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Numerical Investigation of the thermodynamics behaviors in the Central Downward Circular Tube of the 64-element Canadian SCWR Fuel Bundle

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Abstract— The supercritical water-cooled reactor was proposed as one of the Generation IV nuclear systems. Despite many studies on supercritical water in circular channels have been conducted before, only very few studies on the fluid flow and heat transfer process in coolant channels of the supercritical water-cooled reactors have done. In this study, the thermo-hydraulic behaviors of the water in the coolant channel of the 64-element Canadian Supercritical water-cooled reactor are predicted by computational fluid dynamics (CFD) simulations using the software ANSYS FLUENT. The results show that the secondary flow appears at the inner coolant channel, and the high vorticity enhances the heat transfer between the wall and the supercritical water.

Keywords-Supercritical water-cooled reactort; thermo-hydraulic; CFD; secondary flow; vorticity

I. INTRODUCTION

The supercritical water-cooled reactor (SCWR) was proposed as one of the Generation IV nuclear reactors, which is the only one using the supercritical water as coolant. The proposed SCWR configuration is shown in Fig.1 [1]. Canadian supercritical water-cooled reactor concept is based on the design of the typical CANDU reactor. The moderator for the rector is still heavy water, while the coolant is light water. Because of the single-phase coolant, steam separators and steam generators are not needed. Since the configuration of the SCWR is relatively simple, the heat loss can be decreased and the thermal efficiency can be around 44% [2]. Although SCWRs have these advantages, there are still challenges. The supercritical water experiences a dramatic thermophysical properties change near the pseudo-critical point, which can be seen in Fig.2. The pseudo-critical point is where the specific heat of the water has the peak value under a specific pressure above the critical point. Because of the strong properties change of the supercritical water around the pseudocritical point, especially density and specific heat, heat transfer deterioration in the channel is easy to happen.

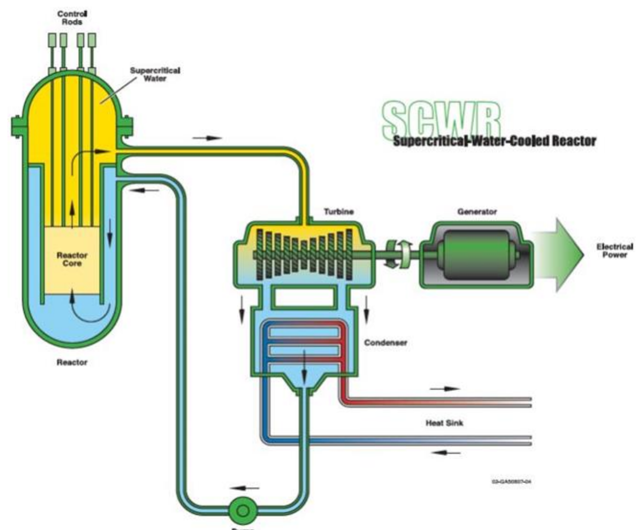
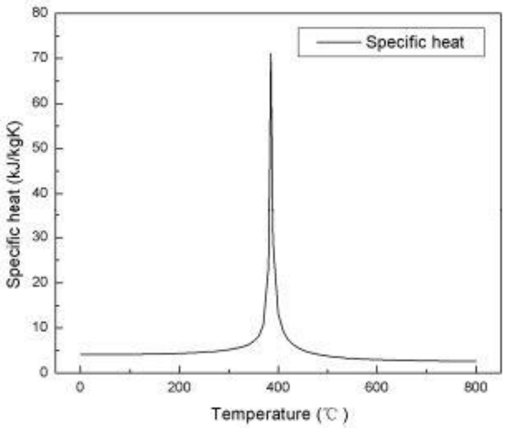


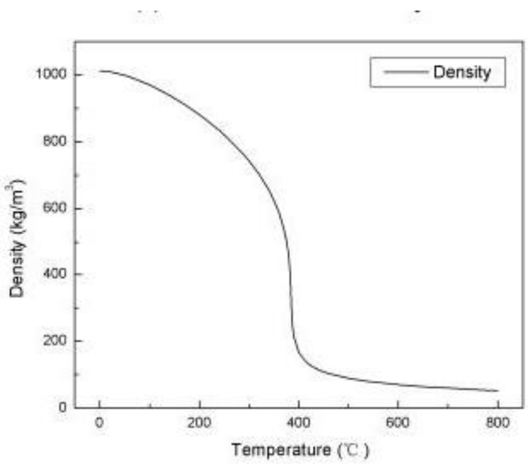
Figure1. Proposed supercritical water-cooled reactor configuration [1]

Only very limited experimental studies were carried out for the heat transfer and flow phenomenon of supercritical fluids because of the experiment environment restrictions. Xi et al. [3] did an investigation on the supercritical water flow between two heated parallel channels. Both inlet mass flow rate and outlet temperature oscillations were observed. Verma et al. [4] carried out the experiments using a scaled test facility of AHWR (Advanced Heavy Water Reactor) rod bundle. The effect of the spacer on the turbulent mixing rate in subchannels was investigated. The results showed that the turbulent mixing rate increased with the increase in the average Reynolds number.

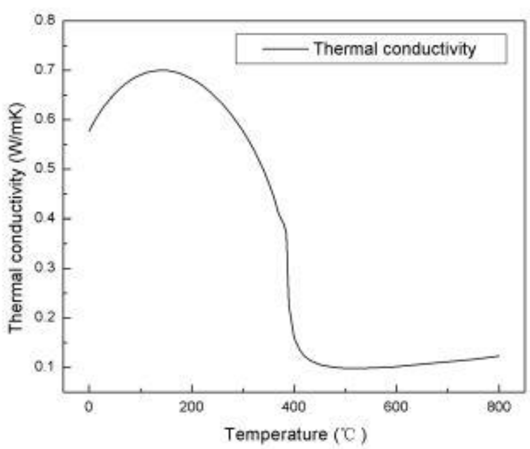
Until now, Canadian SCWR is still in conceptual design stage and no experimental data are available. Numerical method is highly recommended to predict the characteristics of fluid flow and heat transfer in reactor fuel bundles when there are no experimental data.



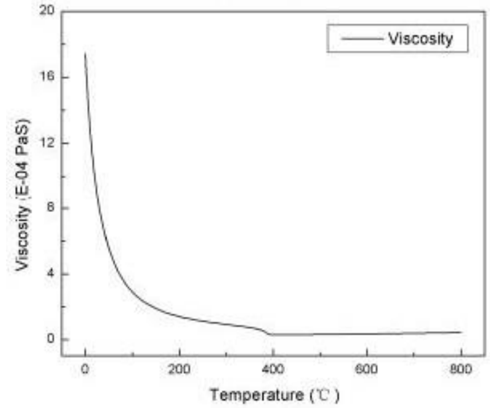
(a) Specific heat



(b) Density



(c) Thermal conductivity



(d) Viscosity

Figure2 Thermohydraulic properties of the water under p=25MPa

The numerical studies for the flow in rod bundles have been conducted by several researchers. Azih et al. [5] studied the convective heat transfer of supercritical fluids without gravity, and obtained the effects of Reynolds number, boundary layer and other factors on heat transfer. Zeng et al. [6] also conducted computational fluid dynamics simulation in circle channel. The gravity and thermal expansion acceleration effects were included in the turbulence model used in the subcritical fluid flow simulation. Zhang et al. [7] proposed a new supercritical fluid flow model to better deal with the physical instability properties of the supercritical fluid around the pseudo-critical point. Zhang et al. [8] simulated heat transfer and flow of supercritical water in a 37-element horizontal arranged SCWR under steady state condition and found that the anisotropic turbulent model, the Reynolds stress model, behaves much better than the isotropic model in predicting the cladding surface temperature. Rohit [9] also simulated heat transfer of supercritical water in circle channels using different turbulence models. The results were compared with the respective experimental data to validate the numerical model. However, these previous researchers mainly investigated either the supercritical water flows in circle channels or based on a simplified geometry of CANDU fuel bundle. The current design of the Canadian SCWR is shown in Fig.3 [10]. The coolant flows downward first in the circle tube, then flows upward in the fuel rods region. The cross-section view of the fuel bundle evolution of the Canadian SCWR is illustrated in Fig.4. The cross-section area of the inner coolant tube is enlarged gradually to reduce the cladding surface temperature of the fuel rod. There is still lack of the investigation of the thermo-hydraulic behaviors of the supercritical water in the inner coolant tube of 64-elelment fuel bundle. Therefore, in this work, the fluid flow and heat transfer phenomenon in the inner coolant tube under the full load condition will be investigated. And the Computational Fluid Dynamics (CFD) simulations are carried out by ANSYS FLUENT 19.1.

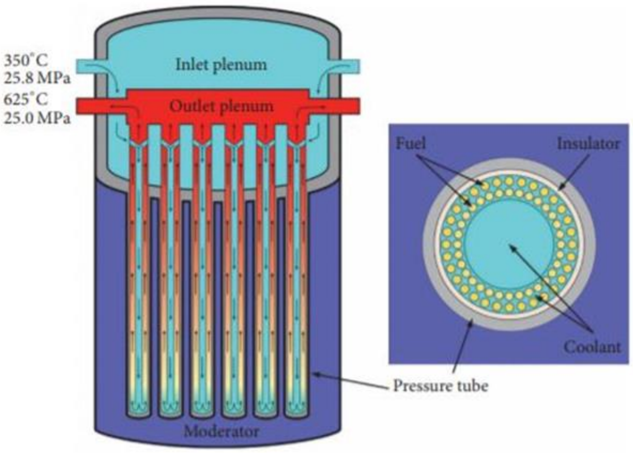


Figure 3. Canadian supercritical water-cooled reactor

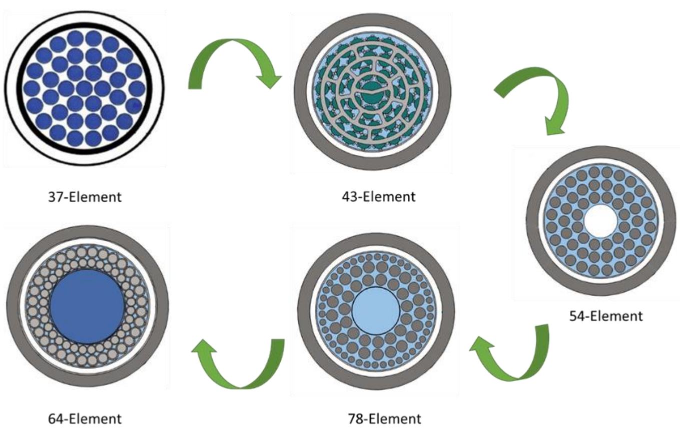


Figure 4. Cross-section view of the Canadian supercritical water-cooled reactor fuel bundle

II. GOVERNING EQUATIONS AND NUMERICAL MODELS

The simulation of the inner downward coolant flow in the circular tube of the 64-element Canadian SCWR fuel bundle is carried out under the full load condition, which is shown in Table1. The properties of the water under 25 MPa are from Wagner [11]. The computational domain and the cross-section view of the mesh constructed used in the simulation are illustrated in Fig. 5.

Table 1 Specifications of the inner circular tube

Center tube radius/mm	46
Center tube wall thickness/mm	1
Center tube length/mm	5000
Center tube inlet temperature/Celsius	350

The governing equations for the three-dimensional steady flow are conservations of mass, momentum and energy:

$$\frac{\partial}{\partial x_i}(\rho \overline{u_i}) = 0 \quad (1)$$

$$\frac{\partial}{\partial x_j}(\rho \overline{u_i}\overline{u_j}) = -\frac{\partial \bar{p}}{\partial x_i} + \frac{\partial}{\partial x_j}\left(\mu \frac{\partial u_i}{\partial x_j} - \rho \overline{u_i' u_j'}\right) + \rho g_i \quad (2)$$

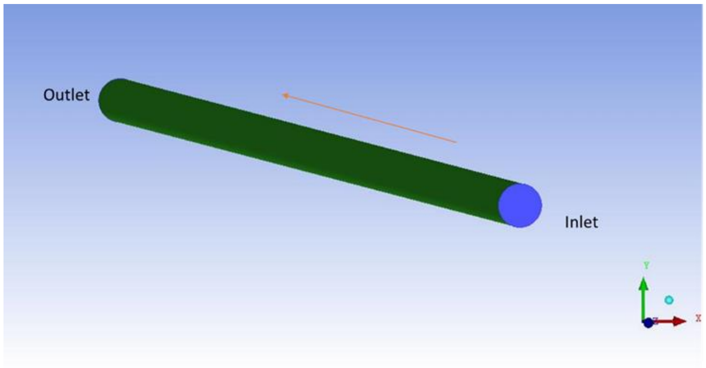
$$\frac{\partial}{\partial x_i}(\overline{u_i}\rho c_p T) = \frac{\partial}{\partial x_i}\left[\left(\lambda + \frac{c_p \mu_t}{Pr_t}\right)\frac{\partial T}{\partial x_i}\right] + \emptyset \quad (3)$$

Here, u is the velocity, T is the temperature, μ is the dynamic viscosity, ρ is the density, λ is the thermal conductivity, c_p is the specific heat, μ_t is the turbulent viscosity, and Pr_t is the turbulent Prandtl number. Previously, Zhang et al. [8] found that the simulation results using the Reynolds stress model (RSM) can give a better agreement with the experimental data. Therefore, the RSM with the enhanced wall treatment is used in study and the transport equation of the RSM can be found from [12]. Gravity, thermal effects, buoyancy effects, and viscous heating are all included. The SIMPLEC scheme is chosen and the second order upwind is chosen for the spatial discretization. The convergence criteria for the continuum, momentum, energy and turbulent parameters are all set as 10^{-6} . Based on the grid independence tests, which are shown in Table 2, 8,184,000 nodes mesh is used for the simulation. Mesh near the wall is refined so that the non-dimensional distance to the wall is approximately 1. The boundary conditions for the simulation are as follows:

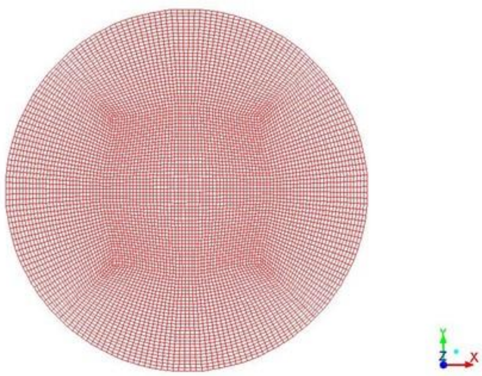
Inlet: The inlet mass flow rate is 3.929 kg/s, and the inlet temperature is 623.15 K (350℃). Turbulent intensity and hydraulic diameter are specified based on the operation parameters of Canadian SCWR design [13].

Outlet: Outflow,

Wall: Smooth wall with no-slip condition. Heat flux is 879,931.2W/m^2 and the wall thickness is 1mm [14].



(a) Computational domain



(b) Cross-section view of the mesh

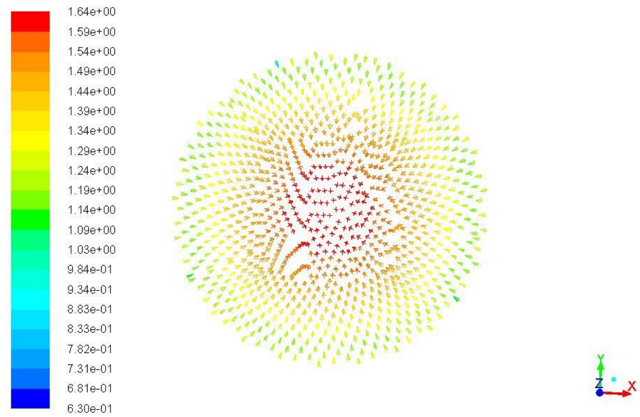
Figure 5. Computational domain and mesh of the inner central tube

Table2 Grid independent tests

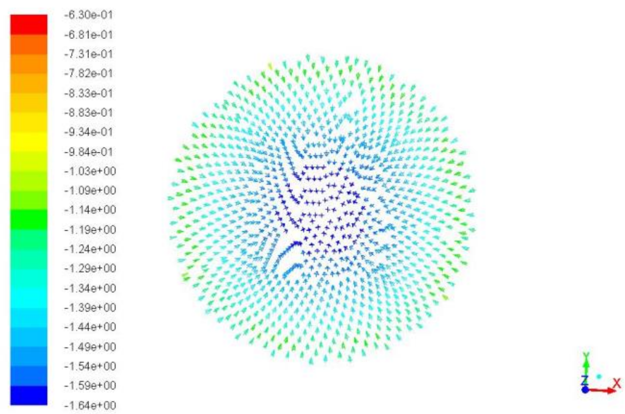
Mesh	Coarse	Medium	Fine
Nodes	2728000	4092000	8184000
Outlet bulk temperature(K)	661.84	652.77	656.13
Difference (%)		1.37	0.51
Outlet velocity magnitude (m/s)	1.3228	1.3801	1.3995
Difference (%)		4.33	1.41

III. Results And Discussions

Fig.6 shows the outlet velocity vectors colored by the velocity magnitude of the supercritical water and the outlet velocity in the z-direction at the inner coolant channel. The velocity vectors colored by vorticity magnitude of the supercritical water at the outlet is presented in Fig.7. It is observed that the secondary flow occurs in the central coolant tube, and there is a big increase in the vorticity magnitude from the center to the wall.



(a) Velocity



(b) Velocity in the z direction

Figure 6. Outlet velocity vector of the supercritical water colored by the magnitude (m/s)

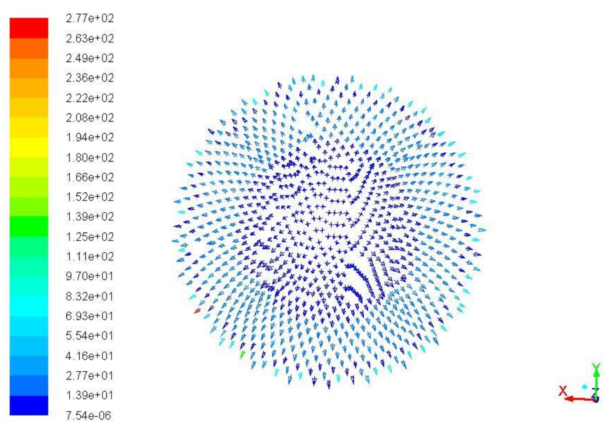


Figure 7. Velocity vectors colored by vorticity magnitude of at the outlet

The outlet bulk temperature of the supercritical water at the central tube is shown in Fig. 8. The temperature of the supercritical water along the wall is not evenly distributed. Comparing Fig. 7 and Fig. 8, it can be seen that higher temperature appears at the higher vorticity location. The high vorticity caused by the secondary flow which enhances the heat transfer between the wall and the supercritical water.

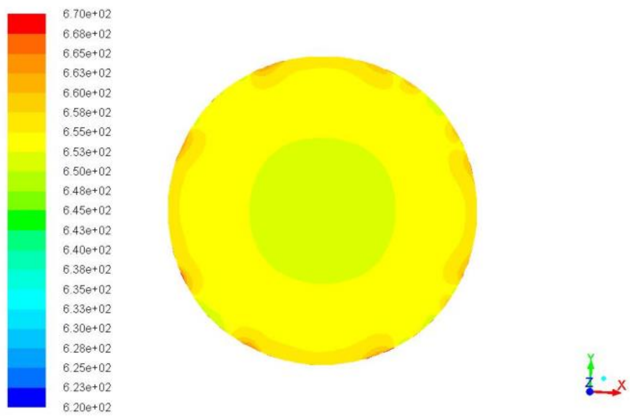


Figure 8. Contour of outlet static temperature

IV. CONCLUSIONS

In this study, the fluid flow and heat transfer characteristics of the supercritical water in the center coolant tube of the 64-element Canadian SCWR are investigated. The results show that the secondary flow appears in the central channel. And the strong vorticity enhances the heat transfer between the wall and coolant. The outlet bulk temperature of the supercritical water at the central coolant tube in the multi-rod channel is 656.13 K (382.98°C). The temperature has experienced the most drastic change at the pseudocritical point. Since the supercritical water will be transported to the outer region with multiple fuel rods, further numerical simulations will be performed in the future for fuel rod bundle region in order to study the cladding surface temperature limitations.

ACKNOWLEDGMENT

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