REVIEW OF RESEARCH ON CANDU-SCWR IN XJTU

Jianqiang SHAN[1], Liangzhi CAO[1] , Qincheng BI[1] and Junli GOU[1]

[1] School of Nuclear Science and Technology, Xi'an Jiaotong University
Xi'an, Shaanxi, 710049, China

Abstract

The pressure channel design of SCWR can avoid a thick wall vessel, and allows, in principle, some key features for safety and performance. The present paper will review the research on CANDU-SCWR in Xi'an Jiaotong University, China.

(1) Thermal-hydraulics and safety analysis: Subchannel analysis of bundle, startup procedure, radiation heat transfer capability analysis were analyzed.

(2) Neutronics/thermalhydraulics coupling analysis: An improved CANDU-SCWR core design with vertical channels in hexagonal arrangement was developed.

(3) Experimental work: A supercritical water heat transfer test section has been built to study heat transfer in annular flow channel. Based on the experimental results, the effects of mass flux and heat flux on heat transfer of supercritical pressure water in vertical annular channel were analyzed.

1. Introduction

The supercritical pressure water-cooled reactor (SCWR) is one of the six reactor technologies selected for research and development under the GIF in 2002. It has the potential advantage of minimization of nuclear waste and low capital cost due to its high thermal efficiency and simplifications of the plant system. A SCWR power plant may achieve high thermal efficiency (about 45% vs. about 35% efficiency for advanced LWR). It is operated above the critical pressure of water, where the reactor coolant experiences no phase change (the coolant flowing into the core changes continuously from a lower temperature, high density compressed liquid to high temperature, low density compressed liquid, without any discontinuous phase change in the core). Because of this, the SCWR plant system can be kept simply as the need for many of the traditional LWR components such as the coolant recirculation pumps, pressurizer, steam generator, and steam separator and dryer is eliminated. One of the main features of supercritical water is the strong variation of its thermal-physical properties in the vicinity of the pseudo-critical line (Figure 1). Although operation above the critical pressure eliminates coolants boiling, and the coolants remains single-phase throughout the system, the large variation of thermal-physical properties may result in unusual heat transfer which demands further investigations. Researches in different areas have been done to analyze CANDU-SCWR in XJTU, China.

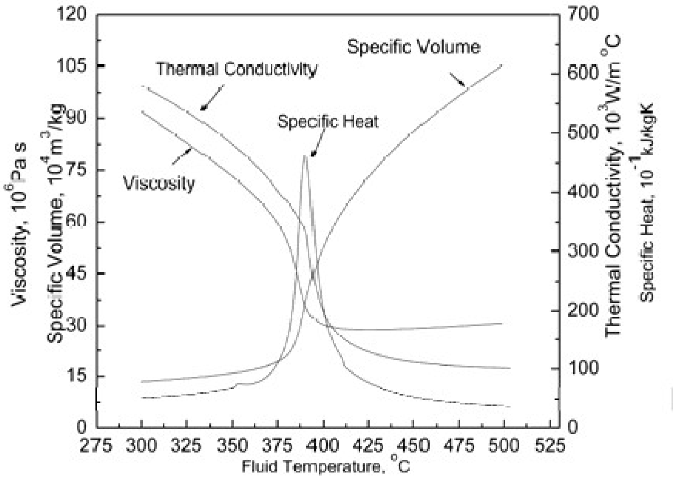


Figure 1 Thermo-physical properties of water at 25MPa

2. Neutronics/thermalhydraulics coupling analysis

Based on 3D Neutronics/TH coupling method, the feasibility of a new design of vertical channel PT-SCWR is analyzed. In order to obtain negative CVR in the new design, we change square lattice to hexagonal lattice, which is showed in Figure 2. Hexagonal lattice with a LP of 25cm can obtain the same level of CVR as the old square design, and the core is smaller.

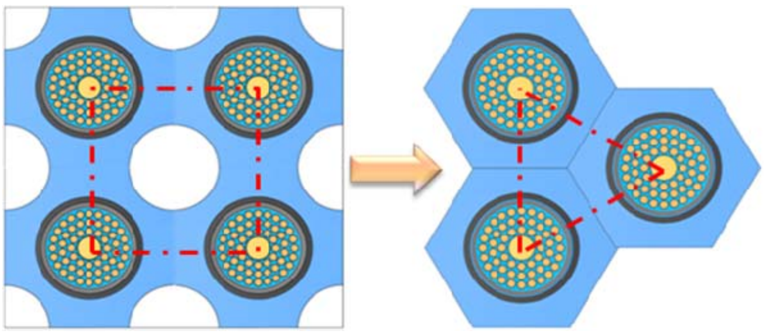


Figure 2 Square lattice to hexagonal lattice

The new design contains changes in channel type, assembly lattice, flow scheme, and axial fuel arrangement. Based on code WIMS9A and single channel code, we get the equilibrium core results of CANDU-SCWR.

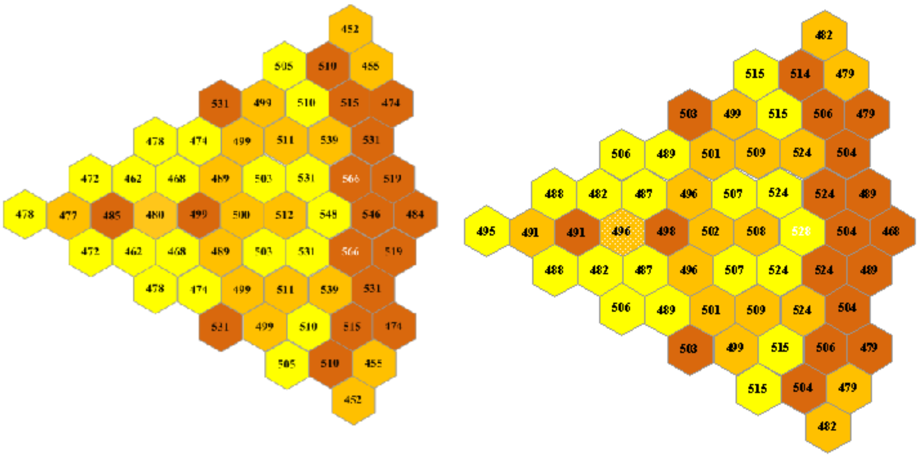


Figure 3 coolant outlet temperature（/℃）(left-BOC,right-EOC)

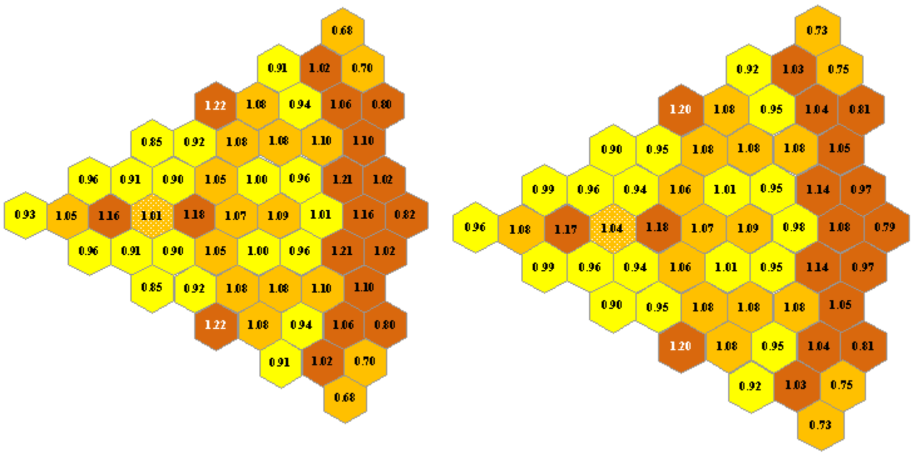


Figure 4 radial core power distribution (left-BOC, right-EOC)

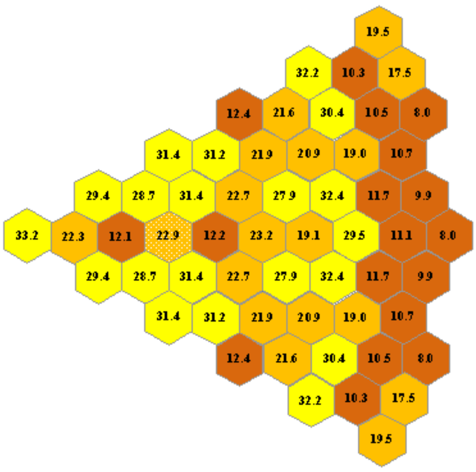


Figure 5 Core burnup distribution（/GWd/tU）

Table 1 Equilibrium Core Results

Parameter		Value
Thermal/electrical power (MW)		2280/1000
Thermal efficiency (%)		43.8
Operation pressure (MPa)		25
Active core height/equivalent diameter (m)		4.95 /4.55
Inlet/outlet temperature (℃)		280/500
Core flow rate (kg·s-1)		1190
Lattice pitch (cm)		25 (hexagonal)
Number of fuel channel		301
Fresh fuel enrichment (%)		4
Keff	BOC	1.129
EOC (350EFPD)		1.005
CVR (mk)	BOC	-1.9
	EOC	-2.8
Average discharge burnup (GWD·t/U)		30.8
Maximum discharge burnup (GWD·t/U)		33.2
Averaged linear generation heat rate (Kw/m)		28.3
Maximum linear generation heat rate (kW/m)		49.4
Maximum cladding surface temperature (℃)		715

From the results showed in the above figures, we can get the conclusion that CVR is -1.9mk at BOC and -2.8mk at EOC. It is always negative during whole cycle. The maximum linear heat generation rate is 49.4 kW/m and value of the maximum discharge burnup is 33.2GWd/tU, which are both below the design limit. The maximum cladding surface temperature is less than 750℃. Based on the above analysis, we can get the conclusion that this design is feasible and promising.

3. Thermal-hydraulics analysis

3.1 Subchannel code ATHAS development

A subchannel code (ATHAS) is developed for preliminary analyses of flow and enthalpy distributions and cladding temperatures at supercritical water conditions. The code is applicable for transient and steady state calculations. A number of heat-transfer correlations, frictional resistance correlations, and mixing models have been implemented into the code as options for sensitivity analyses. In addition, a 3D heat conduction model has been introduced to establish the cladding temperature.

After applied the ATHAS code to the analysis of CANDU CANFLEX bundle, the results show that (1) a CANFLEX bundle is appropriate for use in the CANDU supercritical water-cooled reactor (SCWR) based on heat transfer analysis, as show in Fig. 6; (2) the selection of heat transfer, friction, and mixing correlations has a significant impact on the prediction of the maximum cladding-surface temperature, as show in Fig. 7; and (3) the inclusion of the 3D heat conduction in the calculation has provided a more realistic prediction of the maximum cladding-surface temperature than assuming a uniform cladding temperature due to the heterogeneous characteristic of rods, as show in Fig. 8.

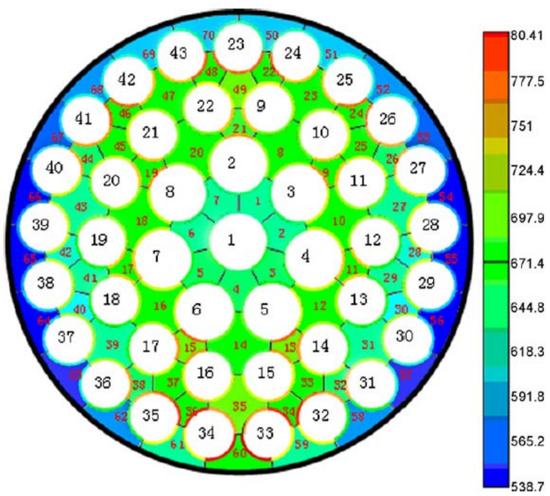


Fig. 6 Distributions of coolant and maximum cladding-surface temperatures at the outlet of the CANDU CANFLEX fuel string

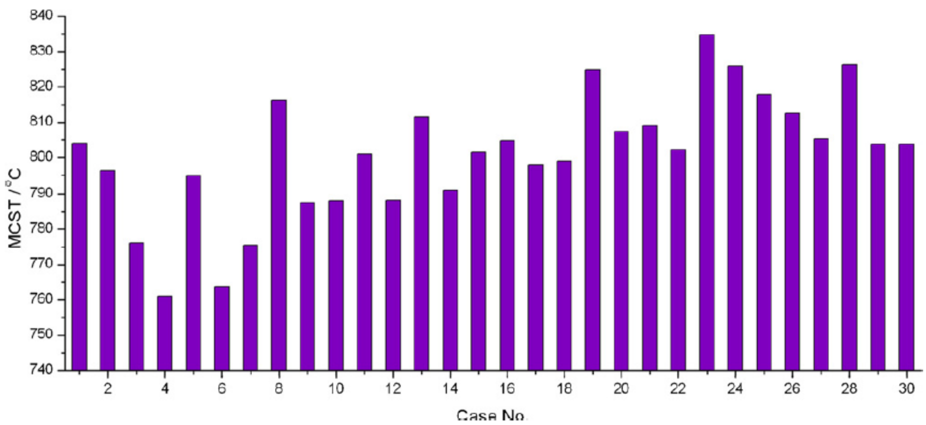


Fig. 7 Summary of maximum cladding-surface temperature predictions for all cases

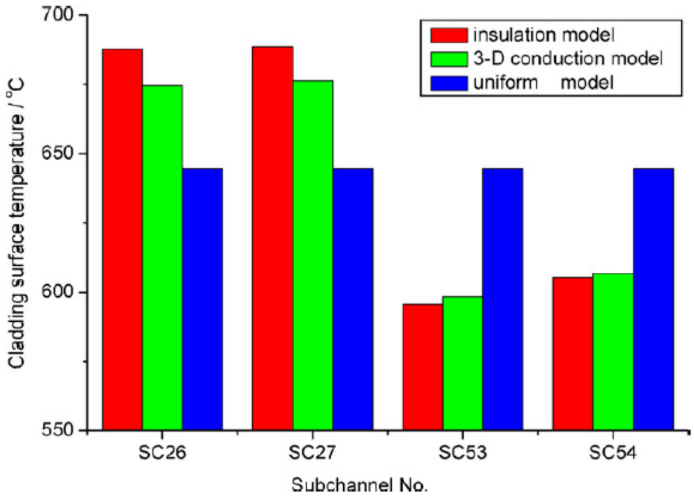


Fig. 8 Comparison of cladding-surface temperature using different fuel model

3.2 CADNU-SCWR Startup Procedure

The feasibility of the sliding pressure startup of CANDU-SCWR is assessed from both thermal and stability considerations. The coupled neutronic/thermal-hydraulics stabilities are investigated for both super- and sub-critical pressure operating conditions. The startup system and startup procedure are designed. The detailed thermal-hydraulics analysis is assessed based on the subchannel analysis and a stability map is constructed based on non-dimensional parameters and frequency domain method.

The startup procedures are developed to meet both thermal-hydraulic and stability considerations, as shown in Fig.9. The procedures can be divided as (1) start of nuclear heating at subcritical pressure; (2) turbine startup; (3) first stage pressurization; (4) first stage temperature raising; (5) second stage pressurization; (6) line switching; (7) second stage temperature raising; (8) power raising.

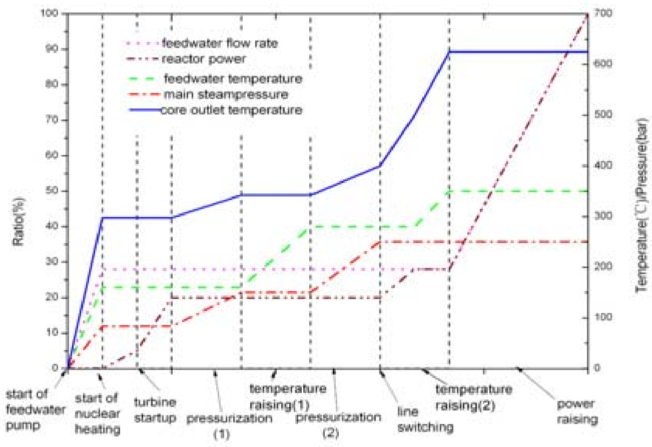


Figure 9 Sliding pressure startup curve

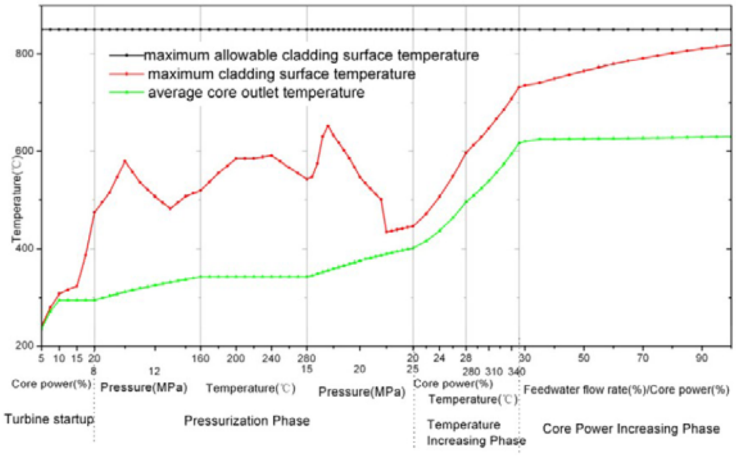


Figure 10 Thermal analysis during startup

Fig. 10 shows the thermal analysis during startup through ATHAS code. The maximum cladding temperature is well below the allowable cladding surface temperature (850°C). Fig. 11-13 show the stability maps at sub- and super-critical pressure. The figures show that the operating points are all in the stable region.

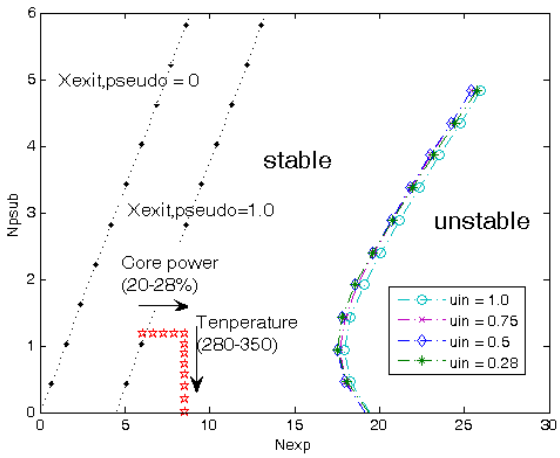


Figure 11 Stability map at 25MPa

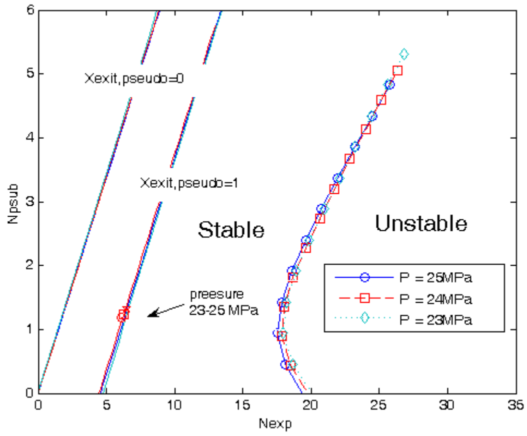


Figure 12 stability map at 23~25MPa

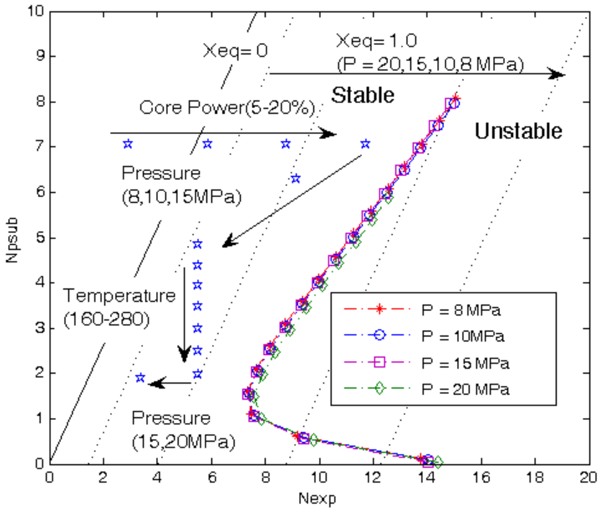


Figure 13 stability map at subcritical pressure region

3.3 Radiation heat transfer calculation

The key advantage of CANDU SCWR is the decay heat can be removed by radiation and convection from the distributed channels even with no active cooling and no fuel melting. Thus the system is potentially inherently safe.

To assess the radiation heat transfer capability of newly designed bundle, CATHENA code is selected. CATHENA GEOFAC code was applied to generate the View Factor Matrix of the model. The View Factor Matrix, as shown in the Figure 14, is generated in such a way that all the symmetric conditions can be met: the center pin and the pressure tube with insulator are divided circumferentially into 15 sectors , the fuel pins in first and second ring are divided into 6 sectors, the fuel pins in third ring are divided into 4 sectors.

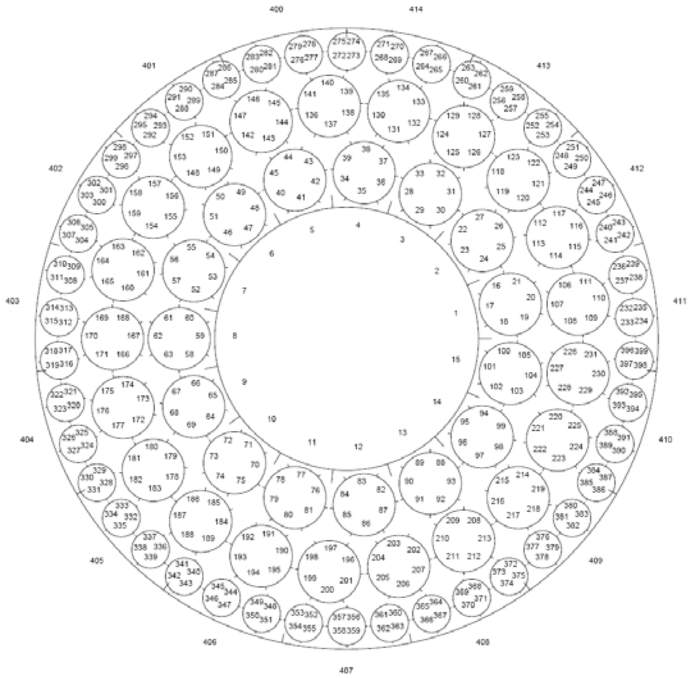


Figure 14 View Factor Matrix generated with GEOFAC

Based on the parameters given in related reference, a CATHENA model for the post-blowdown fuel channel analysis has been developed. With this model, three calculations have been carried out at different decay heat levels, which are 3%, 2% and 1% of rated power, respectively. Here, results of 3% rated power is listed.

The results are shown in the following figures, including the radial temperature distribution of the fuel pins in each ring and the pressure tube.

Fig. 15-17 show temperature distribution in each sector against diameter in different rings. And Fig.18 shows temperature distribution in pressure tube.

We can see that that peak cladding temperatures can meet the criterion in all cases.

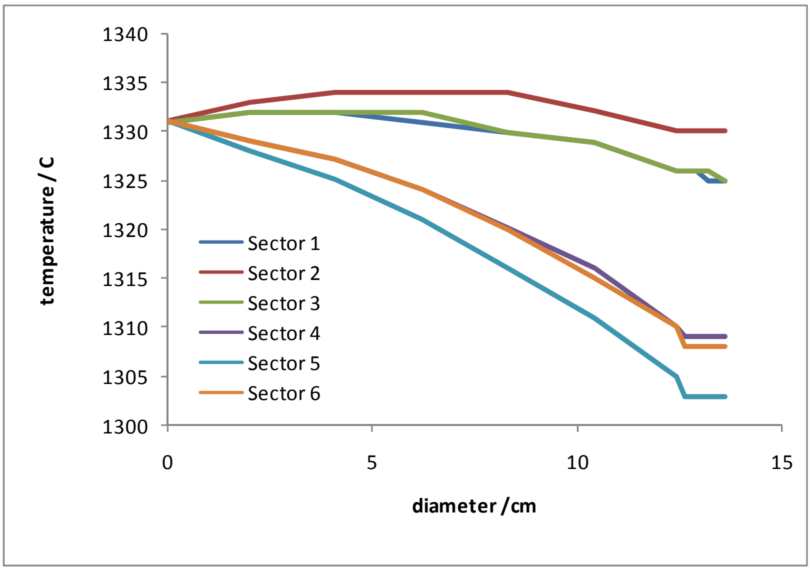


Figure 15 Temperature distribution of the pins in the 1st ring (3% FP)

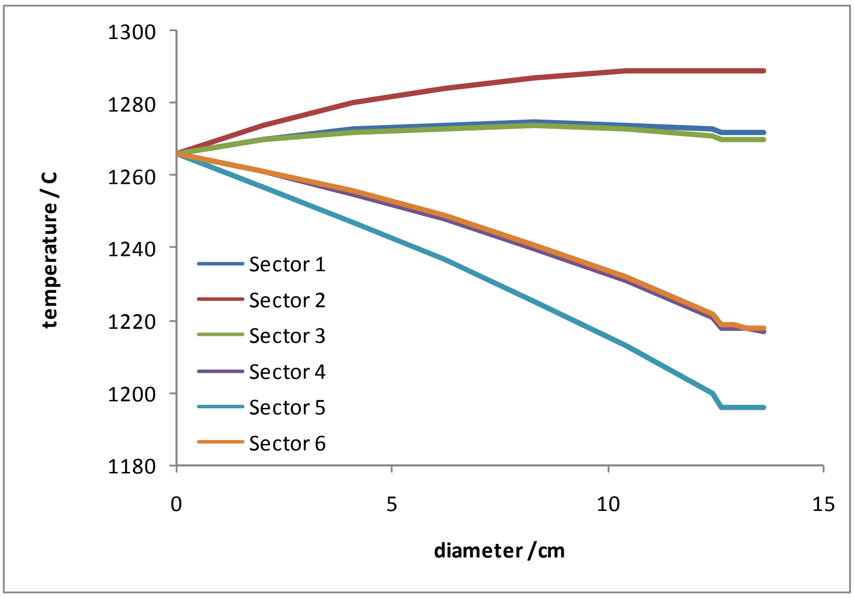


Figure 16 Temperature distribution of the pins in the 2nd ring (3% FP)

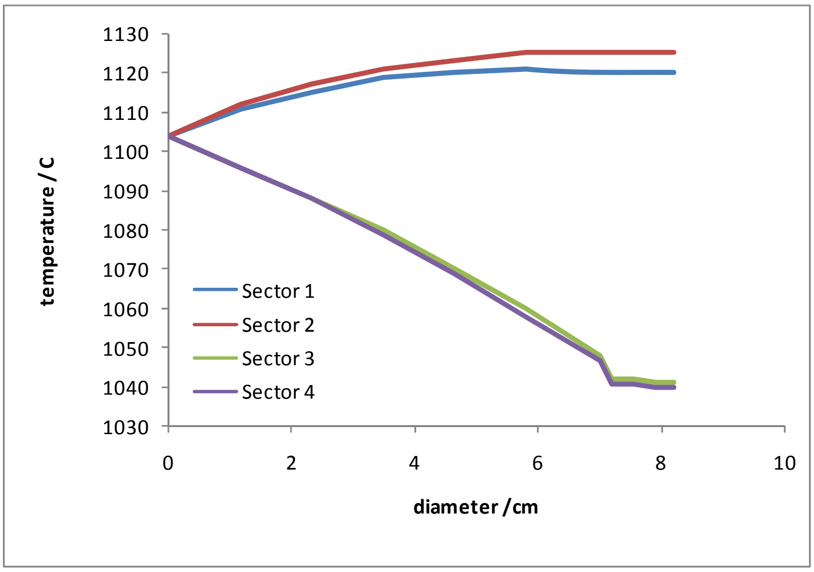


Figure 17 Temperature distribution of the pins in the 3rd ring (3% FP)

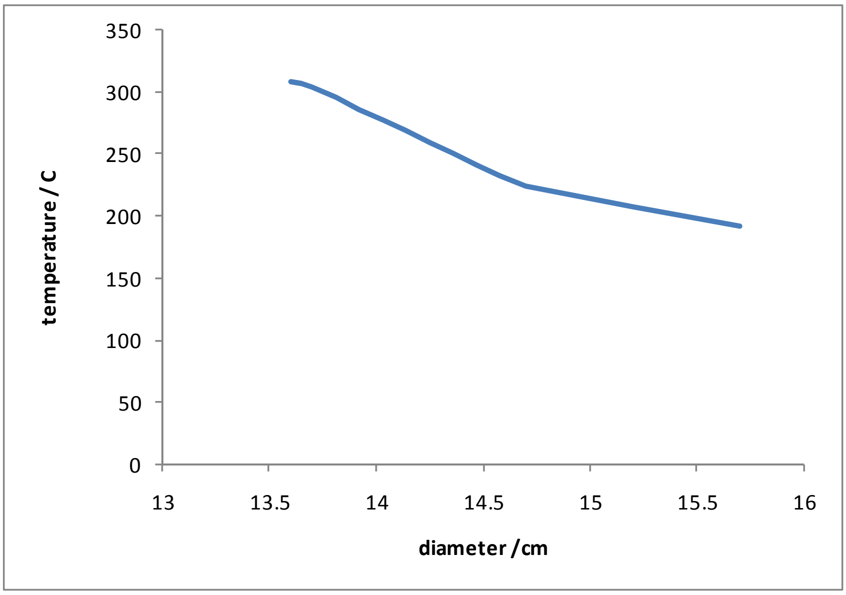


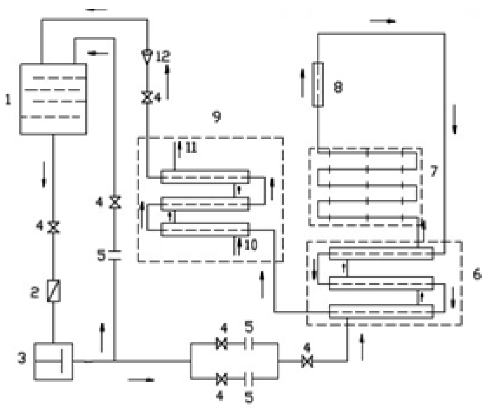
Figure 18 Temperature distributions of the pressure tube (3% FP)

4. Experimental work

A supercritical water heat transfer test section has been built at Xi'an Jiaotong University to study heat transfer in annular flow channel. Based on the experimental results, the effects of mass flux and heat flux on heat transfer of supercritical pressure water in vertical annular channel were analyzed. The characteristics and mechanisms of heat transfer enhancement, and that of heat transfer deterioration, were also discussed. Based on a comparison with two identical flow geometries with and without helical wrapped spacer, it was found that the spacer has a positive effect in enhancing the local heat transfer, especially in the pseudo-critical region.

4.1 Experimental facility

The experiments were carried out in the High Pressure Steam-water Test Loop in Xi'an Jiaotong University. The schematic diagram of the test loop is shown in Figure 19. Distilled and de-ionized feed water from the water tank is driven through a filter by a high pressure plunger-type pump which is cable of operating at up to 40MPa. The feed water is pre-heated in a heat exchanger and a main pre-heater before flowing into the test section. The pre-heater and the test section are electrically heated by alternating current power supply with maximum heating capacities of 1.0MW and 0.5 MW, respectively. Therefore, we can adjust the test section inlet bulk temperature and heat flux simply by controlling the alternating current power supply. The heat of feed water flowing from the test section was removed by a regenerative heat exchanger and a condenser, and then flowed back to the water tank. The pressure and the mass flux in test section are controlled by adjusting the main valve and bypass valve, respectively.



1: Water tank; 2: Filter; 3: Water pump; 4: Valve; 5: Orifice;
6: Heat exchanger; 7: Preheater; 8: Test section; 9: Condenser;
10: Cooling water inlet; 11: Cooling water outlet; 12: Rotor flow meter

Figure 19 Schematic diagram of the test loop

4.2 Experimental Result

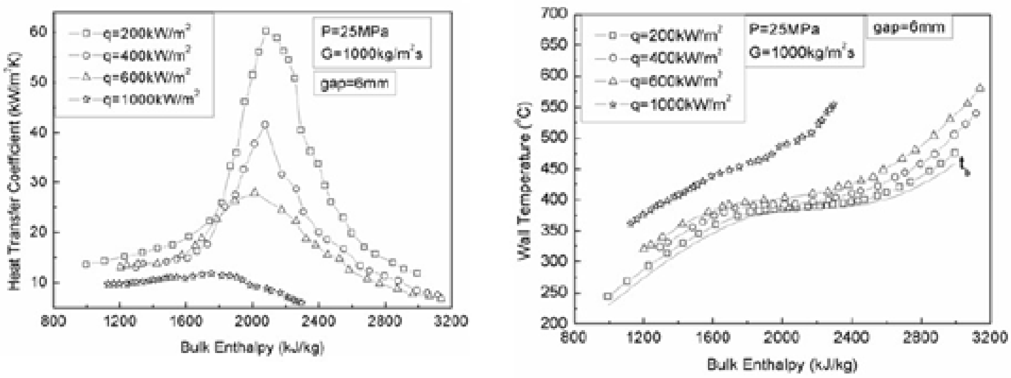


Figure 20 Comparison of wall temperatures and heat transfer coefficients at different heat fluxes

At relatively high mass flux conditions (1000kg/m2s), XJTU data exhibit an improvement in heat transfer near the pseudo-critical temperature region. In low enthalpy and high enthalpy regions which are far away from pseudo-critical point, heat transfer coefficient is independent of heat flux. An increase in heat flux impairs the heat transfer in the region near the pseudo-critical temperature, but no deterioration in heat transfer was seen even the heat flux reaches a relatively high value (1000 kW/m2).

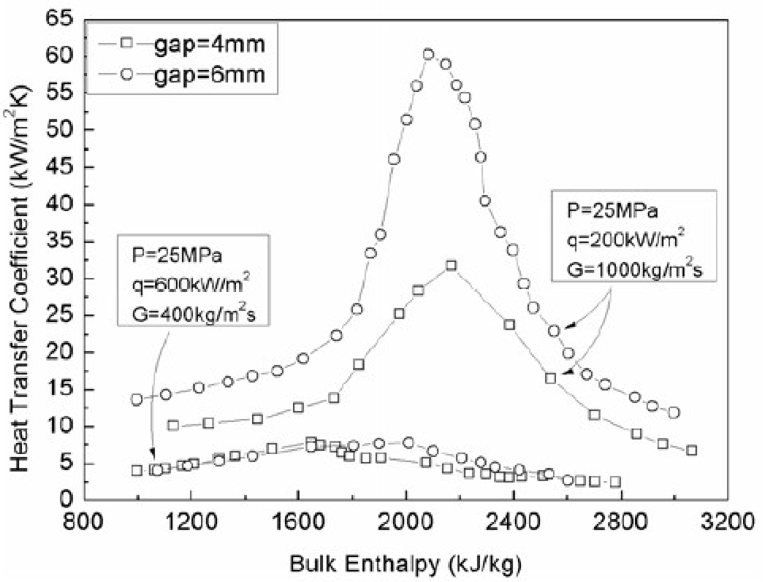


Figure 21 Influence of gap size on heat transfer coefficient

Figure 21 show that the effect of gap size on heat transfer characteristic depends strongly on the flow conditions. At similar operating conditions, normal heat transfer is very susceptible to the changes in gap size, whereas conditions of deterioration were found to differ with that.

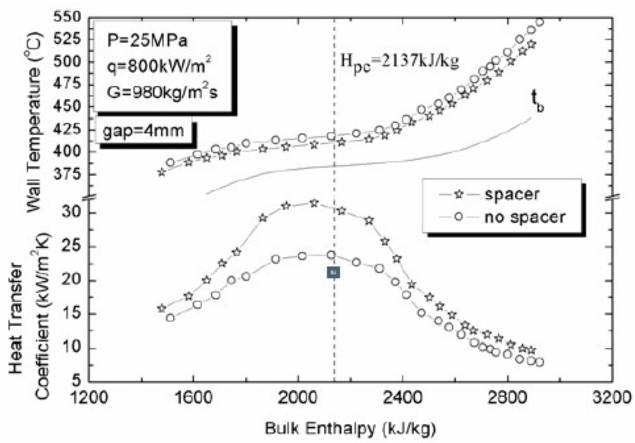


Figure 22 Comparison of wall temperature and heat transfer coefficients with and without spacer

From Fig. 22 we can get the conclusion that the spacer has a positive effect in enhancing the local heat transfer, especially in the pseudo-critical region.

5. Conclusion

The work for CANDU-SCWR studies in XJTU was summarized, which included thermal-hydraulics and safety analysis; neutronics/thermal-hydraulics coupling analysis and experimental work.