Research Article

Preliminary Development of Thermal Power Calculation Code H-Power for a Supercritical Water Reactor

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SCWR (Supercritical Water Reactor) is one of the promising Generation IV nuclear systems, which has higher thermal power efficiency than current pressurized water reactor. It is necessary to perform the thermal equilibrium and thermal power calculation for the conceptual design and further monitoring and calibration of the SCWR. One visual software named H-Power was developed to calculate thermal power and its uncertainty of SCWR, in which the advanced IAPWS-IF97 industrial formulation was used to calculate the thermodynamic properties of water and steam. The ISO-5167-4: 2003 standard was incorporated in the code as the basis of orifice plate to compute the flow rate. New heat balance model and uncertainty estimate have also been included in the code. In order to validate H-Power, an assessment was carried out by using data published by US and Qinshan Phase II. The results showed that H-Power was able to estimate the thermal power of SCWR.

1. Introduction

SCWR (Supercritical Water Reactor) is one of the promising Generation IV nuclear systems, which has higher thermal power efficiency than current pressurized water reactor. Compared to the currently running water coolant reactors, SCWR has the higher thermal efficiency and safety, which makes it a more promising advanced nuclear energy system. The concept of SCWR was originally put forward by Westinghouse and GE (General Electric) in the 1950s and preliminarily studied by the United States and the former Soviet Union from 1950s to 1960s. In the 1990s, Dobashi et al. [1] proposed the concept of SCWR again and made a further development in this area.

For reactor operating more safely, stably, and economically, the accurate calibration for real thermal power has important significance in reactor design and analysis. It is necessary to develop a special thermal power calculation code for SCWR, while there is no available program published in the world. This paper preliminarily developed visual software named H-Power to calculate SCWR thermal power and its uncertainty based on heat balance method, which has been applied to current PWRs [2].

According to the various conceptual SCWR designs [3–5], H-Power divided SCWR into two groups: one is the single-loop type and the other is the double-loop type. The validation of H-Power consists of two parts: for the single-loop SCWR, the data published by Jacopo [6] was used, while for the double-loop SCWR, the values of Qinshan Phase II [7] were used; though it is not the SCWR, we just use it for preliminary validation since the exact detail design data was rarely published.

IAPWS is an international nonprofit association concerned with the properties of water and steam, particularly thermodynamic properties. In 1997, IAPWS adopted the “IAPWS Industrial Formulation 1997 for the Thermodynamic Properties of Water and Steam” for industrial use [8], called IAPWS-IF97 for short, which replaced the previous industrial formulation IFC-67 [9] published in 1967.

We have done lots of researches and work in comparing IAPWS-IF97 with IFC-67 in several aspects. The result showed that IAPWS-IF97 improves significantly in boundary consistency and accuracy and calculation speed [10], which makes it more extensive use in power industry nowadays.

H-Power adopted IAPWS-IF97 to calculate thermodynamic properties (including specific volume, specific

FIGURE 1: H-Power modules diagram.

enthalpy, and viscosity) of water. The code covers all range of IAPWS-IF97 ($273.15 \text{ K} \leq T \leq 1073.15 \text{ K}$, $p \leq 100 \text{ MPa}$, $1073.15 \text{ K} \leq T \leq 2273.15 \text{ K}$, $p \leq 50 \text{ MPa}$), which has been divided into five regions.

2. Theoretical Modeling

The modules of H-Power are given in Figure 1, where READDT is the reading data subroutine, NUSOLV is numerical calculation subroutine, THPROP is the subroutine which calculates the thermodynamic properties of water and steam, FLOWRT is the subroutine for flow rate calculation, ERCALC subroutine is for the uncertainty estimation, and OUTPUT is the output data subroutine.

H-Power provides a visual interface for users and has high module independence, which makes it a practical code in SCWR analysis.

2.1. Thermodynamic Properties Subroutine

2.1.1. Subroutine Flow Chart. The range of IAPWS-IF97 is divided into five subareas; each of them has a basic equation. To make the program more concise and readable, this subroutine used the compiling method of modularization; that is, separate districts of thermodynamics equation were written into separate subroutine.

We can directly obtain the thermophysical properties from pressure and temperature values using the basic equations except region 3. Subregion 3 does not have the formula which can calculate other various thermal parameters directly through the temperature and pressure; it can only rely on iteration calculation. In this subroutine, the first pressure calculation uses temperature and a small specific volume

which was chosen as initial value. If the difference between the calculated value of pressure and user input values is positive, the value of specific volume increases incremental quantity ratio by half and continues the iteration until the pressure difference is less than condition of convergence. The iteration is over and other properties can be calculated.

Through this kind of iteration and close proximity to the input value by increasing incremental quantity in halving bisection method, not only the disadvantages of the increased specific volume increment are too small to calculate quickly was avoided, but also the accuracy of calculation can be ensured.

The subroutine of water and steam thermodynamic properties has been totally developed according to the flow chart shown in Figure 2.

2.1.2. Subroutine Calculation Verification. In order to do the verification, we list the calculation results together with those given by IAPWS-IF97 in Table 1. We can see that the present results are in good agreement with those given by IAPWS-IF97, so that the thermodynamic properties calculated by H-Power are valid.

2.2. Flow Rate Calculation Subroutine. The main feedwater flow rate of the steam generator can be measured by orifice plate, which is widely used in measurement of fluid flow. This part is based on the ISO 5167 standard in [11].

As the schematic diagram shown in Figure 3, upstream fluid pressure P_1 is obtained by (1) taking pressure loss $\Delta\omega$ caused by the existence of orifice plate into account:

$$P_1 = P_{me} + P_a + \Delta\omega, \quad (1)$$

$$\Delta\omega = \Delta P \times (1 - \beta^{1.9}). \quad (2)$$

H-Power adopted the following equation for flow rate measurement:

$$q_m = \frac{C}{\sqrt{1 - \beta^4}} \varepsilon \cdot \frac{\pi d^2}{4} \sqrt{2\Delta P \rho_u}, \quad (3)$$

where q_m is mass flow rate, β is ratio of d (diameter of orifice at operating conditions) and D (diameter of internal pipe at operating conditions), ε is expansibility factor (for compressible fluid, $\varepsilon = 1$), ΔP is differential pressure, ρ_u is the density of upstream, and C is discharge coefficient determined by Reader-Harris/Gallagher equation as follows:

$$\begin{aligned} C = & 0.5961 + 0.0261\beta^2 - 0.216\beta^8 + 0.000521 \left(\frac{10^6 \beta}{\text{Re}_D} \right)^{0.7} \\ & + (0.0188 + 0.0063A) \beta^{3.5} \left(\frac{10^6}{\text{Re}_D} \right)^{0.3} \\ & + (0.043 + 0.080e^{-10L_1} - 0.123e^{-7L_1}) (1 - 0.11A) \frac{\beta^4}{1 - \beta^4} \\ & - 0.031 (M'_2 - 0.8M'_2)^{1.1} \beta^{1.3} + \dots \end{aligned} \quad (4)$$

TABLE 1: Comparison of calculation results between H-Power routine and IAPWS-IF97.

Region	Parameters	Given by	$v/(\text{m}^3 \text{kg}^{-1})$	$h/(\text{kJ kg}^{-1})$	$s/(\text{kJ kg}^{-1} \text{K}^{-1})$	$u/(\text{kJ kg}^{-1})$
Subregion 1	$T = 300 \text{ K}$	IF97	0.00100215168	115.331273	0.392294792	112.324818
	$P = 3 \text{ MPa}$	H-Power	0.0010021516	115.33127302	0.3922947924	112.32481798
	$T = 300 \text{ K}$	IF97	$9.71180894e - 4$	184.142828	0.368563852	106.448356
	$P = 80 \text{ MPa}$	H-Power	$9.7118089e - 4$	184.14282773	0.3685638523	106.44835621
Subregion 2	$T = 300 \text{ K}$	IF97	39.4913866	2549.91145	8.52238967	2411.69160
	$P = 0.0035 \text{ MPa}$	H-Power	39.491386637	2549.9114508	8.5223896673	2411.6915976
	$T = 2000 \text{ K}$	IF97	0.0311385219	6571.22604	8.53640523	5637.07038
	$P = 30 \text{ MPa}$	H-Power	0.0311385218	6571.2260386	8.5364052311	5637.0703825
Subregion 3	$T = 663.15 \text{ K}$	IF97	0.005613	2500.75	5.0320	2366.0
	$P = 24 \text{ MPa}$	H-Power	0.0056134399	2500.7519610	5.0320333072	2366.0291590
	$T = 723.15 \text{ K}$	IF97	0.002487	2284.44	4.5892	2160.1
	$P = 50 \text{ MPa}$	H-Power	0.0024874366	2284.4399286	4.58922040321	2160.0680674
Subregion 5	$T = 1500 \text{ K}$	IF97	1.3845509	5219.76855	9.65408875	4527.49310
	$P = 0.5 \text{ MPa}$	H-Power	1.3845508987	5219.7685512	9.6540887533	4527.4931018
	$T = 2000 \text{ K}$	IF97	0.0311385219	6571.22604	8.53640523	5637.07038
	$P = 30 \text{ MPa}$	H-Power	0.0311385218	6571.2260386	8.5364052311	5637.0703825

FIGURE 2: Flow chart of thermodynamic properties subroutine based on IAPWS-IF97.

If $D < 71.12$ mm, (4) should add the following term:

$$0.011 (0.75 - \beta) \left(2.8 - \frac{D}{25.4} \right). \quad (5)$$

As we can see from the above equation, discharge coefficient C depends on the Reynolds number Re_D , which is dependent on q_m in turn, so the calculation of mass flow rate q_m has to be iterated.

Diameters in the formula for calculating should be corrected due to the difference of temperature between working condition and measurement. If there is drain hole (diameter

is d_k) on the plate, the d should be corrected by the following equation:

$$d = d_m \left\{ 1 + 0.55 \left(\frac{d_k}{d_m} \right)^2 \right\}, \quad (6)$$

where the d_m have already been corrected by temperature as follows:

$$d_m = d_0 + d_0 \lambda (t - t_0), \quad (7)$$

where d_0 is the measurement value under the standard temperature t_0 , λ is the coefficient of linear expansion, and t is the operating temperature.

FIGURE 3: Pressure measuring schematic by orifice plate.

Re_D is the Reynolds number calculated by D (diameter of internal pipe at operating conditions), dimensionless parameters presenting the ratio of the inertia force and viscous force of upstream, calculated by the following equation:

$$Re_D = \frac{4q_m}{\mu\pi D}, \quad (8)$$

where μ is viscosity of the fluid at the working conditions, which is obtained by the thermodynamic properties subroutine.

$L_1 (= l_1/D)$ is the ratio of the distance from the upstream tapping to the upstream face of the orifice plate and the pipe diameter, and the value selection of its conditions is as follows:

$$L_1 = \begin{cases} 0 & \text{corner tappings,} \\ 1 & D \text{ and } \frac{D}{2} \text{ tappings,} \\ \frac{25.4}{D} & \text{flange tappings,} \end{cases} \quad (9)$$

$$A = \left(\frac{19000\beta}{Re_D} \right)^{0.8},$$

$$M'_2 = \frac{2L'_2}{1 - \beta}.$$

$L'_2 (= l'_2/D)$ is the ratio of the distance from the downstream tapping to the downstream face of the orifice plate and the pipe diameter, and the value selection of its conditions is as follows:

$$L'_2 = \begin{cases} 0 & \text{corner tappings,} \\ 0.47 & D \text{ and } \frac{D}{2} \text{ tappings,} \\ \frac{25.4}{D} & \text{flange tappings.} \end{cases} \quad (10)$$

The uncertainty of the feedwater flow measured and calculated by orifice plate and relevant equations will be given in Section 3.2. The computer verification of this subroutine will be integrated in Section 4.2.

2.3. Single-Loop SCWR Program. In single-loop type SCWR, the coolant is supercritical water which will be operated above

FIGURE 4: Sketch of SCWR with one loop.

the critical point of water ($T_c = 647.096 \text{ K}$, $p_c = 22.064 \text{ MPa}$). The coolant remains single-phase when operated above the critical point, which is a stupendous advantage for it will eliminate coolant boiling throughout the system. The no need for recirculation results in the elimination of pressurizer, jet pumps, steam generators, and steam separators. This direct cycle type is greatly simplified as shown in Figure 4.

The thermal power in this type can be calculated with thermal balance using measured values, including inlet and outlet temperatures, working pressure, flow rate of coolant, and the practical speed of pump. The thermal power (W) was obtained by the following equation:

$$W = Q \times \frac{\Omega}{\Omega_0} \times \frac{(H_h - H_c)}{1000} \quad (\text{MW}), \quad (11)$$

where Q (kg/s) is the flow rate of the coolant in the loop, Ω (tr/min) is the practical speed of pump, Ω_0 (tr/min) is the ideal speed of pump, and $H_h - H_c$ (kJ/kg) is the difference between the enthalpy at the hot leg and the cold leg. The enthalpies are calculated using THPROP subroutine.

2.4. Double-Loop SCWR Program. Some conceptual designs of double-loop SCWR have been put forward, like CANDU-SCWR with a steam generator proposed by Dr. William Fatoux [12] and a pressurized water reactor cooled with supercritical water in the primary loop proposed by Vogt et al. [13]. Double-loop SCWR drives a turbine by the steams from the steam generator in the second loop indirectly as shown in Figure 5.

Heat balance method in this type of SCWR is based on the steam generator approximation enthalpy balance. H-Power calculate the thermal power of reactor by the theory of heat balance, which obtains thermal power (of generator) in second loop from primary loop through the measurement values of temperature, pressure, and flow rate in the second

FIGURE 5: Sketch of SCWR with two loops.

loop, counting the internal heat loss in at the same time. The advantages of the working conditions of second loop for easy measurement makes it an important method of obtaining thermal power of the double-loop SCWR.

Figure 6 shows the heat in and out the system (expressed by arrows), which can be described by the following heat balance equation:

$$W_R = \sum_{i=1}^N W_{SGi} - W_{\Delta Pr}, \quad (12)$$

where the W_R is the core thermal power (MW), W_{SGi} is the thermal power obtained from the primary loop in the second loop in i th steam generator, and $W_{\Delta Pr}$ is the thermal power coolant system obtained from other heat sources, (MW), which can be estimated from the design of reactor.

The main physical process occurring in the steam generator is as follows: unsaturated water with the mass flow rate Q_e and specific enthalpy H_e flows into the steam generator through the U tube, exchanges heat with the coolant in primary loop, and mostly becomes wet steam with the mass flow Q_v and specific enthalpy H_v ; after the increase of endothermic enthalpy, the others are the saturated blowdown water with mass flow rate Q_p and specific enthalpy H_p . The thermal power in i th steam generator can be calculated with following equation:

$$W_{SG} = (H_v - H_e) Q_e - (H_v - H_p) Q_p, \quad (13)$$

where H_v is the wet steam enthalpy in steam generator export, H_p is the blowdown enthalpy, Q_p is the flow rate of blowdown in second loop, H_e is the feedwater enthalpy in second loop, and Q_e is the flow rate of feedwater in second loop.

The feed water satisfies the law of conservation of mass as follows:

$$Q_e = Q_v + Q_p. \quad (14)$$

Simplify (13) and (14):

$$W_{SG} = (H_v - H_e) Q_e - (H_v - H_p) Q_p, \quad (15)$$

where feedwater enthalpy H_e and blowdown enthalpy Q_p are calculated by the thermodynamic properties subroutine, flow rate of feedwater Q_e can be obtained from flow rate calculation subroutine, and the flow rate of blowdown Q_p is a measured value.

The wet steam always consists of saturated steam and saturated water, which is determined by vapour fraction x , so the enthalpy of wet steam is characterized by the following equation:

$$H_v = x H_{vs} + (1 - x) H_{ls}, \quad (16)$$

where the H_{vs} is the enthalpy of saturated steam and H_{ls} is the enthalpy of saturated water; both are calculated by the thermodynamic properties subroutine.

3. Uncertainty Analysis of Double-Loop SCWR

The relative uncertainty of thermal power given in (17) is obtained by the uncertainty transmission formula:

$$\frac{\Delta W}{W} = \left[\sum_{i=1}^n \left[\frac{W_{SGi}}{W} \frac{\Delta W_{SGi}}{W_{SGi}} \right]^2 + \left[\frac{W_{\Delta Pr}}{W} \frac{\Delta (W_{\Delta Pr})}{W_{\Delta Pr}} \right]^2 \right]^{1/2}, \quad (17)$$

where the $\Delta W_{SGi}/W_{SGi}$ is the uncertainty of thermal power in steam generation in each second loop and $\Delta (W_{\Delta Pr})/W_{\Delta Pr}$ is the uncertainty of thermal power of coolant system in primary loop:

$$\frac{\Delta W_{SGi}}{\Delta W} \leq \left[\frac{\Delta W_{SG}}{\Delta W} \right]_M, \quad (18)$$

where $[\Delta W_{SG}/\Delta W]_M$ is the max uncertainty of each steam generation.

Assuming that

$$\frac{W_{SGi}}{W} = \frac{1}{i}. \quad (19)$$

We can obtain the following equation:

$$\frac{\Delta W}{W} = \left\{ \frac{1}{i} \left[\frac{\Delta W_{SG}}{W_{SG}} \right]_M^2 + \left[\frac{W_{\Delta Pr}}{W} \times \frac{\Delta W_{\Delta Pr}}{W_{\Delta Pr}} \right]^2 \right\}^{1/2}. \quad (20)$$

FIGURE 6: Heat balance principle diagram of double-loop SCWR.

3.1. *The Calculation of $\Delta W_{SG}/W_{SG}$.* The following equation can be obtained by error propagation formula:

$$\frac{\Delta W_{SG}}{W_{SG}} = \left[\left[\frac{H_v(Q_e - Q_p)}{W_{SG}} \frac{\Delta H_v}{H_v} \right]^2 + \left[\frac{H_e Q_e}{W_{SG}} \frac{\Delta H_e}{H_e} \right]^2 + \left[\frac{H_p Q_p}{W_{SG}} \frac{\Delta H_p}{H_p} \right]^2 + \left[\frac{Q_e(H_v - H_e)}{W_{SG}} \frac{\Delta Q_e}{Q_e} \right]^2 + \left[\frac{Q_p(H_v - H_p)}{W_{SG}} \frac{\Delta Q_p}{Q_p} \right]^2 \right]^{1/2}, \quad (21)$$

$$\frac{\Delta H_v}{H_v} = \left[\left[\frac{x}{H_v} (H_{vs} - H_{es}) \frac{\Delta x}{x} \right]^2 + \left[\frac{H_{vs} x}{H_v} \frac{\Delta H_{vs}}{H_{vs}} \right]^2 + \left[\frac{H_{es}}{H_v} (1 - x) \frac{\Delta H_{es}}{H_{es}} \right]^2 \right]^{1/2}.$$

Assume that the uncertainty of saturated water in the wet steam is “1” as in (22) and inaccuracy of measurement should be in this range:

$$\frac{\Delta(1-x)}{1-x} = \frac{x}{1-x} \frac{\Delta x}{x} = 1. \quad (22)$$

Equation (22) can be deduced by the above formula:

$$\frac{\Delta x}{x} = \frac{1-x}{x}. \quad (23)$$

$\Delta H_{vs}/H_{vs}$ is the uncertainty of saturated steam enthalpy, mainly caused by the uncertainty of pressure measurement and water and steam thermodynamic properties as follows:

$$\frac{\Delta H_{vs}}{H_{vs}} = \left[\left(\frac{\Delta H_{vs}}{H_{vs}} \right)_{P_v}^2 + \left(\frac{\Delta H_{vs}}{H_{vs}} \right)_f^2 \right]^{1/2} \quad (24)$$

and the uncertainty caused by pressure measurement can be calculated by following equation:

$$\left(\frac{\Delta H_{vs}}{H_{vs}} \right)_{P_v} = \frac{P_v}{H_{vs}} \left| \frac{\partial H_{vs}}{\partial P_v} \right| \frac{\Delta P_v}{P_v}, \quad (25)$$

where ΔP_v is uncertainty caused by pressure measurement, root mean square of the uncertainty of pressure transmitter, data acquisition system, and calibration, determined by the design of pressure measurement:

$$\frac{\partial H_{vs}}{\partial P_v} = \tau R T_s \left\{ \sum_{i=1}^{43} n_i J_i (\tau - 0.5)^{J_i-1} I_i \left(\frac{0.1 P_v}{p^*} \right)^{I_i-1} \left(\frac{1}{p^*} \right) \right\}, \quad (26)$$

where I_i, J_i, n_i is given in IAPWS-IF97, and $\pi = 0.1 P_v / p^* \tau = T^* / te, p^* = 1 \text{ MPa}, T^* = 540 \text{ K}$, and $R = 0.461526 \text{ kJ kg}^{-1} \text{ K}^{-1}$.

$(\Delta H_{vs}/H_{vs})_f^2$ is the uncertainty caused by the calculation of water and steam thermodynamic properties, where ΔH_{vs} can be selected in the corresponding section of IAPWS-IF97.

3.2. *The Calculation of $\Delta H_{es}/H_{es}$.* The uncertainty of saturated water enthalpy $\Delta H_{es}/H_{es}$ and feedwater enthalpy $\Delta H_e/H_e$ can be estimated by the method the same as $\Delta H_{vs}/H_{vs}$ mentioned above.

The relative uncertainty of mass flow rate $\delta q_m/q_m$ can be described by the following equation:

$$\frac{\delta q_m}{q_m} = \left(\left(\frac{\delta C}{C} \right)^2 + \left(\frac{\delta \varepsilon}{\varepsilon} \right)^2 + \left(\frac{2\beta^4}{1-\beta^4} \right)^2 \left(\frac{\delta D}{D} \right)^2 + \left(\frac{2}{1-\beta^4} \right)^2 \left(\frac{\delta d}{d} \right)^2 + \frac{1}{4} \left(\frac{\delta \Delta p}{\Delta p} \right)^2 + \frac{1}{4} \left(\frac{\delta \rho_1}{\rho_1} \right)^2 \right)^{1/2}. \quad (27)$$

The uncertainty of discharge coefficient is given by

$$C = \begin{cases} (0.7 - \beta) \% & 0.1 \leq \beta \leq 0.2, \\ 0.5\% & 0.2 \leq \beta \leq 0.6, \\ (1.667\beta - 0.5) \% & 0.6 \leq \beta \leq 0.75. \end{cases} \quad (28)$$

If $D < 71.12$ mm, (10) should add the following term:

$$0.9 (0.75 - \beta) \left(2.8 - \frac{D}{25.4} \right) \%. \quad (29)$$

If $\beta > 0.5$ and $Re_D < 10000$, the above values should add the following relative uncertainty:

$$+0.5\%. \quad (30)$$

The uncertainty of expansibility factor ε is $3.5(\Delta p/\kappa p_1)\%$, for compressible fluid, $\varepsilon = 0$.

The uncertainty of internal diameter of the pipe line can be estimated by the following equation:

$$\sigma_D = \frac{0.05\% \times d^i \times 2}{\sqrt{3}} = 0.05\% \times d^i \times 1.15, \quad (31)$$

where $0.05\% \times d^i$ is the error of the measuring instrument; “2” is an extension coefficient of the confidence interval of 95%; $\sqrt{3}$ is the constant of rectangular distribution.

The volume elasticity coefficient of water is quite large determining that its compressibility is very small, so the influence of pressure on the density can be ignored. The uncertainty of feed water density $\sigma\rho/\rho$ is determined by the uncertainty of temperature measurement and the calculation of water properties as follows:

$$\left(\frac{\Delta \rho}{\rho} \right) = \left[\left(\frac{\Delta \rho}{\rho} \right)_{te}^2 + \left(\frac{\Delta \rho}{\rho} \right)_f^2 \right]^{1/2} \quad (32)$$

and the uncertainty caused by temperature measurement can be calculated by following equation:

$$\left(\frac{\Delta \rho}{\rho} \right)_{te} = \frac{te}{\rho} \left| \frac{\partial \rho}{\partial te} \right| \frac{\Delta te}{te}. \quad (33)$$

TABLE 2: The main parameters reference design of the US SCWR.

Parameter	Value
Thermal power	3575 MWth
Operating pressure	25 MPa
Reactor inlet temperature	280°C
Reactor outlet temperature	510~550°C
Reactor mass flow rate	1843 kg/s

TABLE 3: The input and output values calculated by H-Power.

Input parameter	Value
Operating pressure	25 MPa
Reactor inlet temperature	280°C
Reactor outlet temperature	520°C
Reactor mass flow rate	1843 kg/s
Ideal pump speed	1900 tr/min
Practical pump speed	1850 tr/min
Output parameter	Value
Cold leg enthalpy	1230.2407 kJ/kg
Hot leg enthalpy	3216.4985 kJ/kg
Thermal power	3564.3396 MW

The calculation procedures and method of the parameters are the same as the $\Delta H_v/H_v$ mentioned above.

The relative uncertainty of $\Delta(W_{\Delta Pr})/W_{\Delta Pr}$ is estimated by experience values.

4. Validation of H-Power Code

4.1. *Single-Loop Type Program.* We have done the verification of single-loop program in H-Power using the main parameters design by Jacopo Buongiorno as in Table 2 and assuming the ideal and practical pump speed according to the level of pump speed at present.

The calculation result of thermal power 3564.3396 MW given in Table 3 shows a high consistency with the value 3575MW designed by US in Table 3.

4.2. *Double-Loop SCWR Program.* Due to the lack of design data of SCWR, the validation of this part has been done by using the values of Qinshan Phase II [13] in Table 4 though it is not SCWR. Table 5 shows the comparison between the results of H-Power and the values of Qinshan Phase II.

Although the main calculation result trend of SCWR is same as CNP650 of Qinshan Phase II, there is many detail differences in thermodynamic properties of water and steam and uncertainties calculation. The inconsistencies in Table 5 also come from the different input parameters in measuring instrument.

It is a valid way to verify the H-Power while the main calculation process of both PWR and SCWR is the same and there is no particular data of SCWR fitting for the code. The result in Table 5 shows that H-Power runs well and has a valid trend in thermal power and its relevance computation. So it can be used in SCWR design and calculation.

TABLE 4: Input parameters of H-Power using the values of Qinshan Phase II.

Parameters	Values
Orifice diameter in reference (m)	0.2417
Feedwater pipe diameter in reference (m)	0.36374
Steam pipe diameter in reference (m)	0.739
Orifice linear expansion coefficient (m/m°C)	0.0000166
Feedwater pipe linear expansion coefficient (m/m°C)	0.0000121
Steam pipe linear expansion coefficient (m/m°C)	0.0000121
Orifice reference temperature (°C)	20
Feedwater pipe reference temperature (°C)	20
Steam pipe reference temperature (°C)	20
Feedwater pressure difference (KPa)	182.1147
Feedwater temperature (°C)	228.920334
Feedwater pressure (MPa)	7.11855
Steam pressure (MPa)	6.941479
Blowdown flow rate (t/h)	20.757261

TABLE 5: Comparison between the results of the values of Qinshan Phase II and H-Power.

Parameters	Qinshan Phase II	H-Power
Feedwater density (kg/m ³)	833.12894	832.69758
Feedwater enthalpy (kJ/kg)	986.18622	986.07354
Saturated water enthalpy (kJ/kg)	1264.3947	1265.5310
Saturated steam enthalpy (kJ/kg)	2774.1882	2773.0492
Steam enthalpy (kJ/kg)	2772.6784	2771.5417
Blowdown enthalpy (kJ/kg)	1264.3947	1265.531
Discharge coefficient	0.603068	0.606047
Feedwater flow rate (t/h)	1948.4789	1957.6866
Generator thermal power (MW)	958.2318	970.94089
Feedwater flow rate uncertainty	0.007236	0.006088

5. Conclusions

The thermal power calculation code H-Power for SCWR was developed based on heat balance method, which can be easily applied in designs and operation. In this paper thermodynamic properties calculation subroutine based on IAPWS-IF97 has been verified, and the uncertainty analysis has been proposed. The validation of H-Power has been carried out in two parts: single-loop SCWR by the data given by Jacopo Buongiorno and double-loop SCWR by the values of Qinshan Phase II. Although Qinshan Phase II is a PWR, the result can show that H-Power is valid because the main calculation process of both PWR and SCWR is the same. In the future, the validation will be carried out using the values of SCWR when published.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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