 deg, to the center of the narrow-gap region (180 deg) where a wall-temperature peak was measured (as shown later). Based on the comparison, the k–ω model looks more promising for modeling the wire-wrapped bundle at the subcritical test condition. The better prediction by the k–ω model for the wire-wrapped bundles differs from the choice of the preferred model for bare rod bundles recommended by the earlier study [18].

Similar to the subcritical case, both the turbulence models predicted the temperature peaks and valley at the pseudocritical test condition (Fig. 4(*b*)). The k–ω model predicted two temperature peaks (one peak at near 45 deg, the other at was 135–270 deg (nearly flat)), whereas the v2f predicted only one (at near 270 deg). Although the k–ω model predicted a sudden rise in wall temperature at 135 deg, closer to the narrow-gap region, the temperature increase was marginal (∼1.7 °C) near 270 deg. Based on the predicted rise in temperature at ∼135 deg (as observed in the experiment), the k–ω model was preferred over the v2f model for modeling supercritical test condition. The ability of the k–ω model to predict experimental test condition is presented in Sec. 5.

For the supercritical test case (Fig. 4(*c*)), similarly the k–ω model predicted a temperature peak at rod-to-rod gap region (45 deg), and the second peak was 65 deg away from center of the narrow-gap region (i.e., at near 245 deg instead of 180 deg). Unlike in the case of pseudocritical test condition and similar to the case of subcritical test condition, the v2f model predicted a temperature peak at the location of 45 deg. Also, similar to the previous two test conditions, the v2f model predicted the second temperature peak at the location of 270 deg instead of the narrow-gap region (180 deg).

The shift of the temperature peak away from the circumferential location of 180 deg to near 245 deg suggests that mixing between the narrow-gap region and the wall may not have been properly captured by the k–ω turbulence model. To substantiate this, contour plots for secondary flows that facilitate the interchannel exchange of the fluid at the measurement location of 0.5 m have been presented in Fig. 5. The secondary velocity in this investigation is defined as the magnitude of the component of the velocity vector orthogonal to the mainstream direction, i.e., in the plane of the cross section. As seen at rod#1, the secondary flows at the narrow-gap region are predominant than at the location of 225 deg, thereby causing the peak temperature to shift from the angular location of 180 deg. Also, it should be pointed out that the swirling motion introduced by wire differs from the secondary motions which are induced by the nonisotropy of the stress tensor components in a noncircular channel.

4 Assessment of Computational Fluid Dynamics Predictions

Based on the sensitivity analyses of the turbulence models, and known for its ability to predict the swirling motion of the fluid, the SST k–ω model was chosen for the assessment of the CFD predictions for the 2×2 wire-wrapped rod-bundle experiments using the inlet conditions specified in Table 3. For the assessment of CFD predictions, the experimental data at rod#1 were used which were instrumented with moving thermocouples. The overall temperature distribution on the surfaces of rod and wire-wraps is presented in Fig. 6. The temperature increases from inlet to the outlet of the test section.

For rod#1 at an axial location of 0.5 m along the heated length, the experiment reported a bimodal peak and a valley in the circumferential distribution of temperature on the fuel rod (Fig. 7).

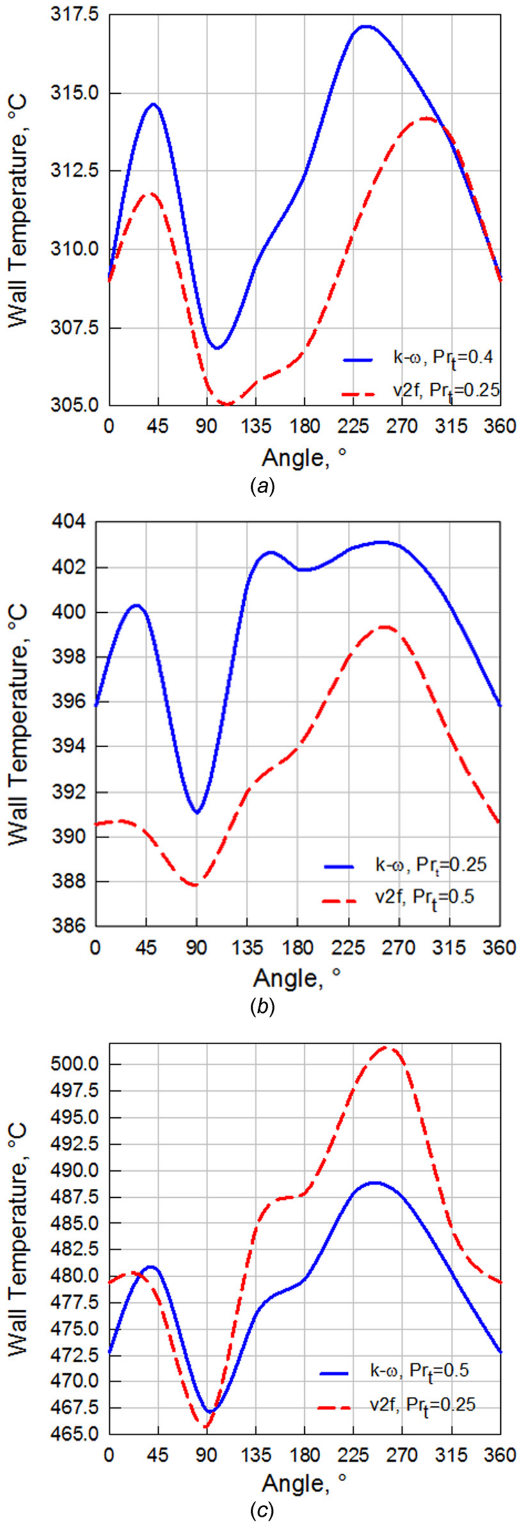


Fig. 4 Variation of circumferential wall-temperature distribution on rod#1 using different turbulence models at the measurement location of 0.5 m under (*a*) subcritical test condition, case 1, (*b*) pseudocritical test condition, case 2, and (*c*) supercritical test condition, case 3

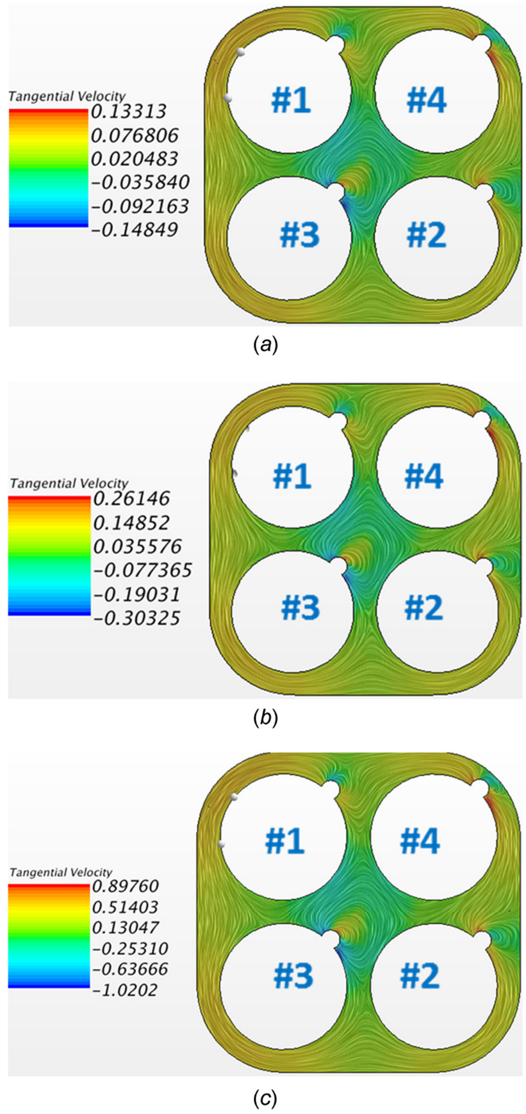


Fig. 5 Predicted secondary flows in m/s on a cross section at 0.5 m using the *k*–*ω* turbulence model under (*a*) subcritical test condition, case 1, (*b*) pseudocritical test condition, case 2, and (*c*) supercritical test condition, case 3

The dominant temperature peak is seen in the narrow-gap region (180 deg) and another smaller peak at the 270 deg location, whereas a small dip in temperature (valley) is generally seen at an angular location of 225 deg. The CFD predictions were able to capture the order of temperature reported in the experiments as seen from Fig. 7. However, the location of the peak temperature was predicted away from the narrow-gap region (180 deg) for all the three cases. The experiment reported the peak temperature in the narrow-gap region, 180 deg, whereas the CFD predicted the peak temperatures further downstream (circumferentially) at 225–245 deg. In addition, the simulations under- and overpredict the experiments at certain locations; the extent varied from one test condition to other. At the subcritical test condition, the simulations overpredicted the experiments by up to 8 °C, whereas the overprediction was 9 °C and 12 °C for in the supercritical and pseudocritical test conditions, respectively. The overprediction was primarily concentrated in the edge of the rod-to-wall gap region (225 deg). On the other hand, a maximum of ∼10 °C under prediction was seen at circumferential location of 90 deg for the supercritical test condition. Based on the results presented in Figs. 5 and 7, it can be inferred that the *k*–*ω* turbulence model was not able to resolve the turbulence correctly in both the corner and rod-to-rod gap regions. It is worth noting that this study is the first of its kind for assessment of CFD predictions of the wire-wrapped bundles under supercritical conditions; further thorough analysis is needed to resolve the observed discrepancies between predictions and measurements. In addition, the flow in the rod

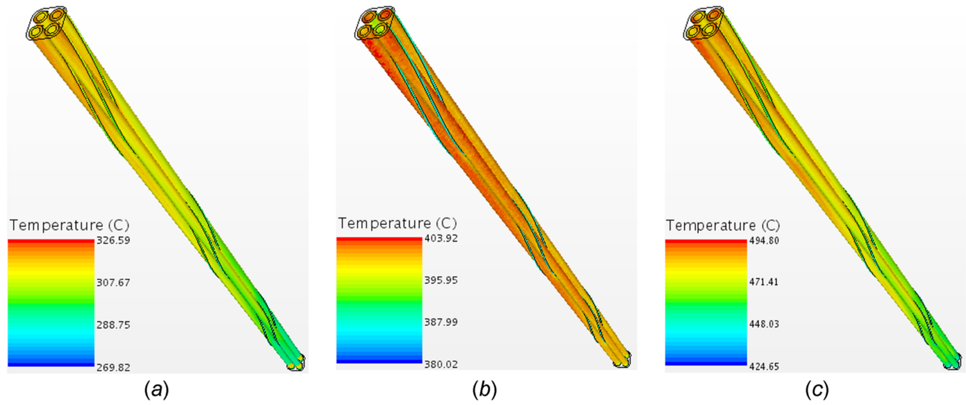


Fig. 6 Overall predicted temperature distribution in the fluid domain along the heated length of the 2 × 2 wire-wrapped fuel bundle assembly under (*a*) subcritical test condition, case 1, (*b*) pseudocritical test condition, case 2, and (*c*) supercritical test condition, case 3

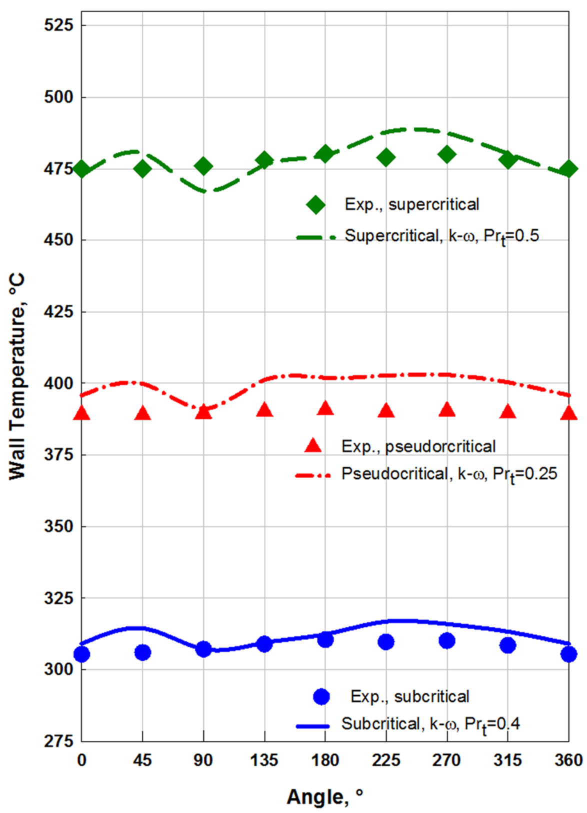


Fig. 7 Assessment of the CFD predictions with measurements on rod#1 at 0.5 m using the *k*–*ω* turbulence model at sub-, pseudo-, and supercritical test conditions

bundle is inherently unsteady due to the presence of wire that constantly introduces a swirling motion to the fluid. For forced convection such as the one in the current analysis, the swirling flow is generally periodic along the axial direction and is a function of the wire position. These effects could be better modeled using a transient solution scheme instead of a steady-state approach that was used in the current analysis. The influence of the wire on the fluid flow could not be quantified as the experimental data set comprised of only wall temperatures, since the velocity distribution and turbulence characteristic were not measured.

5 Conclusions

Canadian Nuclear Laboratories has established a fuel-assembly concept for the Canadian supercritical water reactor that is comprised of 64-elements with wire-wrap spacers. This study was initiated to assess the capabilities of the existing turbulence models within the CFD framework to predict the flow and heat transfer in the fuel bundles subjected to 25 MPa. The assessment of CFD simulations was carried against the 2 × 2 wire-wrapped rod-bundle experiment performed at Xi'an Jiaotong University in China. The wall temperatures predicted using CFD were generally in line with the measurements, with a maximum under- or over-prediction of ∼10 °C and 12 °C, respectively. The location of the predicted peak wall temperature shifted downstream (circumferentially) at 225–245 deg which was inconsistent with the experiments that reported a peak at the narrow-gap region (180 deg). Measurements of velocity and turbulence in the vicinity of wire-wrap are needed to assess the suitability of the turbulence models to simulate wire-wrap bundles subjected to flows at supercritical pressures.

Nomenclature

CFD = computational fluid dynamics
CNL = Canadian Nuclear Laboratories
mp = measurement point
SCWR = supercritical water reactor
SST = shear stress transport
v2f = normal-velocity relaxation turbulence model
XJTU = Xi'an Jiaotong University

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