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# Influence of 2D and 3D convection–diffusion flow on tritium permeation in helium cooled solid breeder blanket units

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**Abstract**

Numerical simulation of tritium permeation from breeding zones to the coolant in the helium cooled pebble-bed blanket is performed in this paper. 2D and 3D convection–diffusion models are developed to account for the effects of purge stream convection. Incompressible transient Brinkman model with variable permeability is used in flow calculation, and transient diffusion and convection equations are simulated for the tritium permeation analysis. Tritium partial pressure, concentration and permeation flux are evaluated. The influence of convection on permeation is evaluated under different flow conditions.


*Keywords:* Tritium permeation; Purge convection; Breeding blanket; 2D and 3D model

## 1. Introduction

Tritium permeation to the coolant should be limited in order to minimize economic and safety penalties associated with tritium processing systems. It is therefore very important to estimate tritium permeation under fusion relevant operating conditions. In this paper, the tritium permeation for a typical helium-cooled ceramic breeder pebble bed design is addressed. In a typical reference blanket design, the breeder and the neutron multiplier, such as $Li_4SiO_4$ and beryllium pebble beds, are contained between steel plates (here F82H properties are considered) that are cooled by high pressure helium coolant. The tritium produced in both beds is carried away by helium purge gas, which operates at atmospheric pressure. The first wall and other parts of the blanket are also cooled by high pressure helium gas. There are two main sources of tritium found in the helium coolant. One is permeation into the first wall cooling helium by implantation from the plasma; another source is through the cooling tubes from the breeding zones [1]. Experimental and analytical studies have shown that under ITER-like plasma conditions, tritium saturation phenomena will take place. Tritium inventories due to implantation in plasma-facing materials and tritium permeation through the components to the coolant will be reduced. Thus, tritium permeation

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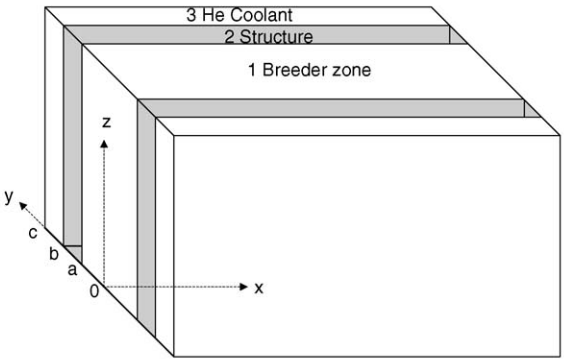


Fig. 1. Schematic view of computational and physical domain.

into the coolant by implantation is negligible compared to other sources with a 2–5 mm thick beryllium protective layer [2].

In this paper, 2D and 3D convection–diffusion models are developed to account for the effects of purge stream convection and the accompanying velocity profile, which is solved from incompressible transient Brinkman equation directly. 2D and 3D transient convection–diffusion equations are simulated for the tritium permeation. Temperature and temperature effects on tritium permeation are taken into consideration by solving the heat transfer equation simultaneously.

## 2. Physics model

The problem is defined in three regions as shown in Fig. 1: a pebble bed breeding region (1) with helium purge gas flowing through it, a coolant tube structure (2) and a helium coolant region (3). The Navier–Stokes equation, convective and conductive heat transfer equations and convective and diffusive mass transfer equations are solved simultaneously in these three regions.

In the model, the purge gas region has a toroidal length of $l = 20$ cm, a pebble bed radial width of $w_1 = 2$ cm and height $h = 1$ m, a structure thickness of $w_2 = 3$ mm, and a coolant channel width $w_3 = 3$ mm. Other operating parameters include a helium coolant inlet temperature of $T_0 = 673$K, nuclear heating $Q_T = 10^7$ w/m$^3$, a uniform tritium production rate $Q_C = 8.5 \times 10^{-6}$ mol/m$^3$ s, He purge gas inlet velocity of $u_0 = 3$ cm/s, and He coolant flows in the same direction with velocity $U = 7.5$ m/s.

In the purge gas region, the wall effect, which reflects the variations of porosity and permeability in the bed near the wall regions, is considered through the Brinkman model incorporating a variable permeability in the flow equation. The governing equation based on the Brinkman model for the velocity distribution of a fully developed flow in a packed bed is [3]:

$$\rho \frac{\partial \mathbf{u}}{\partial t} + \rho \mathbf{u} \nabla \mathbf{u} = \frac{\mu}{\varphi^*} \nabla^2 \mathbf{u} - \nabla p - \frac{\mu \mathbf{u}}{K^*} \qquad (1)$$

$$\varphi^* = \varphi^*_\infty \left\{ 1 + C_1 \exp\left[ -\frac{N_1(w_1/2 - |y|)}{d_\mathrm{p}} \right] \right\},$$
$$\varphi^*_\infty = 0.4, \quad C_1 = 1, \quad N_1 = 2 \qquad (2)$$

$$K^* = K^*_\infty \left\{ 1 + C_2 \exp\left[ -\frac{N_2(w_1/2 - |y|)}{d_\mathrm{p}} \right] \right\},$$
$$K^*_\infty = 1.185 \times 10^{-3} d_\mathrm{p}^2, \quad C_2 = 20, \quad N_2 = 4 \qquad (3)$$

where $\varphi^*$ and $K^*$ are porosity and flow permeability, $\varphi^*_\infty$ and $K^*_\infty$ are the porosity and flow permeability at the bulk of the packed bed. The convection–conduction equation and convection–diffusion equation in region 1 are

$$\rho_1 C_{\mathrm{p}1} \frac{\partial T_1}{\partial t} + \rho_1 C_{\mathrm{p}1} \mathbf{u} \nabla T_1 = \lambda_1 \nabla^2 T_1 + Q_\mathrm{T} \qquad (4)$$

$$\frac{\partial c_1}{\partial t} + \mathbf{u} \nabla c_1 = D_1 \nabla^2 c_1 + Q_\mathrm{c} \qquad (5)$$

The heat transfer equation and mass transfer equation in region 2 and 3 are

$$\rho_2 C_{\mathrm{p}2} \frac{\partial T_2}{\partial t} = \lambda_2 \nabla^2 T_2 \qquad (6)$$

$$\frac{\partial c_2}{\partial t} = D_2 \nabla^2 c_2 \qquad (7)$$

$$\rho_3 C_{\mathrm{p}3} \frac{\partial T_3}{\partial t} + \rho_3 C_{\mathrm{p}3} \mathbf{U} \nabla T_3 = \lambda_3 \nabla^2 T_3 \qquad (8)$$

$$\frac{\partial c_3}{\partial t} + \mathbf{U} \nabla c_3 = D_3 \nabla^2 c_3 \qquad (9)$$

The accurate boundary conditions at the gas-structure interface should ensure both the flux continuity and the concentration discontinuities:

$$c_2 = K P_1^{1/2}, \quad -D_1 \frac{\partial c_1}{\partial n} = -D_2 \frac{\partial c_2}{\partial n} \quad \text{at } y = a \qquad (10)$$

$$c_2 = KP_3^{1/2}, \quad -D_2\frac{\partial c_2}{\partial n} = -D_3\frac{\partial c_3}{\partial n} \quad \text{at } y = b \tag{11}$$

where $K$ is the solubility and $P$ is the tritium partial pressure estimated at the gas side. The tritium partial pressure is calculated by the ideal gas law $P = cRT$. Because of the solubility data [6], calculated concentration at the interface was larger than that in the bulk, therefore, in this paper, the flux at the interface was fixed to be equal to permeated flux.

And the boundary conditions at the symmetry boundary and outer boundary are

$$-D_1\frac{\partial c_1}{\partial n} = 0 \quad \text{at } y = 0, \qquad -D_3\frac{\partial c_3}{\partial n} = 0 \quad \text{at } y = c \tag{12}$$

Diffusivity of tritium in the purge gas and helium coolant is taken from [4]. Since tritium transport in the helium is dominated by the ordinary molecular diffusion, the effective diffusivity is estimated as $D_e = D_{AB}/\tau$, where the ordinary diffusivity is $D_{AB} = (\alpha/P)T^n$ with $\alpha = 4.2 \times 10^{-9}$ atm m$^2$/s for $T_2$ and $\alpha = 4.6 \times 10^{-9}$ atm m$^2$/s for HT, $n = 1.823$ for HT and $T_2$. The tortuosity is evaluated within $1/\varepsilon_1 < \tau < 2/\varepsilon_1$. If the total porosity is 0.4, $\tau$ changes within 2.5 and 5. In the calculation, $\tau$ is taken as 2.5. Sometimes, the effective diffusivity is defined as $D_e = \frac{\varepsilon_1}{\tau} D_{AB}$ [5]. Under this definition, the diffusivity is reduced by a factor of 6, which makes it more difficult for tritium to diffuse.

The physics properties of different materials used in the calculations are shown in Table 1.

Table 1
Physics properties

| | |
|---|---|
| Helium purge | |
| Density | 0.0724 kg/m$^3$ |
| Viscosity | $3.48 \times 10^{-5}$ kg/m s |
| Diffusivity [2] | $2.403 \times 10^{-4}$ m$^2$/s at 673 K |
| Pebble bed | |
| Density | $1.484 \times 10^3$ kg/m$^3$ |
| Conductivity | 1.065 w/m K |
| Heat capacity | $2.22 \times 10^3$ J/kg K |
| F82H | |
| Density | $7.58 \times 10^3$ kg/m$^3$ |
| Conductivity | 29.0 w/m K |
| Heat capacity | 671.8 J/kg K |
| Diffusivity [6] | $D = 8.74 \times 10^{-8} \exp(-13950/RT)$ m$^2$/s |
| Solubility [6] | $K = 0.377 \exp(-26880/RT)$ mol/m$^3$ Pa$^{0.5}$ |
| Helium coolant | |
| Density | 5.80 kg/m$^3$ |
| Conductivity | 0.271 w/m K |
| Heat capacity | $5.192 \times 10^3$ J/kg K |
| Diffusivity [2] | $7.51 \times 10^{-6}$ m$^2$/s at 673 K |

## 3. Numerical results and discussion

### 3.1. 2D model

Because the height of the breeding region is relatively large compared to its width, the problem can be treated as a 2D model. Effects of convective terms on tritium concentration profile and permeation are studied by comparison between the realistic purge flow velocity and the uniform velocity profile. Only half of the model is simulated because of symmetry. Fig. 2 shows the velocity profile in the purge gas region at different locations if the wall effects are considered; as shown, the velocity near the wall reaches four times the inlet velocity.

Fig. 3 shows the calculated tritium partial pressure profile in the breeder region along the purge flow direction in comparison with the no-permeation case. The calculated tritium partial pressure at the outlet is about 0.26 Pa, while it reaches 0.31 Pa if no permeation occurs from the purge gas stream. In addition, there is

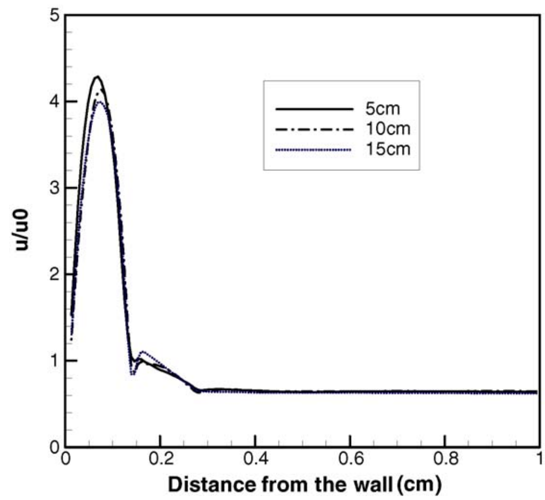


Fig. 2. Velocity variation with distance from the wall.

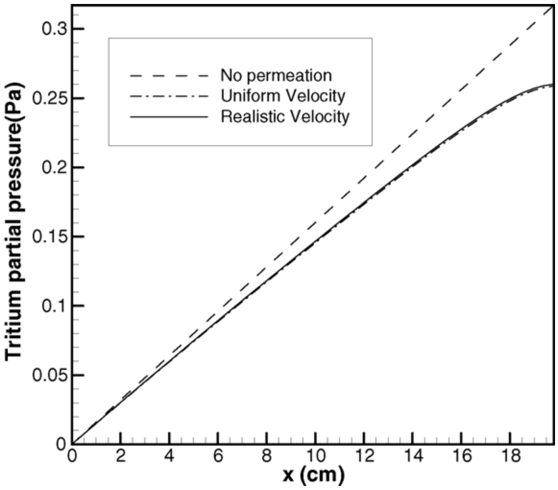


Fig. 3. Average tritium partial pressure along purge gas flow direction.

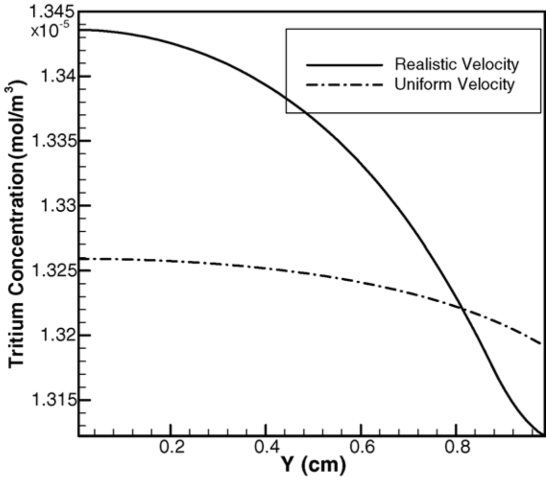


Fig. 4. Tritium concentration distributions at $X = 5$ cm.

a slight difference between the calculated tritium partial pressure profiles for the realistic velocity and the uniform velocity cases. The partial pressure from the realistic velocity profile is higher than that found from the uniform velocity profile. This shows that the jet velocity profile near the wall region in a porous flow has a slight benefit in preventing tritium permeation and results in a slightly higher tritium partial pressure, but in the given conditions, this additional advantage is relatively small.

For a realistic porous flow velocity case, the tritium concentration and partial pressure vary with the $Y$ axes (pebble bed width) direction. Fig. 4 shows the tritium concentration distribution with $Y$ at $X = 5$ cm. The concentration is lower near the wall and higher in the center, while for the uniform velocity case the concentration remains constant except for a small decrease near the wall. The concentration distribution reflects the influence of the velocity profile, but this influence is very small at the parameter ranges studied. Because the purge gas convection has only small effects on temperature distribution, the temperature profile in the breeder region is parabolic. The total permeation in the calculated region is 1.281 mg/day for a realistic porous velocity and 1.283 mg/day in a uniform velocity flow case, nearly 7% of the total production.

To evaluate the convection effect on the tritium permeation, three different inlet velocities are chosen for comparison. The conditions are set to keep the outlet tritium partial pressure the same if no permeation occurs. The results are listed in Table 2. It can be seen from the table that for both realistic and uniform flows,

Table 2
Pressure drop for different inlet velocities

| Inlet velocity (cm/s) | Outlet partial pressure (Pa) | Outlet pressure without permeation (Pa) | Tritium Pressure drop (Pa) |
|---|---|---|---|
| Real flow | | | |
| 1.0 | 0.171 | 0.31 | 0.139 |
| 3.0 | 0.261 | 0.31 | 0.049 |
| 10.0 | 0.302 | 0.31 | 0.008 |
| Uniform flow | | | |
| 1.0 | 0.168 | 0.31 | 0.142 |
| 3.0 | 0.259 | 0.31 | 0.051 |
| 10.0 | 0.299 | 0.31 | 0.011 |

if the inlet velocity is increased, the tritium partial pressure at the outlet increases and approaches the value found in the no-permeation case. This shows that convection plays an important role in reducing tritium permeation. The penalty is in the increase of purge gas hydraulic pressure drop and subsequent pumping power. Certainly, there is room for optimizing the purge gas flow conditions from both points of view.

### 3.2. 3D model for the realistic velocity profile

In the 3D model, due to the computational memory size requirement, the pebble bed height is taken as 2 cm instead of 1 m as in the design. The wall effects from every side are considered.

The integrated average tritium partial pressure along the purge gas flow direction is shown in Fig. 5. The result from the realistic porous flow velocity profile is compared with that calculated based on a uniform velocity profile. As shown, 3D calculation shows a slight increase in tritium permeation reduction using the realistic porous flow. Fig. 6 shows the tritium pressure distribution with *Y* (width) and *Z* (height) at different locations:(a) is the partial pressure distribution near the inlet and (b) is near the outlet. The partial pressure has similar distribution. The lowest pressure appears near the corner of two walls. The asymmetry of pressure distribution is more obvious in the inlet than in the outlet. Still, the pressure difference at the same cross-section is relatively small.

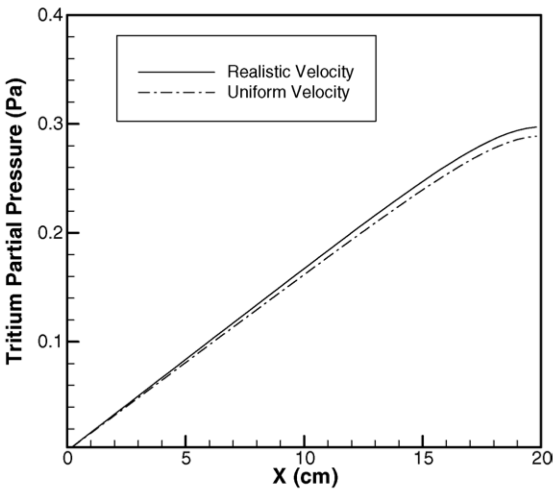


Fig. 5. Averaged tritium partial pressure along the flow direction (3D results).

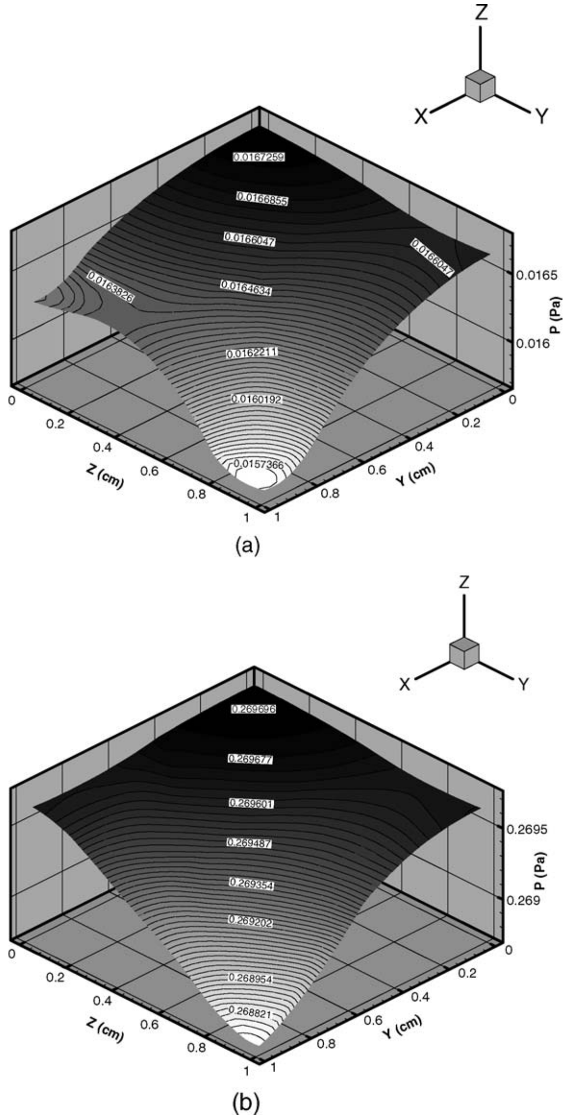


Fig. 6. Tritium partial pressure profile at different flow locations: (a) near the inlet (tritium partial pressure ∼ 0.0165 Pa); (b) near the outlet (tritium partial pressure ∼ 0.269 Pa).

### 3.3. Discussions

Trapping effects are not considered in this model because trapping will delay the flow of atoms in a solid, but will not affect steady state permeation through the

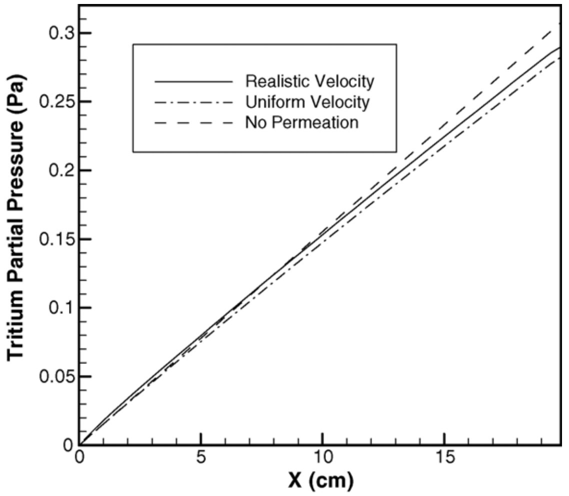


Fig. 7. Average tritium partial pressure along flow direction with lower diffusivity.

wall if the operating temperature is higher than 500 K [6].

The diffusivity of $T_2$ in the purge gas may be overestimated. If diffusivity is five times lower, as defined in [5], the interaction between convection and diffusion will also change the tritium concentration, partial pressure distribution and permeation. Fig. 7 shows the tritium partial pressure along the flow direction. It can be seen that the difference between the realistic flow and the uniform flow becomes larger, and the permeation is smaller due to the lower diffusion coefficient and the tritium partial pressures are closer to the no-permeation condition. In addition, the diffusivity variation should take into account the wall effects. The precise diffusivity is needed to evaluate the convection influence accurately.

## 4. Conclusion

The tritium permeation from the breeder zone to the coolant is simulated for both 2D and 3D models. The tritium concentration, partial pressure and permeation are evaluated for different purge flow conditions. In particular, the advantage of the jet velocity profile for further reducing permeation is estimated by comparing the tritium partial pressures estimated for the realistic gas velocity and the uniform velocity purge flow. The results show no apparent additional benefit until the average purge velocity reaches about 10 cm/s. The influence of convection on permeation is evaluated under different flow conditions. Results show that the permeation cannot be ignored with the low purge velocity. The jet velocity near the wall can reduce the permeation if the tortuosity from the packed bed is to decrease the tritium diffusivity in a porous helium flow system.

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