Thermal-Hydraulic Aspects of SCWR Design*

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Abstract

The Supercritical Water-Cooled Reactor (SWCR) is one of the most promising concepts for Generation IV candidate systems [Kataoka et al., 2002; USDOE, 2002; Buongiorno, 2004]. The SCWR has several advantages compared to the existing light water reactor (LWR) systems, including the use of direct cycle combined with single-phase working fluid, high thermal efficiency, and the existing experience with the proven technology used in fossil power plants. A common feature of most Supercritical Water-Cooled Reactor (SWCR) designs that have been proposed to date is a highly nonuniform temperature distribution inside the reactor core. This is mainly due to the combined effects of core peaking factors and limits imposed on coolant flow rate. Furthermore, statistical uncertainties in the evaluation of hot spot factors normally contribute to an increase in the range of temperature distribution that must be considered in reactor design. The purpose of this paper is to present the results of analysis on the SCWR in-core temperature distribution, aimed at identifying possible methods of reducing the maximum coolant temperature and improving the thermal-hydraulic characteristics of the proposed reactor system.

Key words: SCWR, Hot Channel Temperature, Reactor Design

1. Introduction

Quite a few different designs of the SCWR core have been proposed so far, including a hexagonal lattice fuel assembly [Dobashi et al., 1998] and a square lattice fuel assembly [Oka et al., 2002], both shown in Figure 1.

A common feature of most Supercritical Water-Cooled Reactor (SWCR) designs that have been proposed to date is a highly nonuniform temperature distribution inside the reactor core. Such distribution is mainly caused by the combined effects of core peaking factors and limits imposed on coolant flow rate. The latter effect is associated with a dramatic decrease in coolant density above the pseudo-critical temperature. Furthermore, statistical uncertainties in the evaluation of hot spot factors normally contribute to an increase in the range of temperature distribution that must be considered in reactor design.

The purpose of this paper is to present the results of analysis on the SCWR in-core temperature distribution, aimed at identifying possible methods of reducing the maximum coolant temperature and, thus, improving the thermal-hydraulic characteristics of the proposed reactor. The issues under investigation include: similarities and differences between PWR and BWR designs and the anticipated SCWRs, considerations on the possibility and consequences of lowering the core exit temperature, design concepts leading to flow rate increase and a reduction in the hot channel exit temperature, optimization of the coolant-to-moderator volume, and others. The impact of the accuracy of advanced computational models on flow and heat transfer calculations is also discussed.

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2. Analysis of Thermal Characteristics of SCWR Core

The temperature distribution inside the SCWR core is directly associated with the varying properties of supercritical pressures over the range of temperatures of interest. Whereas most hydrodynamic and thermal properties of water undergo dramatic changes in the near-pseudo-critical temperature region [Gallaway et al., 2006], the most important for the current analysis are the enthalpy vs. temperature and density vs. temperature (or enthalpy) curves. The dependences of both temperature and density on water enthalpy are shown in Figures 2 and 3, respectively.

Figure 1. Typical proposed designs of SCWR fuel assembly.

Figure 2. Temperature vs. enthalpy curves for water at different pressures: 1- typical core inlet conditions (BWR, PWR, SCWR), 2- BWR core exit conditions, 3 - saturated steam parameters in BWRs, 4 - SCWR core exit conditions.
Hot-spot factor analyses are normally performed by directly accounting for the effects of uncertainties in partial temperature differences on the evaluation on the maximum temperature of a given material (such as coolant, cladding, or fuel) with respect to a given (common) temperature of reference. Specifically, the estimated maximum temperature of material-i can be expressed as

\[ T_{\text{max}}^i = T_{\text{ref}} + \sum_{j=1}^{N} \Delta T_j F_j (1 + \varepsilon_j) \]  

where \( F_j > 1 \) are the peaking factors associated with the individual temperature differences, \( \Delta T_j \), and \( \varepsilon_j \) \((j = 0,1,\ldots,N_j)\) represent the uncertainties in the evaluation of both \( \Delta T_j \) and \( F_j \). The reference temperature in Eq.(1) is typically defined as the coolant temperature at core inlet, \( T_{\text{ref}} = T_w \).

Eq.(1) is directly applicable to reactor types in which coolant properties stay approximately constant over the range of temperature of interest (such as PWRs, for example), i.e. for situations in which changes in temperature are directly proportional to the corresponding changes in reactor power. If the properties of the reactor coolant vary with temperature (such as in SCWR) or phase change occurs (in BWRs), the hot-spot-factor analysis should be performed with respect to enthalpy, rather than temperature, changes. In the case of supercritical water reactors, the effect of nonuniform power distribution on temperature is more dramatic due to a significant variation in the specific heat of water in the pseudo-critical temperature region [Gallaway et al. 2006]. Thus, it is important that the uncertainties in the coolant exit enthalpy (including core-area average, hot assembly and hot channel) be estimated first, and then used to estimate the maximum temperature of reactor coolant.

Specifically, the hot channel exit enthalpy can be expressed in terms of the core inlet enthalpy as

\[ \langle h_{\text{exit}}^{\text{HC}} \rangle_{\text{max}} = h_w (1 + \varepsilon_w^h) + \Delta h_{\text{core}} F_h F_e F_i \times (1 + \varepsilon_{\text{core}}^h)(1 + \varepsilon_h^e)(1 + \varepsilon_e^i)(1 + \varepsilon_i^p) \]  

or

![Figure 3. Density vs. enthalpy curves for water at different pressures. Same notation as in Figure 2; 1a – SCWR core inlet conditions, 1b – BWR core inlet conditions.](image)
\[ h_{\text{ex}}^{\text{HCA}} \]_{\text{max}} = h_{n}^{b} (1 + \varepsilon_{n}^{b}) + \Delta h_{\text{o}}^{\text{HCA}} \times (1 + \varepsilon_{\text{cor}}^{b})(1 + \varepsilon_{R}^{F})(1 + \varepsilon_{H}^{F}) \]  

(3)

where

\[ \Delta h_{\text{o}}^{\text{HCA}} = \Delta h_{\text{cor}}^{b}F_{x}F_{i}F_{H} \]  

(4)

Linearizing Eq.(3) yields a standard form of the expression used in the error analysis

\[ h_{\text{ex}}^{\text{HCA}} \]_{\text{max}} - h_{n}^{b} = \left( h_{\text{ex}}^{\text{HCA}} - h_{n}^{b} \right)_{o} + \varepsilon_{n}^{b}h_{n}^{b} + \Delta h_{\text{o}}^{\text{HCA}} \left( \varepsilon_{\text{cor}}^{b} + \varepsilon_{R}^{F} + \varepsilon_{H}^{F} \right) \]  

(5)

If the terms, \( \varepsilon_{j}^{b} \), are defined as measures of the maximum error of uncertainty-(j,k), both Eq.(3) and Eq.(5) yield conservative estimates of the maximum value of the coolant enthalpy at hot channel exit. On the other hand, if the individual uncertainties are treated as statistical variables of given probabilistic distributions, these equations serve as a vehicle to determine the maximum value of \( h_{\text{ex}}^{\text{HCA}} \)_{max} with a desired confidence level. For normal distributions, each \( \varepsilon_{j}^{b} \) term typically represents a multiplicity of standard deviation, \( \sigma_{n}^{b} = \sigma_{n}^{b} \). In such case, the maximum value of the hot channel exit enthalpy, \( h_{\text{ex}}^{\text{HCA}} \)_{max}, can be obtained from

\[ h_{\text{ex}}^{\text{HCA}} \]_{\text{max}} - h_{n}^{b} = \left( h_{\text{ex}}^{\text{HCA}} - h_{n}^{b} \right)_{o} + \sigma_{n}^{b} \]  

(6)

with a confidence limit that depends on n, where \( \sigma_{n}^{b} \) is the ‘nσ’ error for the combined physical uncertainties affecting the estimate of the enthalpy, \( h_{\text{ex}}^{\text{HCA}} \)_{max}. Specifically, the 3σ confidence limit is about 99.865%.

In the present case, \( \sigma_{1}^{\text{tot}} \) can be expressed as

\[ \sigma_{1}^{\text{tot}} = \left( \sum_{j=1}^{5} \sigma_{1}^{2} \right)^{1/2} \]  

(7)

This result is based on the assumption that the individual uncertainties, \( \sigma_{1} = \varepsilon_{n}^{b}h_{n}^{b} \), \( \sigma_{1,2} = \Delta h_{\text{o}}^{\text{HCA}} \varepsilon_{\text{cor}}^{b} \), \( \sigma_{1,3} = \Delta h_{\text{o}}^{\text{HCA}} \varepsilon_{R}^{F} \), \( \sigma_{1,4} = \Delta h_{\text{o}}^{\text{HCA}} \varepsilon_{H}^{F} \) and \( \sigma_{1,5} = \Delta h_{\text{o}}^{\text{HCA}} \varepsilon_{H}^{F} \) are determined with the 3σ accuracy.

Now, the estimate of the maximum possible coolant temperature at hot channel exit can be directly obtained for the property tables of supercritical water

\[ \left( T_{\text{ex}}^{\text{HCA}} \right)_{\text{max}} = T \left( h_{\text{ex}}^{\text{HCA}} \right)_{\text{max}, p} \]  

(8)

Naturally, if changes in the fluid properties (in particular, in \( c_{p} \)) are negligible, Eq.(8) yields
\[
\{T_{ex}^{HCh}\}_{\text{max}} = \frac{\{h_{ex}^{HCh}\}_{\text{max}} - h_{ex}^{RCH} + T_{ex}^{HCh}}{c_p(p)}
\]  

where \(h_{ex}^{HCh}\) and \(T_{ex}^{HCh}\) are the values of the hot channel exit enthalpy and temperature, respectively, at the operating conditions of reference.

Needless to say, the evaluation of the maximum coolant temperature should be followed by a similar analysis for the maximum cladding and fuel temperatures. Assuming that the peak cladding temperature is reached at the location of the maximum heat flux, yields

\[T_{CL}^{HCh} = T_{c,m}^{HCh} + q_m^* / H_{conv}\]  

where

\[q_m^* = \frac{P}{A_{tot}} F_{Tot}\]

\(H_{conv}\) is the heat transfer coefficient at the location of the maximum heat flux, \(T_{c,m}^{HCh}\) is the coolant temperature at the same location, and \(F_{Tot} = F_{R} F_{l} F_{H}\).

For a symmetric axial power distribution, the maximum heat flux is reached at the center of the hottest fuel channel, where the corresponding coolant bulk enthalpy is, \(h_{m}^{HCh} = 0.5(h_{ex}^{HCh} + h_{m})\). Thus the temperature, \(T_{c,m}^{HCh}\), in Eq.(10) is

\[T_{c,m}^{HCh} = T(h_{m}^{HCh})\]

Accounting for the uncertainties in the evaluation of both the maximum heat flux and the heat transfer coefficient, we obtain the following expression for the maximum cladding temperature

\[\{T_{CL}^{HCh}\}_{\text{max}} = \{T_{c,m}^{HCh}\}_{\text{max}} = \{T_{CL}^{HCh}\}_{\text{max}} - T_{c,m}^{HCh} + \left[\left(\sigma_{y,HCh,m}^2 + (q_{m}^* / H_{conv})^2 + e_y^2 + e_{Hconv}^2\right)^{1/2}\right]
\]

Let us consider a typical proposed SCWR design based on the fuel assembly geometries shown in Figure 1. The major core parameters can be assumed as follows:

- Reactor power, \(P_R = 3000\) MW
- Operating pressure, \(p = 25\) MPa
- Core height, \(H = 14\) ft = 4.27 m
- Core equivalent diameter, \(D = 12\) ft = 3.66 m
- Radial peaking factor, \(F_R = 1.3\)
- Local peaking factor, \(F_l = 1.1\)
- Axial peaking factor, \(F_H = 1.4\)
- Total peaking factor, \(F_{Tot} = F_R F_l F_H \approx 2\)
Uncertainty in core inlet temperature, $\varepsilon_{in} = 0.01$

Uncertainty in reactor power, $\varepsilon_{core} = 0.01$ to $0.02$

Uncertainty in coolant flow rate, $\varepsilon_{wcore} = 0.03$ to $0.05$

Uncertainty in flow distribution, $\varepsilon_{local} = 0.02$ to $0.05$

Uncertainty in local peaking factor, $\varepsilon_{f} = 0.02$ to $0.03$

Uncertainty in radial peaking factor, $\varepsilon_{R} = 0.03$ to $0.04$

Typically values of the coolant temperatures as the reference are as follows (see Figure 2):

Coolant temperature at core inlet, $T_{in} = 280^\circ C$

Coolant temperature at core exit, $T_{ex}^{core} = 400^\circ C$

The operating conditions outlined above correspond to the core mass flow rate of 2225 kg/s. Assuming that the flow area is equal to 25% of the total core cross section area, such flow rate yields the inlet velocity only slightly higher than 1.1 m/s and the velocity at hot channel exit of about 10 m/s.

The results of parametric calculations showing the effect of core inlet temperature on the hot channel exit temperature at the operating conditions of reference ($T_{ex}^{HCh}$), as well as the corresponding maximum hot channel exit temperature ($\{T_{ex}^{HCh}\}_{max}$) and maximum cladding temperature ($\{T_{ex}^{HCh}\}_cl_{max}$), both calculated accounting for the uncertainties discussed before (see Eqs.(6)-(13)), are shown in Figure 4. Similar results, but expressed in terms of the corresponding temperature differences across the core, are shown in Figure 5.

![Figure 4](image)

Figure 4. The effect of uncertainties in the evaluation of various SCWR core parameters on the anticipated maximum hot channel exit temperature and the maximum cladding temperature, for two different core-average exit temperatures, 390°C and 400°C.
It is important to mention that the calculations were performed in a conservative manner, using the highest values of the individual uncertainties listed on page 5. As both Figures indicate, whereas a significant degree of nonuniformity is anticipated to occur between the coolant temperature at hot channel exit and the exit temperature averaged over the entire core flow area, the magnitude of the actual temperature difference strongly depends on the average core exit temperature. For instance, for the core inlet temperature of 280°C, the maximum value of this temperature difference (accounting for all major uncertainties in a conservative manner) corresponding to the exit temperature of 400°C, is about 148°C, whereas if the exit temperature is reduced by 10°C (to 390°C), the maximum ‘hot channel’-to-‘core average’ exit temperature difference drops to 78°C. Such a dramatic change is due to the nonuniform enthalpy-to-temperature relationship of superheated water over the range of temperatures of interest. Interestingly, whereas the efficiency of an ideal Rankine cycle for the core exit temperature of 400°C is about 38%, it drops by 1% only as a result of reducing the exit temperature by 10°C.

Figure 5. The effect of uncertainties in the evaluation of various core parameters on the maximum anticipated coolant temperature increase along the SCWR core.

Figure 5 can also be used to deduce the effect of core inlet temperature on the maximum coolant temperature at core channel exit. As can be seen, an increase in the inlet temperature by 10°C results in a reduction of the maximum temperature between 8°C (at $T_{ex}^{core} = 400°C$) and 6°C (at $T_{ex}^{core} = 390°C$).

A similar analysis can be performed for the maximum cladding temperature, using Eq.(13). In this case, the most important issue is concerned with the evaluation of the heat transfer coefficient. Due to the dramatic changes in water properties in the near-pseudo-critical-temperature region, the value of heat transfer coefficient along the heated channels in general, and the hot channel is particular, varies with the axial position [Gallaway et al. 2006]. However, for the range of flow rates corresponding to the anticipated SCWR operating conditions, the value of $H_{conv}$ is typically between 15 and 20 kW/m²-s, or even higher. Since a typical range of uncertainties in the evaluation of $H_{conv}$ can be assumed to be ±15%, taking $H_{conv} = 10$ kW/m²-s as a reference value, leads to a conservative estimate of the maximum cladding temperature. It turns out that, for the given reactor power and peaking factors, the maximum cladding temperature...
corresponding to $T_{in} = 280^\circ C$ and $T_{ex}^{corr} = 400^\circ C$ is about $500^\circ C$, and it drops slightly (by about $2^\circ C$) if the exit temperature is, $T_{ex}^{corr} = 390^\circ C$. This is also shown in Figure 4.

3. Other Design Considerations of SCWR Core

Since a highly nonuniform coolant temperature in the core always adds additional questions that must be addressed by reactor designer, various possible modifications in the current reactor design should be investigated in future works. In particular, the effect of small design changes of core layout should be considered, aimed increasing the coolant flow rate. As it was shown before, for the inlet velocities of the order of 1 m/s, the maximum exit velocity will be about 10 m/s, which is less than the steam/water velocity at the exit of typical BWRs. Thus, an increase in the inlet velocity by 50% should be still quite feasible. At the same time, such increase will lead to a higher inlet temperature and, thus, a lower average coolant density in the core. This in turn, may shift the neutron spectrum toward higher energies. However, since in the current proposed SCWR designs, the coolant channels occupy only a relatively small fraction of the total core area, whereas the remaining space is filled with a moderator, the resultant energy shift may not be significant. Nevertheless, the effect of coupling between the thermal/hydraulic and neutronic characteristics of the SCWR core should be thoroughly investigated using state-of-the art models and computational tools. It has already been demonstrated [Gallaway et al. 2006; Podowski et al., 2006] that using mechanistic multidimensional models of fluid mechanics [Antal et al., 2000] in supercritical fluids yields very promising results concerning the effect of variable fluid properties on both velocity field and temperature distributions in heated channels of various geometries. Furthermore, direct coupling between space-dependent core neutronics and multidimensional fluid mechanics and heat transfer is also becoming an efficient tool [Podowski & Aniel-Buchhreit, 2006] for the analysis of SCWR designs, operational characteristics and dynamic response.

4. Summary

Selected design aspects of SCWR thermal-hydraulics have been discussed. It has been shown that by modifying the reactor operating conditions and/or core design characteristics, significant improvements can be achieved aimed at mitigating the effect of variable properties of supercritical water on the local nonuniform temperature distributions across the reactor core in general, and the exit coolant temperature in particular.

References


