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CHARACTERISTICS OF HELIUM PURGE FLOW IN SOLID BREEDER PEBBLE BED AND ITS IMPACT ON DESIGN CONSIDERATIONS

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One of the design objectives of helium purge in the solid breeder is to keep the HT partial pressure in the purge system low to minimize the tritium inventory and permeation through the clad. The helium purge flow rate is set at the highest possible value to achieve this criterion. A distinguishable feature of the helium purge flow in a pebble bed design is its velocity jet due to high local porosity near the wall. Thermalhydraulic calculations based on 2-D non-Darcian momentum equations showed that the peak velocity is about 8 times or more higher than the bulk velocity at Reynolds number relevant to solid breeder blanket application. This velocity profile results in reducing the tritium permeation rate through the cald based on the low tritium partial pressure at the wall associated with this peak velocity by a factor of 2 or more.

1. INTRODUCTION

Packed bed is an attractive material form option for both solid breeder and Be multiplier in blanket designs. It offers a large surface area and a relatively short pore flow path for tritium release; it is less likely to crack under thermal stress because of the small size of the particles; and it allows to a significant extent for accommodation of swelling or thermal expansion of the beds due to its porosity and the possibility of particle relative motion. In addition, it provides the potential for active thermal control of its thermal conductivity through gas pressure and/or thermal composition adjustment. This applies in particular to ITER blanket where the solid breeder is separated from the coolant by a layer of Be. A Be packed bed in this case could provide for active control of the adjacent solid breeder temperature and, hence, for power increase accommodation. Issues associated with packed bed including the thermal and hydraulic behavior of helium purge are addressed in the paper. In particular, pressure drop considerations call for minimizing the helium purge flow rate while tritium partial pressure and inventory considerations call for maximizing the flow rate. The trade-off is included in the analysis here.

2. MATHEMATICAL FORMULATIONS

The governing equations used in the present analysis were based on the non-Darcian model for the velocity distribution in an annular cylindrical packed bed[1]. The momentum equation in this model accounts for friction caused by macroscopic shear (Brinkman effect) and for flow inertia (Forchheimer effect). These equations in cylindrical coordinate case can be written as:

For r direction:

$$0 = \left[-\frac{\partial P}{\partial r} + \frac{\partial}{\partial z}\mu_{eff}\frac{\partial u}{\partial z} + \frac{\partial}{\partial r}\frac{1}{r}\left(\frac{\partial}{\partial r}\mu_{eff}\, r\, u\right)\right]$$

$$-(\mu/\kappa)\, u - \frac{\rho C}{\sqrt{\kappa}}\,|u|\,u \qquad (1)$$

For z direction:

$$0 = \left[-\frac{\partial P}{\partial z} + \frac{\partial}{\partial z}\mu_{eff}\frac{\partial v}{\partial z} + \frac{\partial}{\partial r}\frac{1}{r}\frac{\partial}{\partial r}\left(\mu_{eff}\, r\, v\right)\right]$$

$$-\left(\frac{\mu}{\kappa}\right)v - \left(\frac{\rho C}{\sqrt{\kappa}}\right)|u|\,v \qquad (2)$$

where u and v are the velocities in the radial and axial directions and | u | is the absolute value of velocity.

The continuity equation is given as:

$$\frac{1}{r}\frac{\partial}{\partial r}(\rho\, r\, u) + \frac{\partial}{\partial z}(\rho\, v) = 0 \qquad (3)$$

with the non-slip boundary conditions.

Key parameters involved in the momentum equation are the permeability (κ) and the inertia coefficient (C), which depend on the nature of the porous matrix. For a matrix consisting of packed spheres of diameter, d, the permeability and the inertia coefficients are described as[2]:

$$\kappa = d^2\phi^3/\left(175\,(1-\phi)^2\right) \qquad (4)$$

$$C = \left(1.75/\sqrt{175}\right)\phi^{-3/2} \qquad (5)$$

where ϕ is the porosity of the packed bed. For the present analysis, it is assumed that $\mu_{eff} = \mu$, where μ is the fluid dynamic viscosity. To account for the wall effect on the packing, the porosity distribution in the packed bed is required. In the present analysis, a porosity distribution for an annular packed bed suggested by Cheng et al.[3] was assumed. This porosity distribution inside an annular packed bed with outer and inner radii, ro and ri, can be approximated as:

$$\phi=\phi_\infty\{(1+\exp[(r_o-r)/d])\}(r_o-r_i)/2\le r\le r_o$$
$$\phi=\phi_\infty\{1+\exp[-(r-r_i)/d]\}\quad r_i\le r\le(r_o-r_i)/2 \qquad (6)$$

where ϕ_∞ is the porosity at the bulk of the packed bed. The experiments performed at UCLA[4] suggested that ϕ_∞ is about 0.375 for single size bed and 0.82 for binary bed. For a binary packed bed, an equivalent diameter is used in the above equation . Such an equivalent diameter, $\bar{d}_p$, can be defined as[5]:

$$\bar{d}_p=\frac{1}{\sum\frac{w_{fi}}{d_{pi}}} \qquad (7)$$

where w_{fi} ,d_{pi} are the weight faction of particle i and diameter of particle i, respectively.

A sophisticated way to estimate the temperature distributions of the purge gas phase and the solid pebble phase is using a heterogeneous model. The heterogeneous model assigns different energy equations for different phases with the consideration of an interfacial heat transfer between the purge gas and the solid pebble. The ability to predict the accurate temperature distributions using this model depends on the availability of mathematical models and experimental correlations. The difficulties in modeling arise from the existence of interfaces between phases and discretization associated with them. Improper modeling may lead to a grossly inaccurate result. A simple way to solve temperature distribution considers the packed bed as a homogenized system. The energy equation in this homogeneous model is written as follows:

$$(\rho\, C_p)_g\, U\, \nabla T=\nabla\cdot(k_e\nabla T)+Q \qquad (8)$$

where ρ_g , C_{pg}, U, k_e T, and Q denote the gas density, the specific heat of the gas, the velocity vector, the effective thermal conductivity of a packed bed, the average temperature of a packed bed and the volumetric heat generation rate inside the packed bed, respectively. The effective thermal conductivity of a packed bed predicted here is using Kunii and Smith's correlation[6]. The effect of flowing gas on the effective thermal conductivity of a packed bed is also incorporated in the model.

3. NUMERICAL METHOD

The aforementioned differential transport equations are converted into a set of algebraic finite difference equations for the specified grid system using power-law differencing schemes (PLDS)[7]. A non-uniform mesh staggered grid system[7] is used for the packed bed to account for the wall effect . A fine mesh is used close to the wall region, where the porosity variation is large. In the staggered grid system, scalar quantities such a P, μ, κ, etc. are stored at the intersections of grid nodes; velocities are stored at the control volume faces. The resultant discretization equations are solved by a line-iterative method using a tri-diagonal matrix algorithm (TDMA) with alternating sweep direction.

In order to solve the pressure field, an indirect method is needed due to the absence of an equation explicitly governing the pressure. The program uses the "Semi Implicit Method for Pressure Linked Equations" (SIMPLE)[7] to handle the velocity-pressure linkage. In this type algorithm, the pressure is implied by the continuity equation which imposes a compatibility condition on u and v. The method starts with a guessed pressure field, p* as well as a guessed velocity field. Unless the correct pressure field is employed, the resulting velocity field (from momentum equations) will not satisfy the continuity equation even if the starting velocity field is the correct one. The correcting quantities are added into the guessed quantities to obtain the corrected velocity and pressure. The pressure is corrected as implied by the continuity equation and the correlated velocity field is calculated. The sequence continues until convergence is satisfied. A detailed description for this method can be found in Ref. (7).

RESULTS AND DISCUSSION

The velocity distribution was calculated for a single size bed with an average particle diameter of 1 mm and for a binary bed with average particle diameters of 1mm and 0.15 mm. The calculations were performed for a bed thickness of 8 mm and the flow rate of 0.4×10^{-3} m^3/sec, which is typical of the helium purge flow rate for this concept. The model showed that for both beds, the fully developed velocity profiles were obtained at a downstream distance of about 10 particle diameters. These fully developed velocity profiles are summarized in Figure 1 and show a high velocity jet near the wall region due to the her local porosity at that location. This velocity profile is beneficial in a blanket concept since it results in a region near the clad where the local tritium partial pressure would be the lowest, thus minimizing tritium permeation through the clad. In addition, such a velocity profile could enhance the heat transfer at the wall, thus increasing the wall conductance[8]. The velocity jet is thinner and shallower for the binary bed due to the smaller particle diameter.

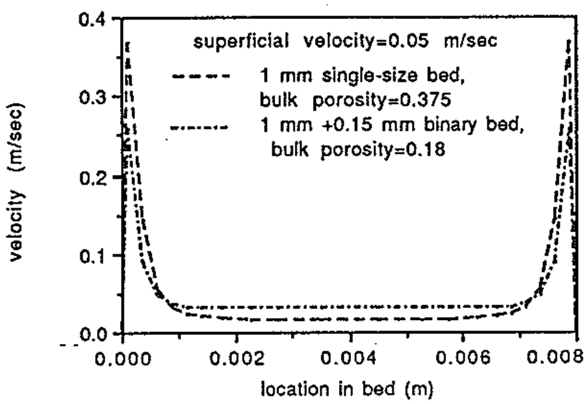

FIGURE 1
Velocity profiles for single-size and binary bed

Figure 2 shows the peak velocity and average velocity for different Reynolds number for a 1 mm single size bed. Both peak and average velocities increase as the Reynolds number increases. However, due to higher frictional forces, the ratio of average to peak velocity approaches 1 at higher Re. For solid breeder blanket design, it is desired to minimize the tritium partial pressure at the wall to reduce the tritium permeation through the clad. For solid breeder blanket application, typical helium flow rate results in a Re of the order of 1. At these low Reynolds numbers, there is a significant benefit at a much higher peak than average velocity in terms of achieving low tritium permeation based on the low tritium partial pressure at the wall associated with the peak velocity while maintaining a reasonable pressure drop based on the average velocity. Since the tritium permeation rate is proportional to the square root of tritium partial pressure[9], the tritium permeation rate to the clad is reduced by a factor of 2 or more (depending on bed characteristics) when compared to the tritium permeation rate based on the average tritium partial pressure at these Reynolds numbers.

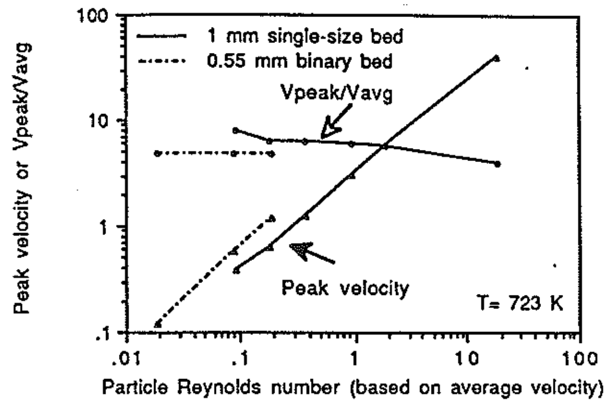

FIGURE 2
Peak velocity and the ratio of peak velocity to average velocity as a function of particle Reynolds number for different beds

The fully developed pressure gradient through the packed bed calculated from the code was compared to the Blake-Kozeny correlation[5]. This correlation was developed for the laminar flow and is rewritten as follows to account for the large system pressure drop which results in the velocity varying along the flow path:

$$\Delta P = 175 \frac{(1-\alpha)^2}{\alpha^3} \frac{\mu_f NRTL}{(\varphi d_p)^2 A_b (P_o + \Delta P/2)} \tag{9}$$

where ΔP is the purge gas pressure drop (MPa), P_o is the purge gas outlet pressure, α is the porosity, φ is the shape factor (= 1 for sphere), d_p is the particle diameter (m), μ_f is purge gas viscosity (Mpa-s), N is purge molar flow rate (mole/s), R is the ideal gas constant , T is purge gas temperature (K), A_b is flow cross sectional area (m^2) and L is purge flow length in m.

To account for the porosity across the bed and, therefore a M-shaped velocity profile across the bed, Eq. 9 is integrated across the bed and rewritten as follows for a plate geometry by assumming that the pressure drop value is small compared with the purge pressure

$$\Delta P = 175 \frac{\mu_f L}{(\varphi d_p)^2} \int \frac{(1-\alpha(y))^2}{\alpha(y)^3} V(y)dy \Big/ \int V(y)\, y dy \tag{10}$$

The pressure drop values predicted by the model are exactly the same as those obtained from the Eq. 10. For a packed bed with 82% packing fraction, binary mixtures with particle diameter ratios greater than 6 are required. To estimate the pressure drop for a helium gas flowing through such a binary packed bed, an equivalent particle diameter, $\bar{d}_p$, estimated from Eq. 7 must be used. Although an additional frictional loss due to Forchheimer effect is included in the model, this effect is not significant at average velocities relevant to the solid breeder blanket application.

Figures 3 and 4 show the calculated pressure drop as a function of purge volumetric flow rate for a plate 8 mm thick and gas outlet pressures of 0.05 MPa and 0.1 MPa respectively. Results for both single-size and binary mixture packed beds are shown in each figure. It can be seen that the pressure drop for the case of the binary mixture is higher than for the single-size case by at least one order of magnitude. The results also indicate that if the average purge pressure has to be minimized because of the design constraints, a single-size bed is perferable. For an outlet pressure of 0.05 MPa in the case, the pressure drop is about 0.002 MPa for a typical helium purge flow rate of 0.4 mol/s per m^3 of solid breeder, resulting in a moderate average purge pressure of about 0.051 MPa. For a binary bed, the pressure drop in this case jumps to about 0.1 MPa. It seems preferable to operate the binary bed case with an outlet pressure of 0.1 MPa. The pressure drop in this case is about 0.06 MPa and the average purge pressure is about 0.13 MPa. Thus, for this type of blanket application, the packed bed characteristics must be carefully chosen by comparing the benefit of higher density and thermal conductivity associated with a binary mixture with the disadvantage of higher pressure drop and, hence, higher purge pressure.

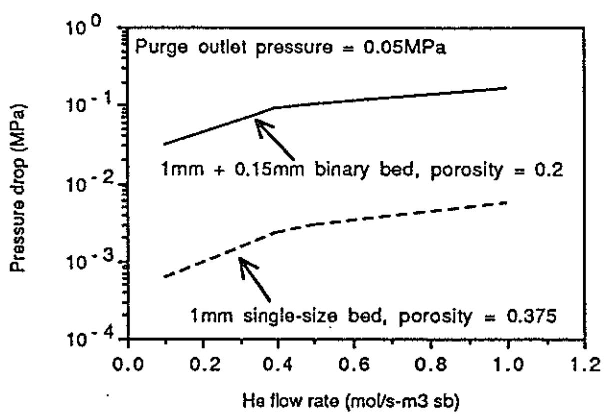

FIGURE 3
Pressure drop as a function of the He flow rate for single-size and binary beds for an outlet pressure of 0.05 MPa

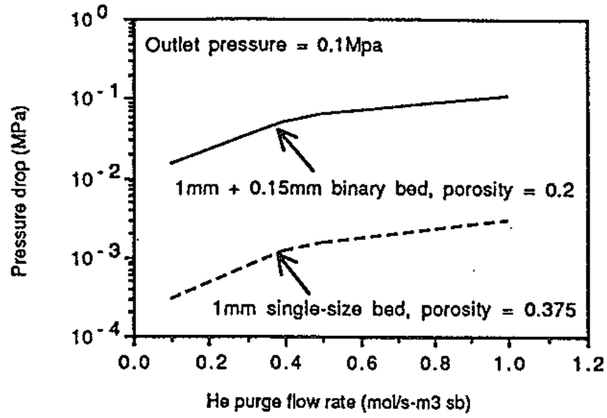

FIGURE 4
Pressure drop as a function of the He flow rate for single-size and binary beds for an outlet pressure of 0.1 MPa

The relationship between pumping power loss (W_p) through the breeder region and the pressure drop is written as:

$$W_p = N_{He}\, RT \ln(1 + \Delta P/P_o) \qquad (11)$$

where N_{He} is the molar He flow rate, R is the ideal gas constant (=8.314 x 10-6 m^3-MPa/mol-k), T is temperature in K and ΔP and P_o are pressure drop and purge gas outlet pressure respectively. The aforementioned equation indicates that for the same bed characteristics, the pumping power is more sensitive to changes in the outlet pressure than the pressure drop as it tends to increase with both decreasing outlet pressure and the corresponding increase in pressure drop.

The results of temperature distributions along the plate using the homogeneous model of a Be/He packed bed temperature distributions are shown in Figure 5 for different average purge velocities. The boundary conditions in the energy equation is that the temperature is fully developed at the exit and the heat is removed from the side of the plate. The pebble bed temperature profile in the bulk region can be seen to be similar for both cases. However, a slightly different temperature profile is found near the wall region. The temperature gradient near the wall becomes less steeper as the average purge velocity increases.

SUMMARY

Velocity profiles, pressure drop and temperature profiles as a function of helium flow rate have been calculated for single-size and binary beds typical of solid breeder blanket application. The velocity profile shows a

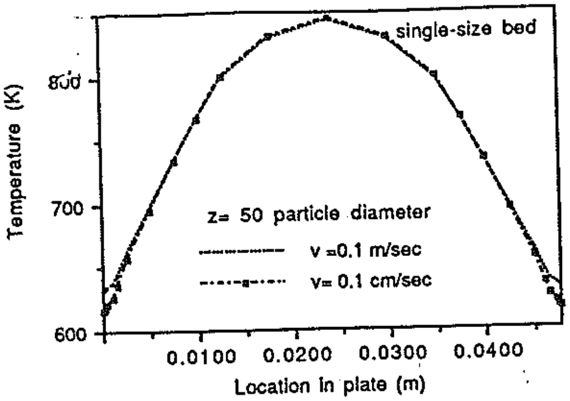

FIGURE 5
Packed bed temperature profiles for different average velocities using homogeneous model

high local velocity region near the walls where the porosity is highest. The thickness of this region is dependent on the particle size and tends to be smaller for binary beds. This particular profile is beneficial resulting in lower tritium partial pressure at the clad and, thus, lower tritium permeation through the clad based on the peak velocity and reasonable pressure drop based on the average velocity. The wall tritium partial pressure is about a factor of 8 (or more) lower than the bulk within the solid breeder blanket application range. In addition, the velocity jet at the wall could enhance the heat transfer at the clad, which would result in higher wall conductance.The pressure drop associated with the binary bed is substantially larger than for the single-size bed. However, the binary bed has advantages of higher packing fraction and thermal conductivity, which have to be weighed carefully against the higher average pressure and pressure drop for solid breeder blanket design application. If purge pressure can be accommodated, a binary bed would be preferable. Conversely, if it is desired to minimize the average purge pressure because of first wall stress and deflection, use of single-size bed would be preferable.

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