Tritium permeation from the primary helium cooling loop for the ESS target

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Abstract. The tritium permeation from the target cooling primary helium loop to the intermediate water loop through heat exchangers is studied, for the 5 MW operation of the target station at European Spallation Source (ESS). Both bi-metallic and mono-metallic heat exchanger concepts are studied, for the co-current and counter flow cases. The quasi two-dimensional temperature profiles in the helium, in the water and in the metallic barrier separating the two flow regions are calculated. The surface temperature of the metallic barrier facing to the helium side determines the tritium concentration dissolved in this region. The diffusion flux of the surface tritium through the wall thickness is calculated. The permeation rates via these different heat exchanger configurations are compared and a recommendation is made. It is shown that the tritium contamination level in the intermediate cooling loop allows controlled discharge of water to the city sewage system. The methodology presented in this paper can be applied to general engineering analyses of the tritium permeation problems in spallation facilities.

1. Introduction

A 5 MW proton beam will deposit up to 3 MW heat in the rotating tungsten target at European Spallation Source (ESS). The target is primarily cooled by gaseous helium flow and the heat is further transferred to the intermediate water loop via heat exchangers. The impinging proton beam on the target generates hydrogen isotopes in tungsten, which subsequently diffuses to the helium coolant flow, forming hydrogen molecules. The helium is constantly purified during normal operation, and the steady state tritium impurity in the helium loop at ESS is calculated to be 0.074 ppm. The permeation of tritium to the intermediate cooling loop water is a concern for the safe operation of the target cooling systems. In this paper, we calculate the tritium permeation rate from the target cooling helium loop to the intermediate water loop through heat exchangers, for the 5 MW operation of the target station at ESS.

A conventional mono-metallic heat exchanger made of 316L stainless steel is studied for a reference case. The structural material SS316L is chosen for its corrosion resistance in radiation environment. A bi-metallic heat exchanger concept is also studied, to evaluate the additional tritium barrier effect that additional aluminum alloy layer might provide.

Figure 1 shows a schematic diagram of the target cooling circuits. The heat exchanger W001 has the highest flow temperatures, as it transfers heat from the hot helium gas directly from the target to the intermediate cooling system. The W001 accounts for most of the tritium permeation between the two loops. Table 1 lists typical flow parameters for W001, which are available on the market.
Figure 1. A schematic diagram of the target cooling circuit with the heat exchanger W001. Also shown is the quasi-2d differential volume for the thermal analysis of heat exchanger.

Table 1. The typical flow parameters for W001, which are available on the market.

| Parameter                  | Symbol | Value | Unit   |
|----------------------------|--------|-------|--------|
| Mass flux: helium side     | $\dot{m}_h$ | 2.85  | kg·s$^{-1}$ |
| Mass flux: water side      | $\dot{m}_c$ | 7.0   | kg·s$^{-1}$ |
| HTC: helium side           | $\alpha_h$ | 700   | W·m$^{-2}$·K$^{-1}$ |
| HTC: water side            | $\alpha_c$ | 900   | W·m$^{-2}$·K$^{-1}$ |
| Total width of flow contact| $\hat{L}$  | 0.3   | m      |
| Total length of flow contact| $L$       | 2.0   | m      |

2. Quasi two-dimensional tritium permeation

The tritium diffusion at heat exchangers can be simplified to a quasi two-dimensional problem, one for the perpendicular direction to the helium flow and the other for the flow direction of the helium flow. We refer the direction perpendicular to the helium direction be "$x$" and the one along the flow direction be "$z$". The tritium permeation rate is highly correlated to the properties of the wall material and temperature field. Therefore, we first calculate the temperature configuration in the heat exchanger. The heat exchanger in general can be described by a quasi two-dimensional geometry model, which consists of thin flat metal plate separating two flow regions. The caption figure in
Figure 2. Temperature profiles for different heat exchanger wall types and flow configurations. The bi-metallic and mono-metallic wall types are denoted by SS:Al and Fe respectively.

Fig. 1 describes the geometry setup for the differential flow section on zx-plane. The bi-metallic wall made of austenitic steel 316L ("Material 1") and aluminium ("Material 2") separates the two flow regions. The wall thicknesses of Material 1 and Material 2 are respectively given by $\Delta \xi_1$ and $\Delta \xi_2$. For this study, the wall thicknesses of $\Delta \xi_1 = 3$ mm and $\Delta \xi_2 = 1.5$ mm are taken. The mono-metallic heat exchanger case is a special case of the bi-metallic case with $\Delta \xi_2 = 0$. The thermal conductivities of these two wall materials are given by $\kappa_1$ and $\kappa_2$ respectively. The specific heat capacities of the helium and water flows are denoted by $C_{p,h}$; $h$ and $C_{p,c}$; $c$ respectively.

The quasi two-dimensional temperature profile on zx-plane can be analytically calculated by solving the set of differential equations,

$$-\kappa \frac{\partial}{\partial x} T(z,x) = q(z) \quad \text{for} \quad 0 \leq x - \xi \leq \Delta \xi_1 + \Delta \xi_2, \quad (1)$$

$$\frac{d}{dz} T_h(z) = -\frac{q(z) \hat{L}}{m_h C_{p,h}}, \quad \frac{d}{dz} T_c(z) = -\frac{q(z) \hat{L}}{m_c C_{p,c}}. \quad (2)$$

Here, $T(z, x)$ is quasi-2D temperature in the bi-metallic wall. $T_h(z)$ and $T_c(z)$ are respectively the bulk flow temperatures of helium and water along the length of the heat exchanger. The convective heat transfer on the heat exchanger surfaces are represented by $q(z)$. The co-current flow and cross flow configurations are distinguished by setting two different boundary conditions for Eqs. (1) and (2),

Co-current Flow Option : $T_h(z = 0) = T_{h,inlet}$, \quad $T_c(z = 0) = T_{c,inlet}$, \quad (3)

Counter Flow Option : $T_h(z = 0) = T_{h,inlet}$, \quad $T_c(z = L) = T_{c,inlet}$. \quad (4)

For this study, the inlet temperatures of $T_{h,inlet} = 250 \, ^\circ\text{C} (523 \, \text{K})$ and $T_{c,inlet} = 50 \, ^\circ\text{C} (323 \, \text{K})$ for the helium and water flows are taken. Figure 2 shows the one-dimensional temperature profiles for different heat exchanger wall types and flow configurations.

Given the temperature field, the tritium permeation at a metallic wall can be calculated. The local concentration of tritium that is dissolved in the metallic lattice and in equilibrium with the tritium gas at the wall surface facing the helium flow is given by

$$\Phi(z, x = \xi) = K \sqrt{P_3 H}, \quad K = K_0 \exp \left[-\frac{\Delta H_S}{RT}\right]. \quad (5)$$

Here, $K$ is the solubility of tritium and $R$ is the universal gas constant, 8.314 J·mol$^{-1}$K$^{-1}$. The material specific values are the constant $K_0$ and the standard enthalpy of dissolution of tritium
Figure 3. Diffusion flux profiles for different heat exchanger wall types and flow configurations, for the steady tritium impurity level of 0.074 ppm in the helium loop. The annual tritium contamination rate of the water in the intermediate cooling loop is shown on the right.

\[ \Delta H_S. \] In this study, we use the empirical values of \( K_0 \) and \( \Delta H_S \) for the austenitic steel and aluminium, which are compiled in Ref. [1].

The tritium permeation rate can be analytically calculated by solving the Fick's first law,

\[
J(z) = -D(z, x) \frac{\partial \Phi(z, x)}{\partial x}, \quad D(z, x) = D_0 \exp \left[ -\frac{\Delta H_D}{RT(z, x)} \right], \quad (6)
\]

for the surface concentration of tritium atoms \( \Phi(z, x = \xi) \), given by Eq. 5. Here, \( J(z) \) is the diffusion flux, \( D(z, x) \) is the diffusivity and \( \Delta H_D \) is the diffusion activation energy of tritium, which are barrier material specific. In this study, we use the empirical values of \( D_0 \) and \( \Delta H_D \) for the austenitic steel and aluminium, which are compiled in Ref. [1]. We assume the tritium concentration on the wall surface facing the water flow is zero.

Figure 3 shows the one-dimensional diffusion flux profiles for different heat exchanger wall types and flow configurations. Also shown is the annual tritiation rate of the water in the intermediate cooling loop at ESS. The mono-metallic heat exchanger W001 with the co-current flow option results in the least annual tritium contamination of 7 GBq/year, among the different heat exchanger wall types and flow configurations compared. All the four cases satisfy the regulatory requirement of 10 GBq/month and 1 GBq/release. There are also tritium permeation via the heat exchangers W002 and W003. But, the amount of permeated tritium there is pretty much suppressed to a negligible level compared to W001 by orders of magnitudes, due to its much lower flow temperatures.

3. Conclusions and outlook

A co-current flow type mono-metallic heat exchanger made of austenitic steel provides a better tritium barrier between the target primary and intermediate cooling loops. The tritium amounts in the target intermediate water cooling loop is allowed for controlled discharge into the city sewage system, during normal operation.

In the future, sensitivity analyses will be performed for an optimal combination of the heat exchanger parameters, using the analytical model developed for the presented study and advanced CFD simulations.

References

[1] Causey R A, Karnesky R A, and San Marchi C 2012 Tritium barriers and tritium diffusion in fusion reactors Comprehensive Nuclear Materials Vol. 4 (Amsterdam, Netherlands) Elsevier 511