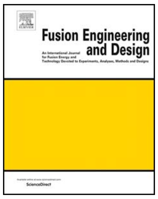
Fusion Engineering and Design 127 (2018) 91–98

Contents lists available at ScienceDirect

Fusion Engineering and Design

journal homepage: www.elsevier.com/locate/fusengdes



An improved method for modelling coolant radiolysis in ITER

Zhong Fang[a], Xuewu Cao[b], Lili Tong[b], Yusa Muroya[c], Giles Whitaker[d], Mojtaba Momeni[d], Mingzhang Lin[a,*]

[a] School of Nuclear Science and Technology, University of Science and Technology of China No.96 Jinzhai Road, Hefei, Anhui 230026, China
[b] School of Mechanical Engineering, Shanghai Jiao Tong University Mechanical Building, 800 Dong Chuan Road, Shanghai 200240, PR China
[c] Department of Beam Materials Science, Institute of Scientific and Industrial Research, Osaka University, 8-1 Mihogaoka, Ibaraki, Osaka 567-0047, Japan
[d] Department of Chemistry, The University of Western Ontario,1151 Richmond Street, London, N6A 5B7, Ontario, Canada

ARTICLE INFO

Keywords:
Water radiolysis
ITER
Corrosion
14 MeV neutron

ABSTRACT

Predicting the effects of coolant water radiolysis induced by neutron and gamma radiation in the International Thermonuclear Experimental Reactor (ITER) is important, as oxidizing species like O_2 and H_2O_2 will corrode structural materials, increasing maintenance costs and potentially compromising safety. In this work, a new model has been developed, by modifying existing models, to evaluate the water radiolysis behaviors in different Primary Heat Transfer Systems (PHTSs) in ITER. The new model takes the circulation of coolant, and the combined gamma and 14 MeV neutron radiation into consideration. We recommend injection of about 5 cc H_2 under standard temperature and pressure (STP) per kilogram of H_2O into the First Wall/Blanket (FW/BLKT) PHTS to both efficiently suppress water radiolysis and avoid problems caused by addition of excessive H_2.

1. Introduction

Water will be used in ITER to remove the heat generated during operation and to cool auxiliary heating systems and current drive systems, cryogenics, and power supplies in a similar manner to the well-established methods used in Light Water Reactors (LWRs). When the coolant enters the reactor core, the intense neutron and gamma radiation produced by the plasma will ionize or excite the water molecules, leading to radiolytic decomposition products. Species like O_2 and H_2O_2 create an oxidizing environment and raise the Electrochemical Corrosion Potential (ECP) of the cooling tubes [1], which induces corrosion of structural materials [2]. Corrosion affects the integrity of the materials and increases maintenance costs [3]. Furthermore, the corrosion products deposited on the fuel cladding surface can be activated by neutron radiation (e.g. ^{58}Ni(n, p)^{58}Co and ^{59}Co(n, γ)^{60}Co) and transported in solution away from the reactor core. These radionuclides are eventually removed via ion exchange resins, the handling of which constitutes a radiation exposure hazard for workers during shutdown repair and maintenance activities. Irradiation conditions for ITER [4] are more challenging than for LWRs because of the larger irradiation intensity, larger LET (Linear Energy Transfer, due to a higher ratio of neutron flux to gamma flux), and higher expected concentrations of Cu^{2+} in the water of the diverter loop. All these factors decrease the efficiency of water radiolysis suppression by hydrogen.

Over the last three decades, several studies on water radiolysis under fusion conditions have been carried out. As early as 1991, P. Lorenzetto and his colleagues [5,6] investigated the first wall water coolant decomposition under different temperatures. At the time of this study, there was not good agreement on the *G*-values (the primary yields per 100 eV of absorbed radiation energy) of the 9–14 MeV neutron irradiation. In addition, some of the rate constants of the elementary reactions at different temperatures used in the simulation were estimated but unconfirmed. During the ITER/Engineering Design Activity (ITER/EDA), the water chemistry issue was investigated [7]. A hydrogen dosing of 0.014–0.5 mM was found to be effective in suppressing O_2, but suppression of H_2O_2 required a higher amount. In 2011, P. J. Karditsas [8] simulated the radiolytic decomposition of water coolant by varying the flow rate of the coolant in the calculation. Genn Saji [9] proposed a ‘long cell’ corrosion theory based on the fact that the uneven nuclear heating rate distribution leads to different concentrations of oxidizing species in different regions. However, the water chemistry assumptions made for his calculation are inconsistent with the operating conditions estimated from thermohydraulic simulations [10].

One more factor that the previous work did not consider is that the irradiation conditions are more likely to involve a periodic pulse rather than steady irradiation. The authors have written a new code named “Water-homo” to address the difficulties of direct measurement of oxidizing species concentration during operation, and the uncertainties in previously published simulation results as outlined above. Our code

---

[*] Corresponding author.
E-mail address: gelin@ustc.edu.cn (M. Lin).

https://doi.org/10.1016/j.fusengdes.2017.12.031
Received 6 June 2017; Received in revised form 16 November 2017; Accepted 18 December 2017
0920-3796/

and our calculation results improve on previously published simulations by taking coolant circulation into account and making use of much more up-to-date water radiolysis rate constants and *G*-values. We have also considered much more carefully the differing irradiation conditions (radiation categories, dose rates, temperatures) in different PHTSs of the components in ITER. The effect of the cooling paths in the PHTS on the calculation results has also been considered. The authors believe that these innovations have allowed us to model oxidant concentrations and the predicted effect of H_2 injections much more confidently than the previously published simulation results.

2. "Water-homo" characterization

We first describe the governing equations in our model and then look at the input data for the code such as the *G*-values, dose rates, temperatures, and specific flow rates at different locations.

2.1. Governing equations

There are two possible methods to study the fluid evolution behaviors in the circuit: Eulerian coordinate and Lagrangian coordinate. The former focuses on the fluid particles and the latter focuses on a constant volume. If we focus on a constant volume dV in the core region, and consider three effects that will change the concentration of i^{th} species in that volume, then:

(1). Radiolytic yield:

$$R_i^{yield} = \left(\frac{G_i^\gamma DR^\gamma}{100N_A} + \frac{G_i^n DR^n}{100N_A}\right)F\rho dV \tag{1}$$

G_i^γ/G_i^n:G-values ofγ/n radiation for i^{th} species, unit/100 eV

DR^γ/DR^n:Dose Rate forγ/n radiation, unit Gy/s

F: Unit transfer factors,

N_A:Avogadro's Constant,

ρ: Density (temperature dependent), unit g/ml

(2). Reaction formation and consumption:

Consider a certain reaction that produces i: m + l → i + … with a reaction rate constant $k_{l,m}$ and a certain reaction that consumes i: i + j → … with a reaction rate constant $k_{i,j}$, where m, l, i, j represent different species in water radiolysis. The concentration of i will be represented by [i], and similarly for the rest of the species. The net reaction rate is then the sum of all the reactions that produce i^{th} species minus the sum of all the reactions that consume i^{th} species.

$$R_i^{reaction} = \left(\sum_{l,m} k_{lm}\cdot[l]\cdot[m] - \sum_j k_{ij}\cdot[i]\cdot[j]\right)dV \tag{2}$$

$\sum_{l,m} k_{lm}\cdot[l]\cdot[m]$: Chemical production of i^{th} species

$\sum_j k_{ij}\cdot[i]\cdot[j]$: Chemical consumption of i^{th} species

The unit for concentration is M and those for the n^{th} order reaction rate constants are M^{-n+1}/s.

(3). Convection:

$$R_i^{convection} = \frac{d(uC_i)}{dx}dV = \left(u\frac{dC_i}{dx} + C_i\frac{du}{dx}\right)dV \tag{3}$$

Where u is the velocity of the coolant and $\frac{d(C_i)}{dx}$is the derivative of C_i over location x.

It should be noted that, if R_i^{yield} and $R_i^{reaction}$ are positive, it means the concentration increases in the volume of dV; if $R_i^{convection}$ is positive, it means that there is a net concentration flow away from the volume dV. Under steady-state conditions, the following equation can be derived due to mass conservation:

$$R_i^{convection} = R_i^{yield} + R_i^{reaction} \tag{4}$$

Finally, we get:

$$\frac{dC_i}{dx} = \frac{1}{u}\left(\frac{G_i^\gamma DR^\gamma}{100N_A} + \frac{G_i^n DR^n}{100N_A}\right)F\rho + \frac{1}{u}\left(\cdot[l]\sum_{l,m} k_{lm}\cdot[m] - \sum_j k_{ij}\cdot[i]\cdot[j]\right) - \frac{C_i}{u}\frac{du}{dx} \tag{5}$$

Furthermore, if we assume that the tubes along the cooling path have the same inner diameter, then the $\frac{du}{dx} = 0$ coolant flow rate remains the same at different distances from the core. In other words,

Based on this assumption and $dx = udt$, Eq. (5) can be simplified to:

$$\frac{dC_i}{dt} = \left(\frac{G_i^\gamma DR^\gamma}{100N_A} + \frac{G_i^n DR^n}{100N_A}\right)F\rho + \left(\sum_{l,m} k_{lm}\cdot[l]\cdot[m] - \sum_j k_{ij}\cdot[i]\cdot[j]\right) \tag{6}$$

In Eq. (6), the effect of convection is missing. The reason for this is that for the volume dV, the amount of i^{th} species that flows into and out of the volume is the same. The net result is that the convection of coolant does not affect the concentration in volume dV. This is also the reason we have reservations about the calculation results in P. J. Karditsas' paper [8], which has investigated the influence of coolant velocity. On the other hand, the analysis above explains why we can reproduce his calculation result just based on Eq. (6). However, Eq. (5) is still useful when the inner diameter of the cooling tube varies with the distance from the core or when considering the finite element analysis.

The concentration of the radiolytic species inside and outside the core are different and we should take this into consideration in our model. See details in part 2.2.

These stiff differential Eq. (6) can be solved using different numerical methods, such as Gear's arithmetic, which is a multistep integration method and useful for systems with a wide range of stiffnesses. We have written our own solver based on this method.

2.2. Input data

The input data for the model are the following: temperature, dose rate, initial concentration, G-value, and flow rate. The reliability of the final results can only be as good as the input data, so in order to get the proper input values, we need to describe the cooling path more explicitly so that we can evaluate the irradiation conditions.

2.2.1. First wall and blanket PHTS in ITER

The cooling water system (CWS) consists of the tokamak cooling water system (TCWS), the component cooling water system (CCWS), the chilled water system (CHWS), and the heat rejection system (HRS). The PHTSs in TCWS are: First Wall and Blanket PHTS (FW/BKT PHTS), Vacuum Vessel PHTS (VV PHTS), Divertor and Limiter PHTS (DIV/LIM PHTS), and Neutron Beam Injection PHTS (NBI PHTS). The coolant in different systems is subjected to different temperatures and irradiation conditions, and which will result in different radiolysis behaviors.

There are eight cooling tubes (named A, B, C, D, E, X, Y, Z) in FW/BKT PHTS. All cooling pipes have the same inner diameter of ~ 65 mm, and the water velocity is 5–6 m/s. The length of the pipes in the ports varies from ~4–5 m, and the remainder of the pipe lengths (~11.3 m) are located outside of the port plugs. Each tube is responsible for several module regions as shown in Fig. 1. For example, tube A is responsible for cooling module regions 10, 11, 12, and 13 while tube Z is responsible for module regions 1, 2, and 3. The detailed cooling path can be found in Molander's review [10]. The cooling path parameters vary with the region in question. Detailed information about the residence times can be found in the ITER nuclear analysis report in 2002 from [11]. In summary, the total average residence time in the Blanket is about 9 s, and 2 s in the high neutron flux regions (at the first wall). The residence time in all the eight tubes is much longer than the time (usually less than 0.1 s) needed to reach steady-state.

The cooling tubes inside the First Wall are connected to the cooling tubes for the Blanket in every individual module. This interconnected