Progress of thermal-hydraulic research on SCWR in NPIC

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Abstract

For advantages of higher efficiency of thermal cycle, simpler primary coolant circuit etc, Supercritical Water Reactor (SCWR) is much competitive in the Generation-Ⅳ nuclear system. Based on the supercritical water reactor engineering, NPIC has started related numerical analysis, test technology research, test facility design and some experimental researches of thermal hydraulics of supercritical water since 2005. The progress of thermal hydraulic research on SCW in NPIC in the past five years, will be introduced briefly, included numerical research of SCW thermal hydraulic performance, test technology research, design and construction of thermal hydraulic test facilities, and related experimental research of SCW flow resistance and heat transfer behavior.

1. Introduction

To meet the growing demand for clean, safe, cost-effective energy now and in the future, nuclear energy becomes more and more prominent with certainty of long-term supply and without adverse environment impacts. To enhance the future role of nuclear energy systems, six innovative nuclear energy systems (GFR, LFR, MSR, SFR, SCWR, VHTR) were selected to Generation IV by the GIF for sustainability, economics, safety and reliability, and proliferation resistance and physical protection [1]. The SCWR system is competitive and promising in Chinese Generation IV system for high thermal efficiency (approaching 44%), plant simplification, billion-We plant power level [2-3], successive technology of Chinese PWR roadmap etc. And much of the technology base for the SCWR can be found in the existing PWR and in commercial supercritical-water-cooled fossil-fired power plants.

However, there are some immature areas in SCWR. One of the important SCW technology gaps is thermal hydraulic performance of the reactor system, which influences the SCWR safety, plant design and economics directly [4]. The supercritical water environment is unique and deficient data exist on the thermal hydraulic performance of water with complicated fuel assembly geometries under high heat flux (about megawatt per square meter level) in near-critical and pseudo-critical area [5]. Several topics of SCWR thermal hydraulic performance should be researched necessarily, for example, the fuel cladding-to-SCW heat transfer research, the SCW critical flow experiment, the flow stability of SCWR, the out-of-pile test of SCWR design etc[1].

As an important PWR R&D centre in China, Nuclear Power Institute of China (NPIC) has started thermal hydraulic research on SCWR since 2005. This paper introduces the progress of thermal hydraulic research in NPIC, including numerical analysis, test facilities design and construction, and some experimental researches of thermal hydraulics under supercritical water.

2. Design and construction of T-H test facilities

In the past 40 years, NPIC designed and constructed several thermal hydraulic facilities for experimental research to support PWR design, for example, Large-scale T/H test loop with 10 megawatts of power for full length rod bundles simulator test, Passive residual heat removal system experimental loop, Freon T/H experimental loop, DNB thermal experimental loop etc. The outlines of the major thermal hydraulic experiments for PWR R&D are listed below [6-9].

- ✓ CHF Test with single pipe and 4×4 Bundles Simulator
- ✓ Non-uniform heated CHF Test with 5×5 full length rod bundles simulator
- ✓ Experiment of flow instability in double pipes and seven pipes of SG
- ✓ Experiment of AC600/AC1000 passive residual heat removal system
- ✓ Experiment of Advanced Reactor Passive residual heat removal system
- ✓ Fundamental experiment of Passive residual heat removal system

In 2008, NPIC designed small-scale SCW T/H test loop [10] in SJTU, China, as a member of 973 Project on SCWR scientific problems (as shown in Figure 1). The medium of this loop is water, and the primary parameters are listed here: design pressure is 30MPa, design temperature is 550℃, flowrate of the loop is 2m^3/h and the heating power is 0.8MW.

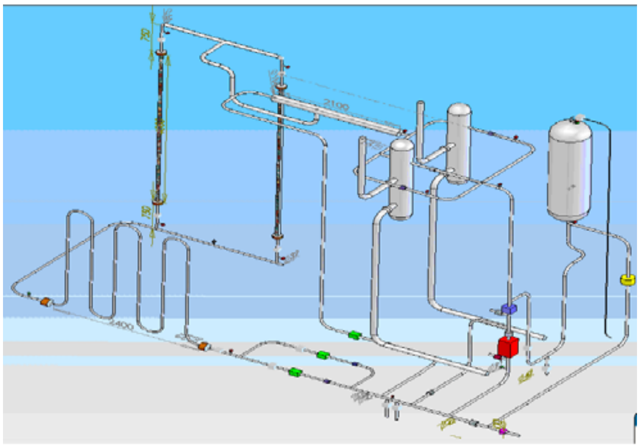


Figure 1 Small-scale SCW T/H test loop in SJTU, China

In Sep. 2009, SCWR mechanism T/H test loop (as shown in Figure 2) was funded in NPIC for experiment research on SCW flow resistance and heat transfer with single/double pipe. The mechanism T/H test loop not only supports SCW T-H test technology research, but also produces basic thermal hydraulic experimental data of SCW for CFD model and numerical research. The primary parameters of the loop are listed here: design pressure is 30MPa, design temperature is 550℃, flowrate of the loop is 0.5m^3/h and the heating power is 0.32MW.

Figure 2 SCWR mechanism T/H test loop, funded in 2009, NPIC

3. Thermal-hydraulic numerical research

Various numerical T-H researches of SC fluids were performed in the past 30 years. In general, the convection heat transfer of SC fluids was treated as single phase convection heat transfer with variational properties. In this method, some explanation of the flowing and heat transfer mechanism of SC fluids was got, and primary thermal hydraulic computation of SCWR was preformed. However, there is pivotal doubt about the applicability of turbulence model and wall treatment in sub-critical pressure to supercritical condition, especially when heat transfer deterioration occurs. Several numerical investigations on thermal hydraulic performances of SCW were started in NPIC.

3.1 Evaluation of CFD model for SCW

The investigation on the applicability of the computational models was performed. Based on the heat transfer experimental data of SCW in vertical circular tubes from publications, the computational results with different turbulence models and wall treatments in Fluent6.3 and CFX10 at the same parameters to the experiment were compared. When heat transfer deterioration does not occur, the prediction with the RNG k-ε turbulence model and the low-Re two-layer model is the best, as shown in Figure 3; When heat transfer deterioration occurs, the computational results with the SST turbulence model and the low-Re k-ω model in CFX10 approximately conform to experimental data and theory, but the same turbulence model in Fluent6.3 can't, as shown in Figure 4.

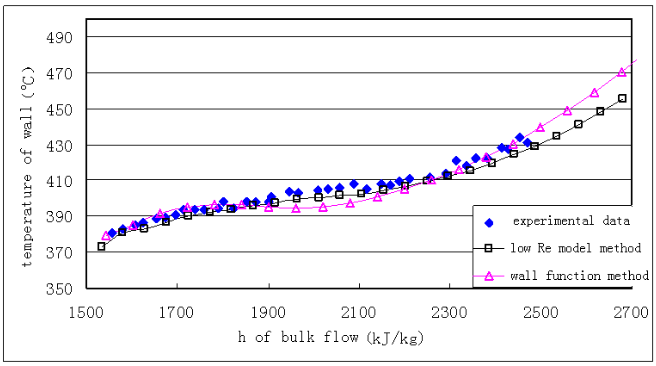


Figure 3. Computational results in two method compared with Yamagata data [11] (24.52MPa, 1260kg/m^{2}s, 698kW/m^2, with 7.5mm diameter, vertical tube, upward flow)

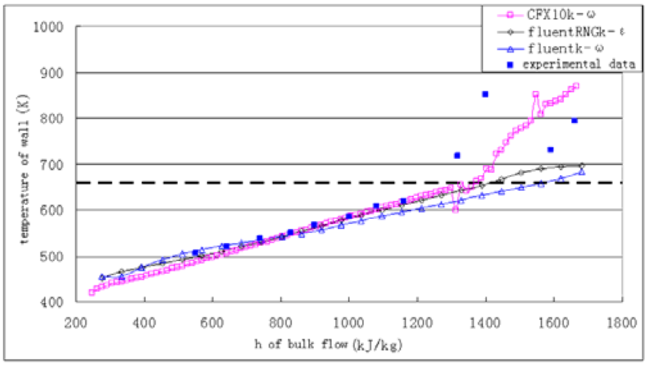


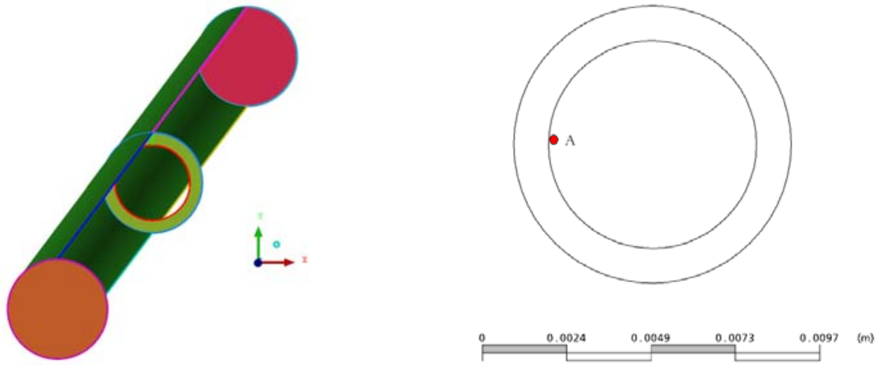
Figure 4. Computational results with different turbulence models in low-Re wall treatment method compared with Ornatskijdata [12] (25.5MPa, 1500 kg/m^{2}s, 1630 kW/m^2, with 3.0mm diameter, vertical tube, upward flow)

3.2 T-H Numerical research of SCW in tube

The investigation on the thermal-hydraulic characteristic of supercritical water in vertical circular tubes was performed with numerical simulation and theoretical analysis [13]. Based on the investigative results, the gravity plays the main role in heat transfer deterioration, but it has little influence in heat transfer enhancement. Heat transfer coefficient relates strongly to the average temperature of wall area other than the bulk temperature, when the average temperature of wall area approaches the pseudo-critical temperature, the heat transfer coefficient becomes larger. Heat flux and mass flux influence heat transfer by changing the radial velocity grads or turbulent kinetic energy near the heating wall, while pressure influences heat transfer by changing the thermal-physical properties of the fluid near the heating wall.

3.3 Numerical research of SCW with local geometrical components

The numerical investigation on heat transfer to supercritical water in simple channels with local geometrical components was performed with RNG k-ε turbulence model and Scalable wall function in CFX10. The circular baffle (OD.8.0mm, ID.6.0mm, 500mm to the outlet) in vertical tube (1.0m long, 8.0mm inner diameter) with upward SCWR flow was selected as the first local geometrical component, as shown in Figure 5. Based on the results, the circular baffle enhanced heat transfer greatly, as shown in Figure 6. The circular baffle changed streamline of the boundary layer and mixed the fluid in boundary layer with bulk flow. After the mixture, radial temperature gradient of the flow decreased and the average temperature of boundary layer decreased rapidly, but recovered after the circular baffle in some distance, as shown in Figure 7.



(1) flow channel (2) projection of the flow channel cross section

Figure 5. Design of circular baffle in vertical tube

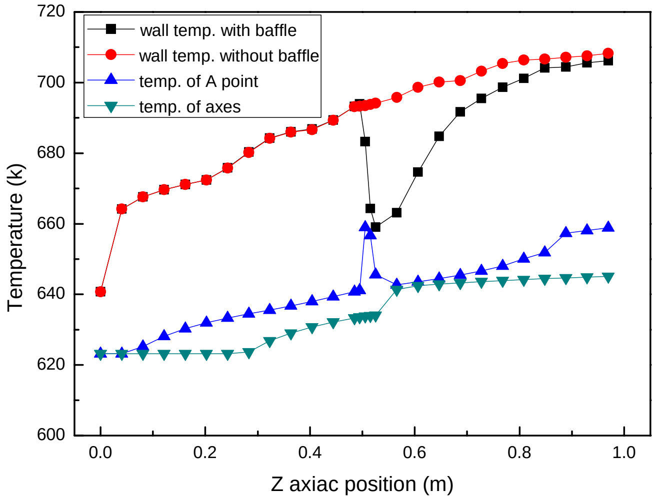
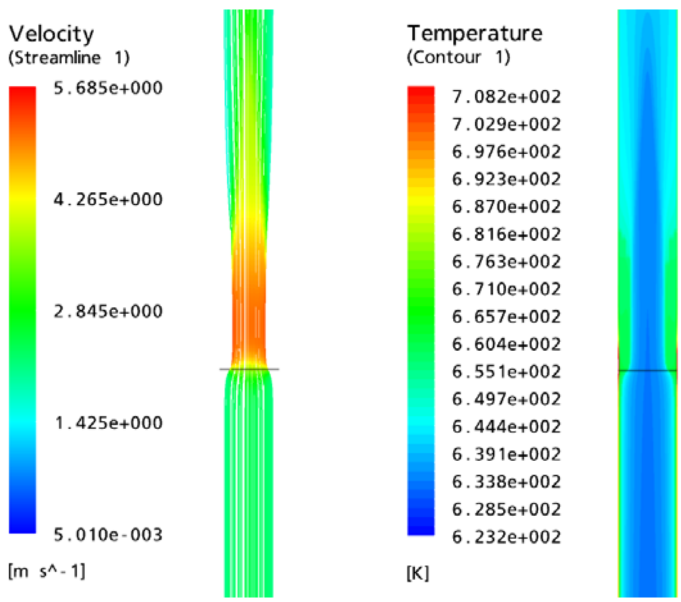


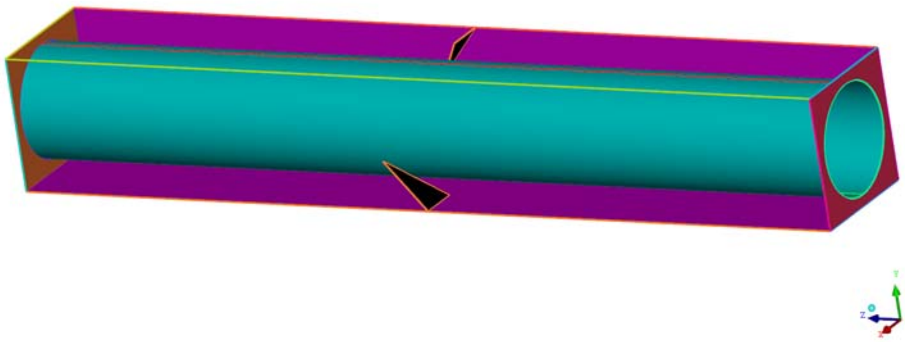
Figure 6. Temperature distributing of different sections in axial direction



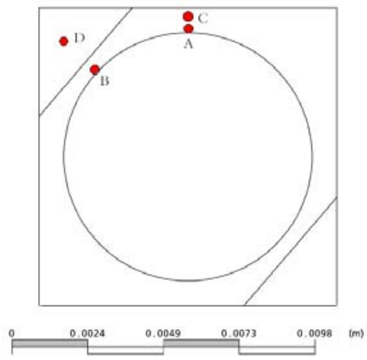
(1) streamline (2) temperature

Figure 7. Nephogram of streamline and temperature near the circular baffle

The vane (horizontal projection 3.5×3mm triangular shape, 50° elevation, rotational symmetry, 500mm to the outlet) in vertical rectangular channel (9.6×9.6mm, 1.0m long)with one heated rod (8.0mm inner diameter) with upward SCWR flow was selected as the second local geometrical component, as shown in Figure 8[14]. Based on the results, the circular baffle enhanced heat transfer greatly and prevent from heat transfer deterioration effectively, as shown in Figure 9 and 10. The vane produced secondary flow downstream and mixed higher temperature fluid at the narrowest flow channel with lower temperature fluid at the widest flow channel, as a result, the circumferential temperature distributing of the rod became less asymmetrical, as shown in Figure 11.



(1) flow channel



Point A(0,0.004m), the point on the edge of rod at the narrowest flow channel
Point B(0.00283mm, 0.00283mm), the point on the edge of rod to the wane
Point C(0,0.0044mm), the point in the middle of the narrowest flow channel
Point D(0.00381mm,0.00381mm), the point at the center of the vane

(2) projection of the flow channel cross section

Figure 8. the design of vertical rectangular channel with The vane

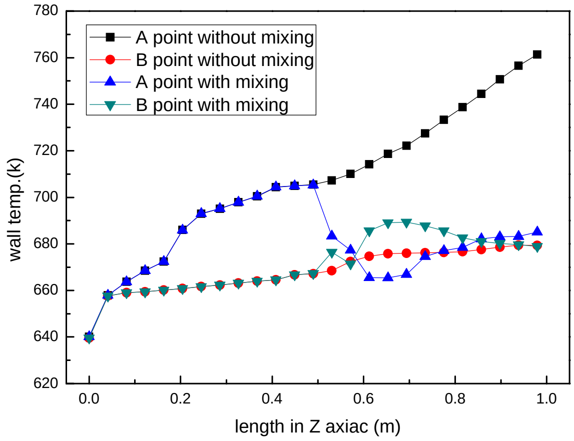


Figure 9. Wall temperature distribution of Point A and B in axial direction

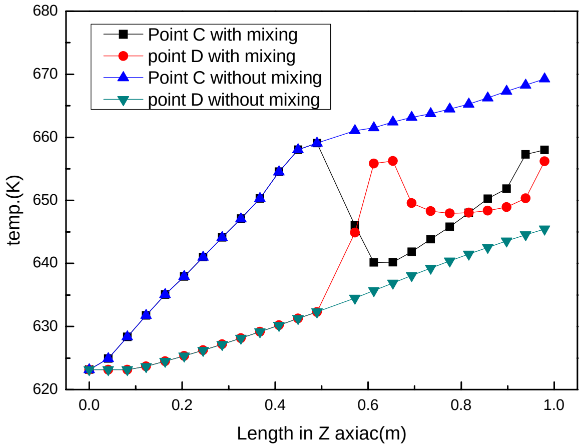


Figure 10. Temperature distribution of Point C and D in axial direction

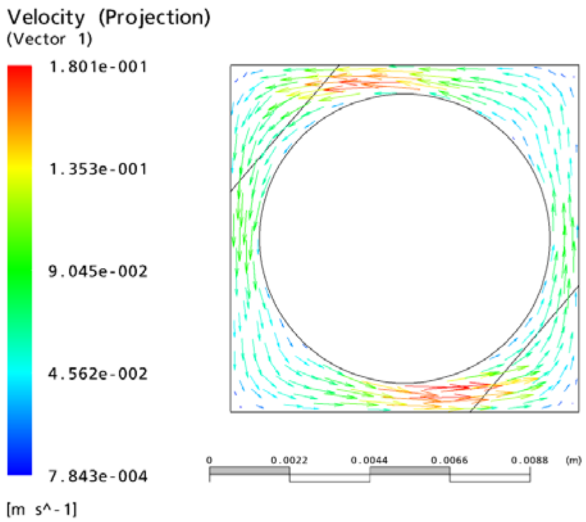


Figure 11. Cross section nephogram of secondary flow, 600mm to the inlet

4. Experimental research of SCW T-H

The purpose of the SCW experimental research is to develop the basic thermal hydraulic database for the development of China SCWR. The SCWR mechanism T/H test loop of water in NPIC is used. The test section of smooth circular tubes and with circular baffle and vanes is being tested, which focus on heat transfer, flow resistance, especially heat transfer deterioration in supercritical condition.

5. Conclusion

NPIC has done several work on numerical analysis, test technology research, test facility design and some experimental research of thermal hydraulics under supercritical water in the past 5 years, and there is a professional team on SCWR thermal hydraulic research in NPIC, which consists of 20 engineers. Based on these foundations and long-term research program, NPIC will accept the challenges of thermal hydraulic research on SCWR in the future.

6. References

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