Modelling and Simulation of Dynamic Characteristics of CANDU-SCWR

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Abstract

Owing to the thermal properties of supercritical water and features of heat transfer correlation under supercritical pressure, a detailed thermal-hydraulic model with movable boundary of is developed for CANDU-SCWR (Supercritical Water-Cooled Reactor). Steady-state results of the model agree well with the design data. The dynamic responses of CANDU-SCWR to different disturbances are simulated and characteristics are analyzed. A dynamic model for ACR is also developed using CATHENA. Differences between dynamic characteristics of CANDU-SCWR and those of ACR are highlighted and investigated. It is concluded that CANDU-SCWR has a larger time constant, but with a higher response amplitude.

1. Introduction

CANDU-SCWR has been considered as a potential choice for the next generation CANDU reactor after ACR (Advanced CANDU Reactor). The preliminary specifications of CANDU-SCWR are summarized in Table 1. Significant amount of efforts have been made to develop CANDU-SCWR, for example, safety analysis [1], thermal hydraulic analysis [2], material studies [3] and fuel channel designs [4]. Unfortunately, little work has been done on the dynamic response analysis and control system design for such a reactor.

The dynamic characteristics of CANDU-SCWR are different from those of CANDU and ACR. The thermal properties of coolant are unique. The coolant flow rate of the CANDU-SCWR is about one-sixth of those of ACR and CANDU. Therefore, the reactor core is more sensitive to disturbances. Direct cycle of coolant system in CANDU-SCWR is adopted and the disturbances from turbine side have direct influence on the reactor. The coolant density at the reactor outlet is about one-seventh of that at the reactor inlet. The coolant density reactivity feedback has larger effect on the reactor kinetics. Thus, it is necessary to examine the dynamic characteristics of CANDU-SCWR in detail.

It is important to point out that around the pseudo-critical point of supercritical water, the thermal properties change significantly. When a control volume is around the pseudo-critical point, the abrupt change in thermal properties can result in large calculation errors. Thus, a movable boundary method is adopted for CANDU-SCWR dynamic modeling to reduce such errors. There are several advantages of using movable boundary method. Firstly, the time step can be increased. Secondly, it can deal with severer conditions, for example, faster or larger disturbances. In addition, the calculation oscillation and divergence can be potentially avoided.

Table 1 Preliminary Specifications of CANDU-SCWR [4]

Spectrum	Thermal
Moderator	Heavy Water
Coolant	Light Water
Thermal Power	2540 MW
Flow Rate	1320 kg/s
Number of Channels	300
Electric Power	1220 MW
Efficiency	48%
Fuel	UO_2/Th
Enrichment	4%
Inlet Temperature	350°C
Outlet Temperature	625°C
Cladding Temperature	<850°C
Calandria Diameter	4m

To model the dynamic characteristics of CANDU-SCWR, a movable boundary technique is developed in this paper. To investigate the differences of dynamic characteristics of CANDU-SCWR and ACR, one ACR dynamic model is also developed using CATHENA. The two systems are compared by introducing the same magnitude perturbation to input variables. The differences in their dynamic characteristics are highlighted.

The rest of the paper is organized as follows: in Section 2, the detailed thermal-hydraulic model of CANDU-SCWR is developed. In Section 3, the steady-state results are presented. Reactor transients as a result of different disturbances are investigated and dynamic behaviours of these transients are analyzed. In Section 4, one ACR dynamic model is developed using CATHENA and comparisons of dynamic characteristics of CANDU-SCWR with ACR are made. The conclusions are drawn in the last section of the paper.

2. Thermal-hydraulic Model of CANDU-SCWR

To investigate the dynamic characteristics of CANDU-SCWR, a CANDU-SCWR model is needed to generate the responses of the system to different disturbances. In the current work, only the thermal-hydraulic dynamics are considered. Reactor kinetics model, feedwater pump model and turbine governor control valve model will be included to complete the system model of CANDU-SCWR elsewhere.

The bundle geometry of a CANDU-SCWR has not been officially established yet. Previous studies showed that CANFLEX fuel bundle could be appropriate for CANDU-SCWR [5]. Therefore, such fuel bundles are assumed in the current study.

Heat transfer under the supercritical pressure has been investigated in [6]. In this study, Yamagata correlation is chosen because its experiment conditions are close to the working conditions of a CANDU-SCWR. The Yamagata correlation is described in the following equation [7]:

$$Nu_b = 0.0135 * Re_b^{0.85} * Pr_b^{0.8} * F_c \quad (1)$$

where, $F_c = 1.0$, for $E > 1$; $F_c = 0.67 * Pr_{pc}^{-0.05} * (\bar{c}_p / c_{pb})^{n_1}$, for $0 \le E \le 1$; $F_c = (\bar{c}_p / c_{pb})^{n_2}$, for $E < 0$; $n_1 = -0.77 * (1 + 1/Pr_{pc}) + 1.49$; $n_2 = 1.44 * (1 + 1/Pr_{pc}) - 0.5$; $E = (T_{pc} - T_b)/(T_w - T_b)$; $\bar{c}_p = (h_w - h_b)/(T_w - T_b)$.

The Yamagata correlation can be divided into three parts by parameter E. The two boundary points are $T_b = T_{pc}$, and $T_w = T_{pc}$.

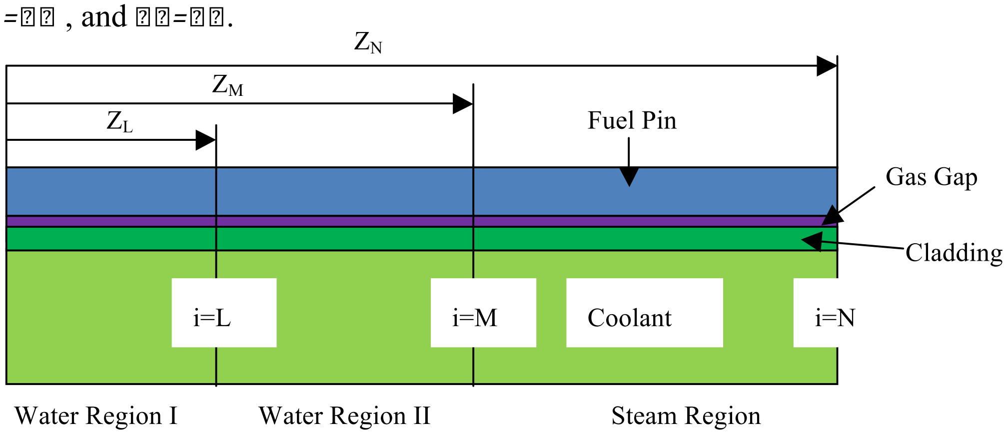


Fig 1 A simplified CANDU-SCWR thermal-hydraulic model

A simplified dynamic model of a CANDU-SCWR is shown in Fig 1. It includes a coolant model and a fuel rod model. The coolant model can further be divided into three regions: (1) Water Region I; (2) Water Region II; and (3) Steam Region. From the thermal properties of supercritical water, it is known that, before the pseudo-critical point, the coolant is water-like fluid and after this point it becomes steam-like fluid. For simplicity, before pseudo-critical point, it is called Water Region and after this point, it is referred to as Steam Region. Within the Water Region, it can further be divided into two sub-regions: Water Region I and Water Region II. In Water Region, the Yamagata correlation is divided into two parts by the point where the cladding temperature equals the pseudo-critical temperature.

2.1 Fuel Rod Model

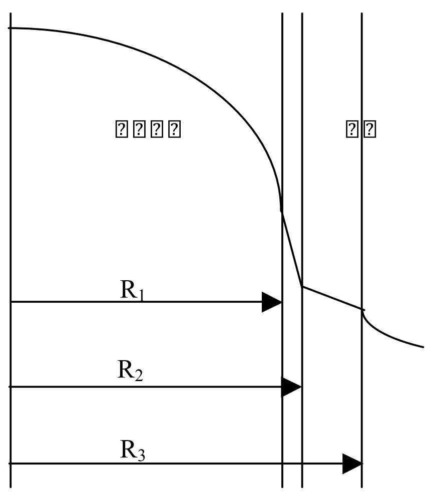


Fig 2 Fuel Rod Temperature Distribution

A lumped dynamic model developed at BNL (Brookhaven National Laboratory) to calculate the thermal conduction in a fuel rod is applied herein [8]. The temperature distribution in the fuel pin, gas gap and cladding can be illustrated in Fig 2. The temperature distribution in the fuel pin is assumed to be a second order power polynomial while in the gas gap and cladding they are assumed to be linear. The average temperature of the fuel pin can be described by:

□□□□□□□□=2(□3−□2)□3□□□□□□□□□,□1+(□□□+□□□)□□□,□□□−□□□□□□+□1□32□□′′′ □□□(□□□□□□)□ (2)

where,

□□□□: the average temperature of the fuel pin,

□□□,□=□□3−□2□□,

□□□=(□1□3)2+1−(□2□3)23□2+□3−(□3−□2)6(□2+□3),

□□□=□13(□3−□2)□32(□□4□□+□□□11ℎ□□□).

The cladding surface temperature, the average temperature of the fuel pin and the coolant bulk temperature can be related as:

□□−□□=□□□□−□□1+(□□□+□□□)□□□,□ (3)

2.2 Coolant Model

The conservations of fluid mass and energy at a position *Z* in the flow channel and at time *t* give the following set of partial differential equations:

∂□∂□=−∂□∂□ (4)

∂(□ℎ)∂□=−∂(□ℎ)∂□+□□+∂□∂□ (5)

In the CANDU-SCWR reactor core, the pressure drop is only a small fraction of the absolute pressure and the momentum equation is not considered.

By applying Leibnitz theorem □(□)□(□)∂□(□,□)∂□□□=□□□□(□)□(□)□□,□□□−□(□□,□)□□(□)□□+□(□□,□)□□(□)□□ to (4) and (5), the mass and energy conservation equations can be represented in (6) and (7)

□□□□−□□−1−□□−1□□−□□−1+□□−□□−1=0 (6)

□□ℎ□□□□□−□□−1−□□−1(□ℎ)□−(□ℎ)□−1+□□ℎ□−□□−1ℎ□−1=□□□□□−□□−1+□□□−□□−1 (7)

The density of the supercritical water can be considered as a function of the pressure and specific enthalpy. The derivative of this density function becomes

□=∂□∂□□+∂□∂ℎℎ (8)

Substituting (8) into (6) and (7) and the following relationships can be obtained:

ℎ□=□□−1□□−□□−1−(□□−□□−1)−∂□□∂□□(□□−□□−1)∂□□∂ℎ□(□□−□□−1) (9)

□□=−□□−1∂□□∂ℎ□□□−1ℎ□−ℎ□−1−□□□□−□□−1−□□□−□□−1∂□□∂ℎ□+∂□□∂□□□−∂□□∂ℎ□□□□(□□−□□−1)+□□−1∂□□∂ℎ□ℎ□−ℎ□−1+□□/□□ (10)

The specific enthalpy and coolant flow rate for each node can be solved from (9) and (10). But the term □□ still needs to be determined. It can be derived from the boundaries between the regions.

The boundary between Water Region I and Water Region II is the point where the cladding surface temperature equals to the pseudo-critical temperature. The *Lth* node, the following equation can be obtained by taking derivative of Equation (3),

□□=□□□1+(□□□+□□□)□□□,□−□□□□□(□□□+□□□)□□□,□ (11)

The temperature of the supercritical water can be considered as a function of the pressure and specific enthalpy. The derivative of the temperature is

□=∂□∂□□+∂□∂hh (12)

Using (9), (11) and (12), the following equation can be obtained:

□□−1=□□□1+□□□+□□□□□□,□−□□□□□□□□+□□□□□□,□−∂□□∂□□∂h□∂□□∂□□∂h□□□−
□□−1+□□−□□−1−∂□□∂□□(□□−□□−1)□□−□□−1 (13)

The boundary position between Water Region I and Water Region II can be calculated by (13).

The boundary between Water Region II and Steam Region is the pseudo-critical point of supercritical water. At the pseudo-critical points, the relationship between the pressure and the temperature can be described by the following equation at the supercritical pressure:

□□=294.13+3.63∗□ (14)

At the pseudo-critical points, the density at pressures from 23 to 27MPa is only slightly different. Thus it can be considered as constant. Consequently,

□□=0 (15)

Substituting (15) into Equation (10), the boundary position between Water Region II and Steam Region can be obtained from the following equation

□□−1=ℎ□□□(□□−□□−1)+□□ℎ□−□□−1ℎ□−1−□(□□−□□−1)−□□□(□□−□□−1)(□□ℎ□

−□□−1ℎ□−1) (16)

The total length of channel does not change with time, and then the following equation can be obtained

□=−□□−□(□−□)□−□ (17)

The boundary positions of the coolant model can be described as

□□=□□, 1≤□≤□ □□+□−□□, □<□≤□□□+□−□□+□−□□,

□<□≤□ (18)

The dynamic behaviours of coolant can be described by (9), (10) and (18).

3. Simulation Results and Dynamic Analysis

A computer program is developed to solve the differential equations for CANDU-SCWR thermal-hydraulic model: Equations (2), (9), (10) and (18). The structure of CANDU-SCWR thermal-hydraulic is shown in Fig 3. Feedwater flow rate, reactor power and outlet pressure are the input variables. Boundaries between regions, outlet temperature and outlet flow rate are the output variables.

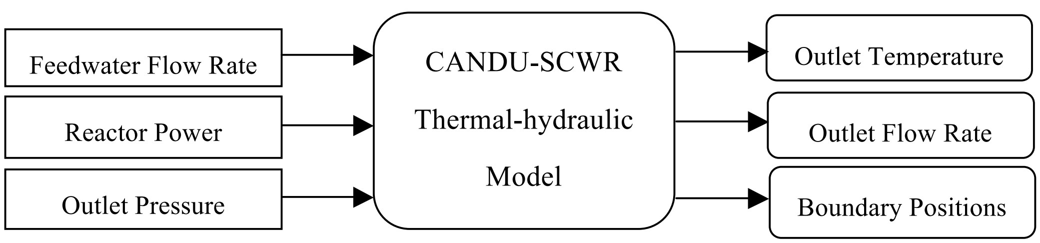


Fig 3 Structure of CANDU-SCWR thermal-hydraulic model

3.1 Steady-State Results

The steady-state simulation results are shown in Fig 4.

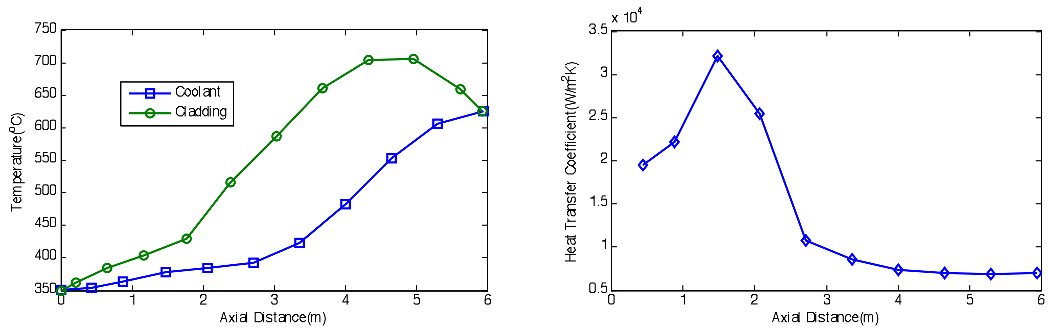


Fig 4 Temperature distribution and heat transfer coefficient along the fuel channel

The outlet temperature is 625.0^{o}C, which agrees well with the design specification. The pseudo-critical temperature at 25MPa is 384.8^{o}C.The maximal cladding temperature is 705.2^{o}C below the limit temperature. In the water region II, heat transfer coefficients are higher than those of other regions. The boundary positions between the regions are 0.876m and 2.067m.

3.2 Transient Results

To investigate the dynamic behaviours of CANDU-SCWR subject to different disturbances, 2% step perturbations have been introduced at the inputs. One input variable is perturbed at a time, while others are kept unchanged.

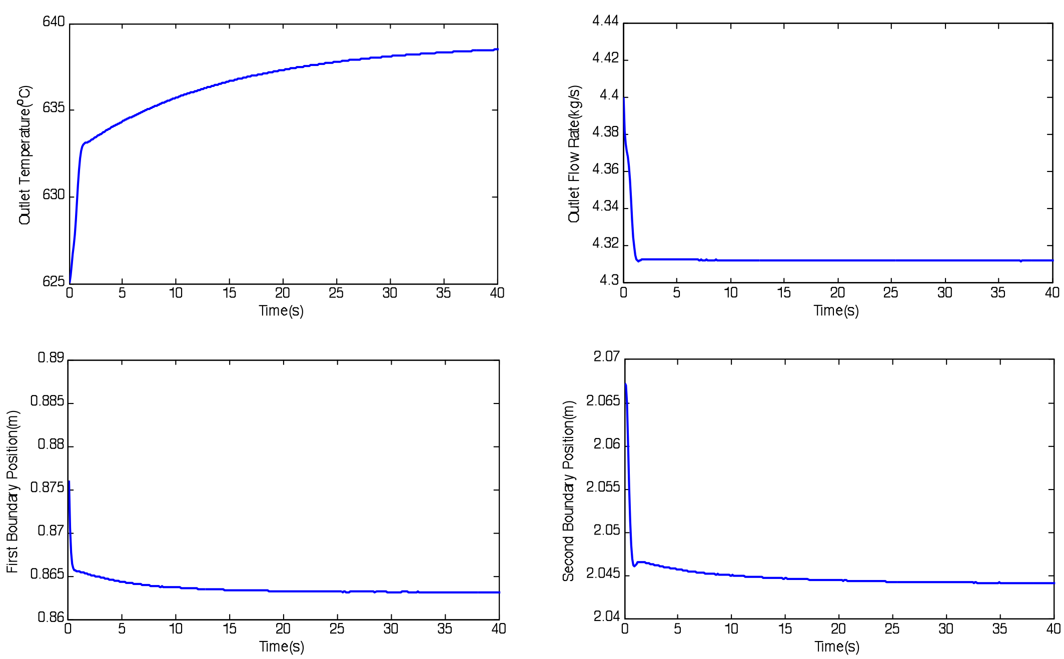


Fig 5 Responses to feedwater flow rate disturbance

The responses to step change from 4.4kg/s to 4.312kg/s in the feedwater flow rate are illustrated in Fig 5. The outlet temperature increases as the feedwater flow rate decreases and stabilizes around 638.0^{o}C. The outlet temperature is increased by about 13.0^{o}C. The response time of the outlet temperature is 1.8s. The outlet flow rate follows the change of the feedwater flow rate promptly. The position of pseudo-critical point has changed 0.023m.

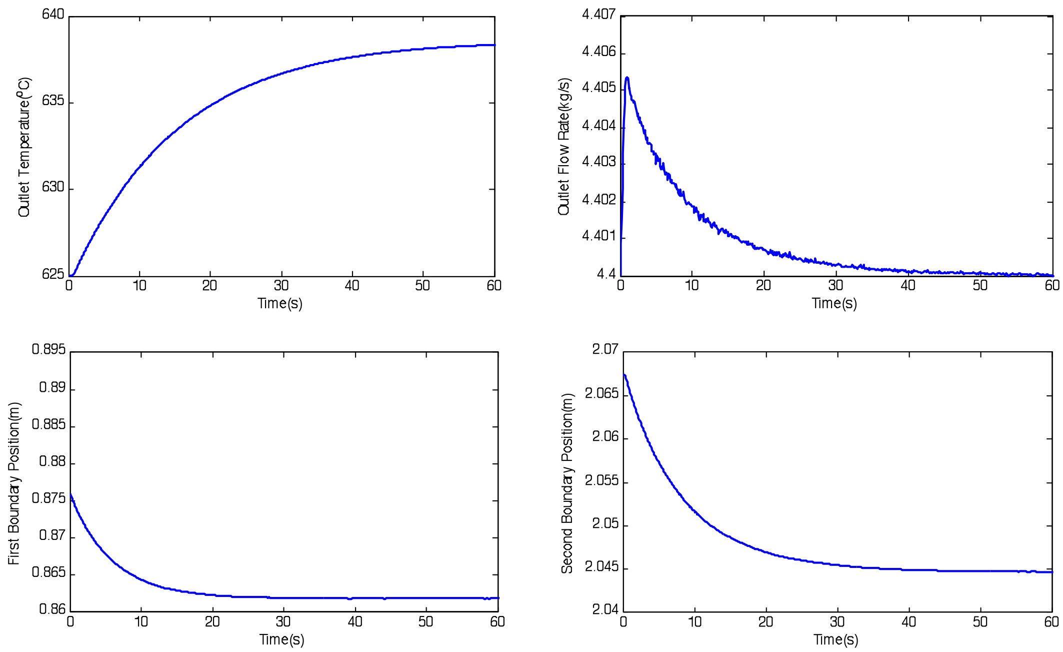
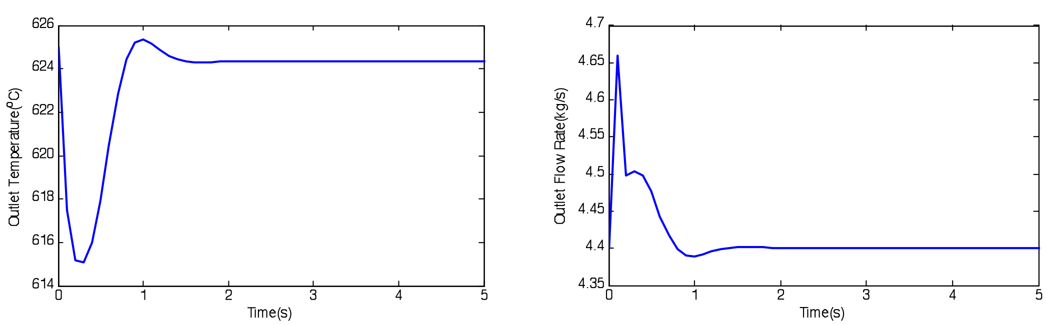


Fig 6 Responses to reactor power disturbance

The responses to step change in the reactor power from 100%FP (Full Power) to 102%FP are shown in Fig 6. The outlet temperature increases as reactor power increases and stabilizes around 638.0^{o}C. The outlet temperature is increased by about 13.0^{o}C. The response time of the outlet temperature is 14.6s. Coolant density decreases for the increase of temperature and the outlet flow rate increases quickly. It is observed that outlet flow rate slowly decreases and stabilizes at 4.4kg/s. The position of pseudo-critical point has changed 0.022m.



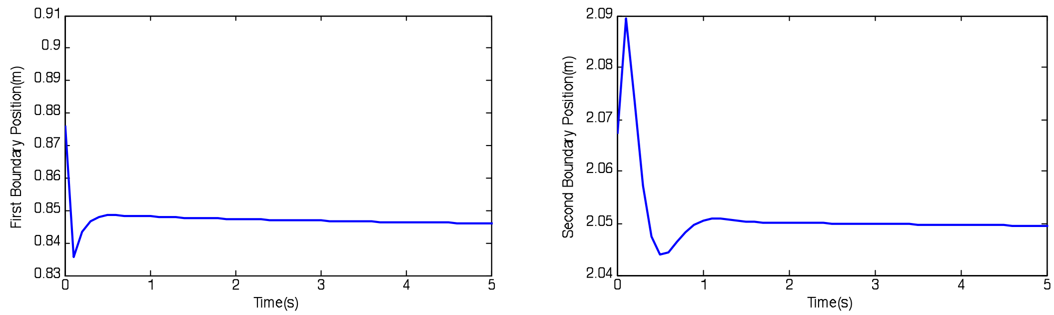


Fig 7 Responses to outlet pressure disturbance

The responses to outlet pressure step change from 25MPa to 24.5MPa are shown in Fig 7. The outlet flow rate increases quickly as the pressure decreases. As a result, the outlet temperature decreases and at 0.3s the outlet temperature reaches the lowest value 615.0°C. The outlet flow rate increases and returns to 4.4kg/s to keep the balance with feedwater flow rate. The outlet temperature increases and stabilizes at 624.2°C. The pseudo-critical temperature at 24.5MPa is 383.03°C. The position of pseudo-critical point has changed 0.020m.

4 Comparisons with ACR

The thermal-hydraulic model of ACR-700 is developed using CATHENA. If the feedwater temperature is 280°C as designed, the void fraction at the outlet will be around 2.0% and it is also two phases fluid. The coolant in CANDU-SCWR is single phase fluid. For the convenience of comparison, the feedwater temperature of ACR-700 is decreased by 10°C to ensure that the coolant at the outlet is also single phase. 2% step perturbations are introduced to the input variables.

The responses to feedwater flow rate step change from 26kg/s to 25.48kg/s are shown in Fig 8. The response time of the outlet temperature is 0.7s. The outlet temperature is increased by about 0.9°C.

The responses to reactor power step change from 100%FP to 102%FP are shown in Fig 9. The response time of the outlet temperature is 5.8s. The outlet temperature is increased by about 0.8°C.

The responses to the outlet pressure step change from 12MPa to 11.76kMPa are shown in Fig 10. At 0.3s the outlet temperature reaches the lowest value. However, the outlet temperature is decreased by less than 0.1°C.

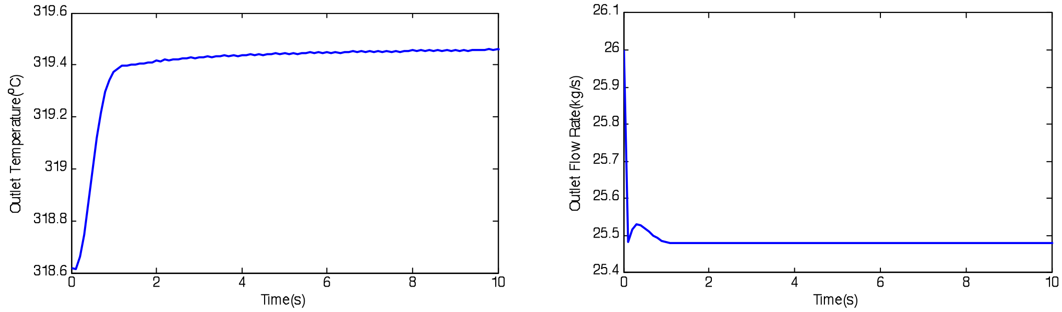


Fig 8 Responses to feedwater flow rate disturbance

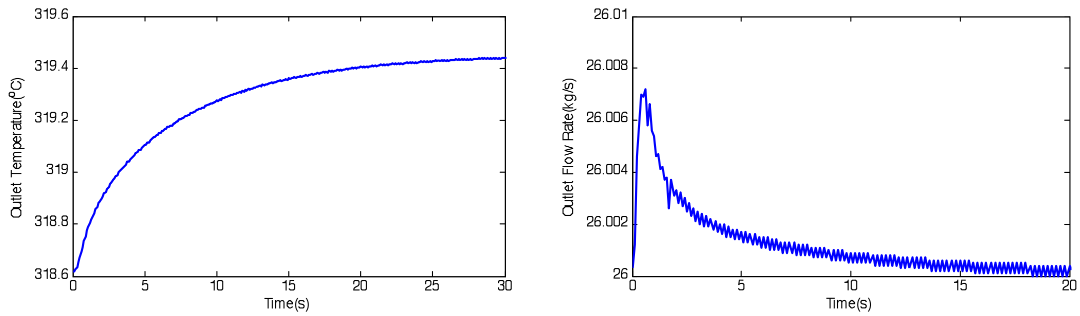


Fig 9 Responses to reactor power disturbance

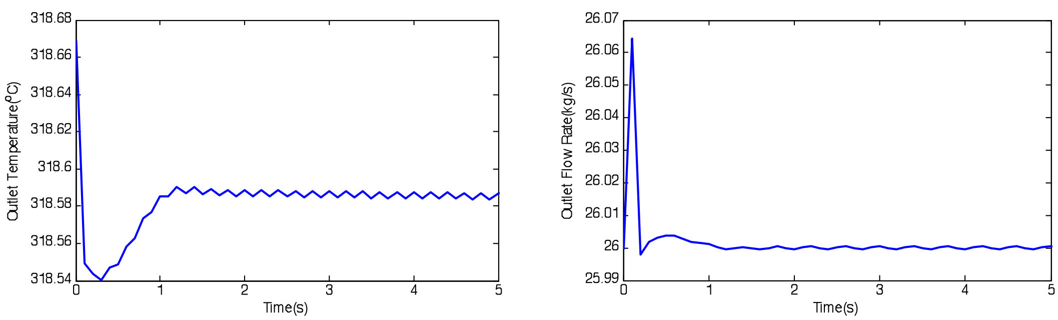


Fig 10 Responses to outlet pressure disturbance

The main differences on outlet temperature dynamics of CANDU-SCWR and ACR are summarized in Table 2. It can be concluded that CANDU-SCWR responses slower than ACR, but the amplitude is much larger for the same magnitude disturbances.

Table 2 Comparisons on dynamics of CANDU-SCWR and ACR

Disturbances	CANDU-SCWR		ACR	
	Response Time	Response Amplitude	Response Time	Response Amplitude
-2% Step Change of	1.8s	13.0°C	0.7s	0.9°C

Feedwater Flow Rate				
+2% Step Change of Reactor Power	14.6s	13.0°C	5.8s	0.8°C
-2% Step Change of Outlet Pressure	0.3s*	-0.8°C	0.3s*	-0.1°C

Note: * it is the time to reach the lowest temperature.

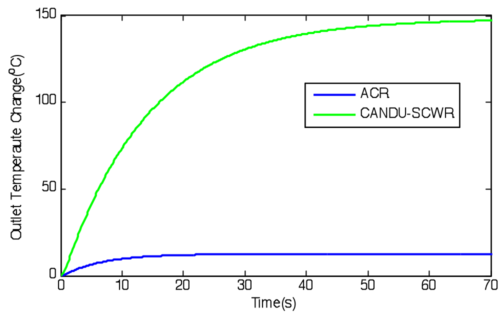


Fig 11 Step responses of transfer functions

To illustrate the differences clearly, a system identification technique is adopted to derive transfer function from the simulation data. Take the feedwater flow rate step change as an example. The feedwater flow rate is the input and outlet temperature is the output. Introducing the disturbances to feedwater flow rate, the responses of outlet temperature are recorded. Least square based system identification technique is adopted to derive the mathematical relationship from the recorded data set using system identification toolbox of MATLAB. The transfer function from feedwater flow rate to outlet temperature of CANDU-SCWR is $148.1601+13.863s(1+0.454s)$, and that of ACR is $12.5381+6.443s(1+0.382s)$. The step responses of these two transfer functions are shown in Fig 11. From this figure, the differences are clear.

5 Conclusions

A detailed CANDU-SCWR dynamic model with movable boundaries is developed. The numerical simulations of the model show that the steady-state results agree well with the design specifications and dynamic behaviours of CANDU-SCWR can be predicted using transient responses. To demonstrate the differences of dynamic characteristics of CANDU-SCWR and ACR, one ACR model is developed using CATHENA. CANDU-SCWR has larger time constant than that of ACR with higher amplitude.

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NOMENCLATURE

A area (m^2)

c_p specific heat (J/(kg K))

D mass velocity (kg/(s m^2))

h specific enthalpy (J/kg)

H heat transfer coefficient (W/(m^2 K))

k thermal conductivity (W/(m K))

P pressure (MPa)

Q heat flux per length (W/m)

q''' heat generation rate per unit volume(W/m^3)

t time(s)

T temperature (^{o}C)

Z length (m)

Greek letters

□, □, □ node length (m)

□ density (kg/m^3)

Subscripts

b bulk fluid

c cladding

m pseudo-critical conditions

i node number