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Effects of simultaneous transfer of heat and tritium through Li-Pb or Flibe blanket

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Abstract

Transport of tritium (T) and heat is calculated to estimate the performance of liquid $Li_{17}Pb_{83}$ (Li-Pb) or Li_2BeF_4 (Flibe) as a T-breeder in a fusion reactor blanket. T is bred in such a way of low leak to facilities outside and continuous recovery by a removal system, and heat is transferred through structural walls to He coolant efficiently. In this paper, T permeation in a blanket composed of structural materials and liquid Li-Pb or Flibe is calculated based on data of previous experiment. The effects of T recovery ratio by the outside removal apparatus and fluid-film T diffusion resistance in the liquid blanket on overall T permeation rates are analytically clarified. Design of a liquid blanket with low T leak and high T recovery is discussed here. In addition, possibility in that microbubbles may be generated at interfaces between a liquid blanket and a structural wall is investigated.

Keywords

Liquid blanket, Tritium, Permeation, Lithium lead, Flibe

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1. Introduction

High tritium (T) recovery from a blanket loop and control to low T leak from the system are important issues for the proper design of a liquid breeding blanket system in the future fusion reactor. Promising liquid T breeders are $Li_{17}Pb_{83}$ (Li-Pb) and Li_2BeF_4 (Flibe). Previously, several conceptual designs are proposed as Helium-Cooled Lithium-Lead blanket (HCLL) [1], Dual-Coolant Lithium-Lead (DCLL) [2] and FFHR-2 [3]. At least two necessary conditions of self-sufficient T production of $TBR>1$ and authorized T leak to outside of 1 g/year (≃ 10 Ci/day) should be satisfied in any combinations of breeders and structural materials. In order to satisfy these conditions, development of high T recovery system and low T permeation materials is inevitable. However, the design policy is not sufficiently understood in order to achieve the necessary conditions that should be satisfied in the outside T removal apparatus and low T permeation materials. In this study, necessary conditions for the outside T removal apparatus and low T permeation systems are discussed based on the overall balances of T and heat and several experimental results.

2. Conjugate T transfer from Li-Pb through structural wall to He coolant

We consider a blanket system of a DEMO such as HCLL [1], where a breeder of $Li_{17}Pb_{83}$ (Li-Pb) flows with a comparatively low flow rate, it is bounded by a structural wall of reduced activation ferritic/martensite steel, and He coolant circulates in its outside duct with a high flow rate. When T permeates from liquid Li-Pb flow through structural solid walls to gaseous He coolant, the boundary conditions on the two interfaces denoted by the subscripts, S1 and S2, are described in terms of the third-kind one as follows:

$$j_{T,LiPb\rightarrow He}=-D_{LiPb-T}\left.\frac{\partial c_{LiPb-T}}{\partial y}\right|_{S1}=D_{wall-T}\frac{c_{wall-T,S1}-c_{wall-T,S2}}{l_{wall}}=-D_{He-T_2}\left.\frac{\partial c_{He-T}}{\partial y}\right|_{S2} \qquad \text{(1abc)}.$$

When a steady-state rate of T permeation denoted by $j_{T,LiPb\text{-}He}$ is achieved in any regions and equilibrium is held at the interfaces between Li-Pb and a wall and between the wall and He, the following equations are valid on S1 and S2, respectively:

$$\frac{c_{LiPb-T,S1}}{S_{LiPb-T}}=\frac{c_{wall-T,S1}}{S_{wall-T}} \qquad \text{(2)},$$

$$\frac{c_{wall-T,S2}}{S_{wall-T}}=\left.\left(c_{He-T}R_gT\right)^{0.5}\right|_{S2} \qquad \text{(3)}.$$

The differential diffusion terms on the two right-hand sides in Eq. (1abc) are also described in terms of the mass-transfer coefficient for the flowing LiPb-T system, $k_{LiPb\text{-}T}$, and that for the He-T system, $k_{He\text{-}T}$, which are familiar to the chemical engineering terminology and are defined as follows:

$$j_{T,LiPb\rightarrow He} = k_{LiPb-T}\left(c_{LiPb-T,bulk} - c_{LiPb-T,S1}\right) = k_{He-T}\left(c_{He-T,S2} - c_{He-T,bulk}\right) \quad \text{(4ab).}$$

Eliminating $c_{wall\text{-}T,S1}$ and $c_{wall\text{-}T,S2}$ after combining Eqs. (1)-(4) leads to the following relation for the T transfer in the conjugate system of the Li-Pb flow, a structural wall and a He flow:

$$j_{T,LiPb\rightarrow He} = \left(\frac{S_{wall-T}D_{wall-T}/l_{wall}}{\dfrac{S_{wall-T}D_{wall-T}}{l_{wall}S_{LiPb-T}k_{LiPb-T}}+1}\right)\left(\frac{c_{LiPb-T,bulk}}{S_{LiPb-T}} - \left(R_g T_{S2}\right)^{0.5}\left(c_{He-T,bulk} + \frac{j_{T,LiPb\rightarrow He}}{k_{He-T}}\right)^{0.5}\right) \quad \text{(5).}$$

Usually, $k_{He\text{-}T}$ is much larger than $k_{LiPb\text{-}T}$, and the last bracket of Eq. (5) is approximated to $(R_g T_{bulk} c_{He\text{-}T,bulk})^{0.5} = p_{He\text{-}T,bulk}^{0.5}$. In other words, the mass-transfer resistance in the He side is neglected. The first term of the denominator in Eq. (5) is a constant called by the dimensionless Biot number, Bi_T, to define the rate-determining step of the overall T transfer in the conjugate system of Li-Pb and a solid wall, which is defined as follows:

$$Bi_T = \frac{S_{wall-T}D_{wall-T}}{l_{wall}S_{LiPb-T}k_{LiPb-T}} = \frac{\delta_{LiPb}S_{wall-T}D_{wall-T}}{l_{wall}S_{LiPb-T}D_{LiPb-T}} \quad \text{(6).}$$

The Biot number of Eq. (6) is defined as the ratio of two resistances for the conjugate T transfer; $S_{LiPb\text{-}T}k_{LiPb\text{-}T}$ for Li-Pb and $S_{wall\text{-}T}D_{wall\text{-}T}/l_{wall}$ for the solid wall. When $Bi_T >> 1$, the rate-limiting step of T transfer is diffusion in Li-Pb. On the contrary, when $Bi_T << 1$, the step is that in wall. The right-hand side of Eq. (6) is also rewritten in terms of a boundary layer thickness of the Li-Pb flow, δ_{LiPb}, in place of $k_{LiPb\text{-}T}$. On the other hand, the mass-transfer coefficient of $k_{LiPb\text{-}T}$ can be well estimated by the following correlations according to different flow patterns [4]:

$$Sh\left(=\frac{k_{LiPb-T}d_e}{D_{LiPb-T}}\right) = 0.023\left(\frac{\rho_{LiPb}u_{LiPb}d_e}{\mu_{LiPb}}\right)^{0.8}\left(\frac{\mu_{LiPb}}{\rho_{LiPb}D_{LiPb-T}}\right)^{0.4} \quad \text{for turbulent convection flow (7a),}$$

$$Sh\left(=\frac{k_{LiPb-T}L}{D_{LiPb-T}}\right) = 0.56\left(\frac{L^3 g\beta(T_W - T_{bulk})}{vD_{AB}}\right)^{0.25} \quad \text{for natural convection flow (7b),}$$

$$Sh\left(=\frac{k_{LiPb-T}d}{D_{LiPb-T}}\right) = 3.66 - 4.18 \quad \text{for laminar convection flow} \quad \text{(7c).}$$

The hydrodynamic equivalent diameter of d_e in Eq. (7a) is determined as $d_e=2L_1L_2/(L_1+L_2)$ for the rectangular duct. When natural convection is dominant in the Li-Pb flow, Eq. (7b) is used to evaluate $k_{LiPb\text{-}T}$. Thus the overall T permeation rate for the conjugate system of Li-Pb and the solid wall is estimated using Eq. (5) and any of Eqs. (7a)-(7c).

Fig. 1 shows our experimental and calculation results of the overall H_2 permeation rate from a static Li-Pb layer through an α-Fe wall to Ar purge gas. Calculation is made under the condition where the diffusion equation of H in the $Li_{17}Pb_{83}$+αFe+Ar conjugated system is solved numerically. The details of the calculation as well as the experimental method are described in our previous papers [5-7]. As seen in the figure, the mass-transfer resistance through the static Li-Pb layer is around 100 times larger than the α-Fe wall. Therefore, the rate-limiting process of the present system is considered H diffusion through Li-Pb. However, it is expected that the $\delta_{Li\text{-}Pb}$ value in a fluidized Li-Pb becomes thinner. In other words, the rate-determining step depends on the *Sh* number. **Table 1** shows the values of the Bi_T number for several combinations of liquid breeders and structural materials. The analysis for the Flibe blanket is shown in Appendix 2. As seen in the values in Table 1, the mass-transfer resistances for several combinations of Li-Pb and solid walls become comparable. Therefore, two resistances should be taken into consideration by using the equations derived in our present paper.

The overall T material balance in a Li-Pb breeding blanket with a form of a slit flow is described as follows:

$$W_{LiPb}\frac{dc_{LiPb-T,bulk}}{dz}=\iint \phi_n\sigma_{Li}\frac{N_{Li}}{N_A}dL_1dL_2-\int j_{T,LiPb\rightarrow He}dL_2 \qquad (8),$$

where dz is a differential length along the Li-Pb flow direction, and dL_1 and dL_2 are two differential lengths in the directions vertical to the flow one. In especial, dL_2 is the differential length in contact with $j_{T,LiPb\text{-}He}$. The integration on dL_2 is carried out in the range of the contact surface area, and that on dz is performed from inlet to outlet. It is assumed that T permeation occurs only from the Li-Pb flow to one He side. The other side is faced on a first wall region, and T permeation to the first wall side is ignored because of simplicity. Then, the overall T transfer rate included in Eq. (5) is assumed constant along the flow direction.

The differential equation of Eq. (8) can be solved by using the boundary conditions as follows:

$$z=0 \qquad c_{LiPb\text{-}T,bulk}=c_{T,in} \qquad (9a),$$

$$z=L \qquad c_{LiPb\text{-}T,bulk}=c_{T,out} \qquad (9b).$$

Our strongest interest is how much ratio of T generated in a blanket permeates through the secondary He coolant flow or how much ratio of T generated can be recovered by an outside removal apparatus from the Li-Pb breeder. Therefore, we correlated the results in terms of the permeation ratio of R_{perm} defined as follows:

$$R_{perm}=\iint j_{T,LiPb\rightarrow He}dL_2dz\Big/\iiint \phi_n\sigma_{Li}\frac{N_{Li}}{N_A}dL_1dL_2dz \qquad (10).$$

The denominator of the right-hand side of Eq. (10) is equal to the total T generation rate in the blanket. When a steady-state condition on T concentration is achieved for a Li-Pb blanket loop, the value of $1\text{-}R_{perm}$ corresponds to the ratio of T recovered by the outside removal apparatus to the total T generation rate. The value of R_{perm} is calculated numerically in the present study.

Fig. 2 shows effects of the dimensionless operational parameters of α and β defined in the nomenclature and another parameter of $E_{recovery}$ on R_{perm}. The last parameter is the efficiency of T recovery by the outside apparatus per once-through operation, $E_{recovery}$, defined as follows:

$$E_{recovery} = 1 - c_{T,in} / c_{T,out} \qquad (11).$$

When the blanket system is operated under a condition where the value of $\frac{S_{wall-T} D_{wall-T} A_{wall}}{W_{LiPb} S_{LiPb-T} (1 + Bi_T) l_{wall}} (= \alpha)$ is much smaller than unity, the R_{perm} value is approximated to the following relation:

$$R_{perm} \cong \alpha \left\{ \frac{1}{E_{recovery}} - (0.5 + \beta) \right\} \qquad \text{when } a \ll 1 \qquad (12).$$

The permeation area of A_{wall} included in the definition of α is equal to LL_2. In the case of the HCLL blanket [2], the value of α=1.6 is estimated with the use of l_{wall}=3mm, A_{wall}=5.2x10^{4}m^2, $S_{wall-T}D_{wall-T}$=6.9x10^{-11}mol/msPa$^{0.5}$ and Bi_T=10 for F82H [8] and W_{LiPb}=0.068m^3/s and S_{LiPb-T}=1.0x10^{-3}mol/m^{3}Pa$^{0.5}$ for Li-Pb [11]. Judging from Fig. 2, almost all T generated in Li-Pb permeates from the Li-Pb flow to the He flow unless a permeation protection film. This means that the outside recovery apparatus attached in a Li-Pb flow plays no important role. From the viewpoint of T safety, overall T leak rate should be lowered down to an authorized T release rate limit of 1g/year (or 10Ci/day). Since the T generation rate under the steady-state operation of DEMO is demanded to be 1.6MCi/dayGW, the R_{perm} value should be greater than 10^{-5}. In order to achieve that, the wall condition of $S_{wall-T}D_{wall-T}A_{wall}/l_{wall}(1+Bi_T)$<1.4x10^{-9} mol/sPa$^{0.5}$ is necessary. When an oxide film such as Al_2O_3 or a metal coating such as Au or Cu is coated on the downstream side of the structural wall to reduce T transfer from Li-Pb to He, the permeation reduction factor (*PRF*) = 1.2x10^6 is necessary. The value has never been achieved by any low-permeation materials experimented previously. It results in R_{perm} = 8.0x10^{-4} for the case of realistic *PRF* = 10^3. Consequently, the T recovery in the He side is necessary at any rate to lower down to the authorized release limit from the viewpoint of T safety.

3. Heat transfer from breeder through wall to He coolant

Variations of temperature along the flow directions of Li-Pb and He are analyzed in a similar way to the overall T transfer in the HCLL blanket. Heat of E_{Li-n} per ^{6}Li(n,α)T reaction is generated in Li-Pb and is transferred to the He coolant. When Li-Pb flows in parallel with the He one, the heat balance equations in the two flows of Li-Pb and He coolant are described as follows:

$$W_{LiPb} \rho_{LiPb} c_{P,LiPb} \frac{dT_{LiPb,bulk}}{dz} = \iint \phi_n \sigma_{Li} \frac{N_{Li}}{N_A} E_{Li-n} dL_1 dL_2 - \int q_{LiPb \to He} dL_2 \qquad (13),$$

$$W_{He}\rho_{He}c_{P,He}\frac{dT_{He,bulk}}{dz} = \int q_{LiPb\to He}\,dL_2$$

(14).

Rates of heat transfer per unit area from the Li-Pb flow through the structural wall to the He coolant, $q_{LiPb\text{-}He}$, are described in terms of the two heat-transfer coefficients of the Li-Pb flow side and the He flow side, h_{LiPb} and h_{He}, and a thermal conductivity of the wall, λ_{wall}, as follows:

$$q_{LiPb\to He} = \frac{T_{LiPb,bulk} - T_{He,bulk}}{1/h_{LiPb} + l_{wall}/\lambda_{wall} + 1/h_{He}} \qquad (15).$$

The h_{LiPb} and h_{He} values for the turbulent convection flow are also determined by the Dittus-Boelter equation [4]. For examples, the following values are estimated; h_{LiPb}=6x10^{3}W/m^{2}K (λ_{LiPb}=19W/mK [12]) when W_{LiPb}=0.056m^3/s [1], λ_{wall}/l_{wall}=1.1x10^{4}W/m^{2}K (λ_{wall}=32.5W/mK [13]) for F82H, h_{He}=7x10^{3}W/m^{2}K (λ_{He}=0.21W/mK [4]) when W_{He}=1.3x10^{4}Nm^3/s [1]. Thus, the three thermal resistances are comparable in the LiPb-He system.

Combining Eqs. (13) and (14) and integrating it from inlet to outlet results in the following overall heat balance equation under the assumption of constant physical properties:

$$W_{LiPb}\rho_{LiPb}c_{P,LiPb}\left(T_{LiPb,out} - T_{LiPb,in}\right) + W_{He}\rho_{He}c_{P,He}\left(T_{He,out} - T_{He,in}\right) = \iiint \phi_n\sigma_{Li}\frac{N_{Li}}{N_A}E_{Li-n}\,dL_1dL_2dz \qquad (16).$$

As seen in Eq. (16), the total enthalpy flows of Li-Pb and He increase linearly from the inlet to the outlet. A set of Eqs. (13)-(16) gives temperature distribution in the HCLL blanket. If heat remaining in Li-Pb at the blanket outlet of HCLL is not utilized for outside heat use and only heat transferred to He is utilized through steam turbine to produce electricity, the ratio of the net He-side heat use to the total heat generation, $R_{Q,He}$, is defined as follows:

$$R_{Q,LiPb\to He} = W_{He}\rho_{He}c_{P,He}\left(T_{He,out} - T_{He,in}\right) \Big/ \iiint \phi_n\sigma_{Li}\frac{N_{Li}}{N_A}E_{Li-n}\,dL_1dL_2dz \qquad (17).$$

Combination of Eqs. (13)-(17) leads to the following solutions:

$$R_{Q,LiPb\to He} = \frac{N_{LiPb}}{N_{LiPb}+N_{He}} - \left\{\frac{N_{LiPb}\left(1+\gamma N_{He}+\gamma N_{LiPb}\,T_{He,in}/T_{LiPb,in}\right)}{\left(N_{LiPb}+N_{He}\right)^2} - \gamma\right\}\left\{1-\exp\left(-\left(N_{LiPb}+N_{He}\right)\right)\right\} \qquad (18).$$

Fig. 3 shows calculation results of $R_{Q,LiPb\text{-}He}$ as a function of the two number of transfer units of N_{LiPb} and N_{He} and a parameter of γ that are defined in the nomenclature. It is found that $R_{Q,LiPb\text{-}He}$ mainly depends on N_{LiPb} and the effects of N_{He} and γ are small. The condition of $N_{LiPb}>10$ is preferable for high heat utilization in a fusion reactor system.

4. Effects of interface inventory

When a liquid with high surface tension, *e.g.*, $Li_{17}Pb_{83}$ eutectic alloy, contacts with metallic or SiC walls, there is possibility in that micro-bubbles are generated due to low wettability. If the concentration of T dissolved in liquid blankets is lower than the saturation concentration or if the vapor pressure is lower than the saturation one, bubbles are not generated at the interface between liquid and flat solid walls thermodynamically. However, when a liquid Li-Pb of high surface tension contacts with rough solid surfaces with small curvature, there is possibility in that microbubbles are generated at the interface even under the under-saturation condition. The critical radius, r_{crit}, is estimated by applying the following Kelvin equation to Li-Pb:

$$r_{crit} = \frac{2v_{m,LiPb}\sigma_{LiPb}}{k_B T \ln\left(p / p_{saturation} \right)} \quad (19).$$

The Li-Pb vapor pressure, $p_{saturation}$, is calculated by the equation:

$$p_{saturation} = 1.5 \times 10^{10} \exp\left(-\frac{22900}{T} \right) \text{ [Pa]} \quad (20).$$

When concave surface showing a minus curvature of r_{crit} contacts with liquid, microbubble is generated and grows even under the under-saturation condition. **Figure 4** shows the relation between the under-saturation ratio defined by $S(=p/p_{saturation})$ and $-r_{crit}$. Consequently, even if the under-saturation ratio is less than 1/10, microbubbles can be generated around a concave region with small curvature, which is smaller than 0.01 μm. When a diameter of a microbubble generated is smaller than the critical diameter, the bubble disappears from thermodynamic instability. On the contrary, the diameter is larger than the critical one, the bubble grows. The microbubble is too small to observe, because its diameter is under micrometer. The problem is whether microbubble is generated or not and whether the inventory at the interface increases or not. Even if the microbubble is generated, the effect of microbubble can be ignored when the interface properties does not change and the inventory does not change. Figure 1 shows an example our experimental results of the overall H permeation for Li-Pb and α-Fe system. The experimental permeation rate are well simulated by our calculation where no microbubble is generated at the interface and the steady-state permeation rate is expressed by the product of diffusivity and solubility of H in Li-Pb.

5. Conclusions

Two dimensionless equations are derived for predicting T permeation ratio and heat recovery ratio from a fluidized liquid breeder of $Li_{17}Pb_{83}$ or Flibe to He coolant. The results were correlated in terms of a dimensionless number of Bi_T, two dimensionless parameters of

α, β for T permeation, two dimensionless numbers of N_{LiPb} and N_{He} and a dimensionless parameter of γ. Demand for achieving two necessary conditions of low T permeation to the blanket system outside and high heat recovery are discussed. The results were applied to a HCLL blanket system using Li-Pb and FFHR-2 using Flibe. It was found that the T permeation is serious problem for any combinations of Li-Pb or Flibe and structural materials. Design conditions to achieve low T permeation and high heat recovery were given based on the present analysis. Although there is possibility in that microbubbles are generated at the interfaces between liquid blanket and solid walls, our experimental result showed no additional T inventory at the interfaces.

Nomenclature

Bi_T	dimensionless parameter to define the ratio of T diffusion resistance in solid wall to fluid-film T transfer resistance (Eq. (5) for Li-Pb and Eq. (A6) for Flibe) [-]
c_{LiPb-T}, c_{wall-T} or c_{He-T}	T concentration in Li-Pb, solid wall or He [mol/m^3]
d_e	hydrodynamic equivalent diameter [m]
D_{LiPb-T}, D_{wall-T} or D_{He-T}	T diffusivity in Li-Pb, solid wall or He [m^2/s]
E_{Li-n}	energy generated per ^{6}Li(n,α)T reaction [J]
$E_{recovery}$	efficiency of T recovery of outside removal apparatus defined as $1-c_{T,in}/c_{T,out}$ [-]
$j_{TLiPb-He}$	T mass flux from LiPb flow to He flow [mol-T/m^{2}s]
k_{LiPb-T} or k_{He-T}	mass-transfer coefficient of T transfer in Li-Pb or He [m/s]
l	thickness of solid wall [m]
L	characteristic length of flow duct [m]
N_A	Avogadro's number [particles/mol]
N_{Li}	number density of ^{6}Li [particles/m^3]
N_{LiPb}	dimensionless number of transfer unit in Li-Pb side defined by $A_{wall}/W_{LiPb}\rho_{LiPb}c_{P,LiPb}\left(1/h_{LiPb}+l_{wall}/\lambda_{wall}+1/h_{He}\right)$ [-]
N_{He}	dimensionless number of transfer unit in He side defined by $A_{wall}/W_{He}\rho_{He}c_{He}\left(1/h_{LiPb}+l_{wall}/\lambda_{wall}+1/h_{He}\right)$ [-]
$p_{saturation}$	vapor pressure [Pa]
R_{perm}	ratio of T permeation to T generation [-]
$R_{Q,LiPb-He}$	ratio of heat recovered by He to generated in Li-Pb defined by Eq. (17) [-]
S_{LiPb-T} or S_{wall-T}	Sieverts' solubility constant of T in Li-Pb or solid wall [mol-T/m^{3}Pa]
u_{LiPb}	averaged Li-Pb flow velocity [m/s]
v_m	molecular volume [m^3]
W_{LiPb}	volumetric Li-Pb flow rate ($=u_{LiPb}L_1L_2$) [m^3/s]
dz	differential length along Li-Pb flow direction [m]

Greek symbols

α	dimensionless parameter defined as $\alpha = S_{wall-T} D_{wall-T} A_{wall} / W_{LiPb} S_{LiPb-T} l_{wall} (1+Bi_T)$
β	dimensionless parameter defined as $\beta = W_{LiPb} S_{LiPb-T} p^{0.5}_{T_2,He} \Big/ \iiint (\phi_n \sigma_{Li} N_{Li} / N_A) dL_1 dL_2 dz$
γ	dimensionless parameter defined by $\gamma = W_{LiPb} \rho_{LiPb} c_{P,LiPb} T_{LiPb,in} \Big/ \iiint \phi_n \sigma_{Li} N_{Li} E / N_A dL_1 dL_2 dz$
δ	boundary layer thickness [m]
ϕ_n	neutron flux [neutrons/m^{2}s]
σ_{LiPb}	surface tension of Li-Pb [N/m]
σ_{Li}	cross-sectional area of ^{6}Li(n,α)T reaction [m^2]
subscripts	
bulk	bulk flow
LiPb	$Li_{17}Pb_{83}$
S	interface
T	tritium
wall	wall of structural material

Appendix

A.1. *Analysis of R_{perm} under the condition where T is generated in a blanket uniformly*

The overall T material balance of Eq. (8) with use of Eqs. (5) and (12) can be reduced in terms of the three parameters of α, β and $E_{recovery}$ to the following relation:

$$R_{perm} = 1 - \frac{E_{recovery}(1+\alpha\beta)(1-e^{-\alpha})}{\alpha\{1-(1-E_{recovery})e^{-\alpha}\}} \qquad \text{(A1).}$$

The design values of $\iiint (\phi_n \sigma_{Li} N_{Li} / N_A) dL_1 dL_2 dz$=160g/day for 1GW heat power, W_{LiPb}=0.068m^3/s [9], S_{LiPb-T}=1.02x10^{-3}mol/m^{3}Pa$^{0.5}$ [4] gives the value of $\beta = 0.035$ under the condition of $p_{T2,He} = 0.1$ Pa.

A.2. *Definition of Bi_T number for Flibe and T permeation flux*

When the chemical condition of Flibe in a blanket is controlled at reduction atmosphere by Be, the chemical form of T dissolved in Flibe is considered T_2. However, hydrogen molecules are affected by solid boundaries under different chemical conditions [13], there is a case of atomic hydrogen. When tritium is present as T_2 molecular form [14,15], the overall T permeation rate is described as follows:

$$j_{T,Flibe\rightarrow He} = k_{Flibe-T}\left(c_{Flibe,bulk} - c_{Flibe,S1}\right) = \frac{D_{wall-T}}{l_{wall}}\left(c_{wall,S1} - c_{wall,S2}\right)$$

(A2).

The equilibrium at the two interfaces of S1 and S2 is described as follows:

$$\frac{c_{Flibe,S1}}{H_{Flibe-T}} = \left(\frac{c_{wall,S1}}{S_{wall-T}}\right)^2 \qquad \text{(A3),}$$

$$\frac{c_{wall-T,S2}}{S_{wall-T}} = p_{H_2,He}{}^{0.5}\Big|_{S2} \qquad \text{(A4).}$$

Then, eliminating the interfacial values at S1 and S2 leads to the following equation:

$$j_{T,Flibe\rightarrow He} = \frac{S_{wall-T}D_{wall-T}p_{T_2,He}{}^{0.5}}{l_{wall}}\left[\sqrt{\left(1+Bi_T\right)^2 + 2\left(\frac{c_{Flibe,bulk}}{H_{Flibe-T_2}p_{T_2,He}} - 1\right)} - \left(1+Bi_T\right)\right] \quad \text{(A5).}$$

The Biot number for Flibe is given by the following equation:

$$Bi_T = \frac{S_{wall-T}D_{wall-T}}{2l_{wall}k_{Flibe-T}H_{Flibe-T}p_{T_2,He}{}^{0.5}} \qquad \text{(A6).}$$

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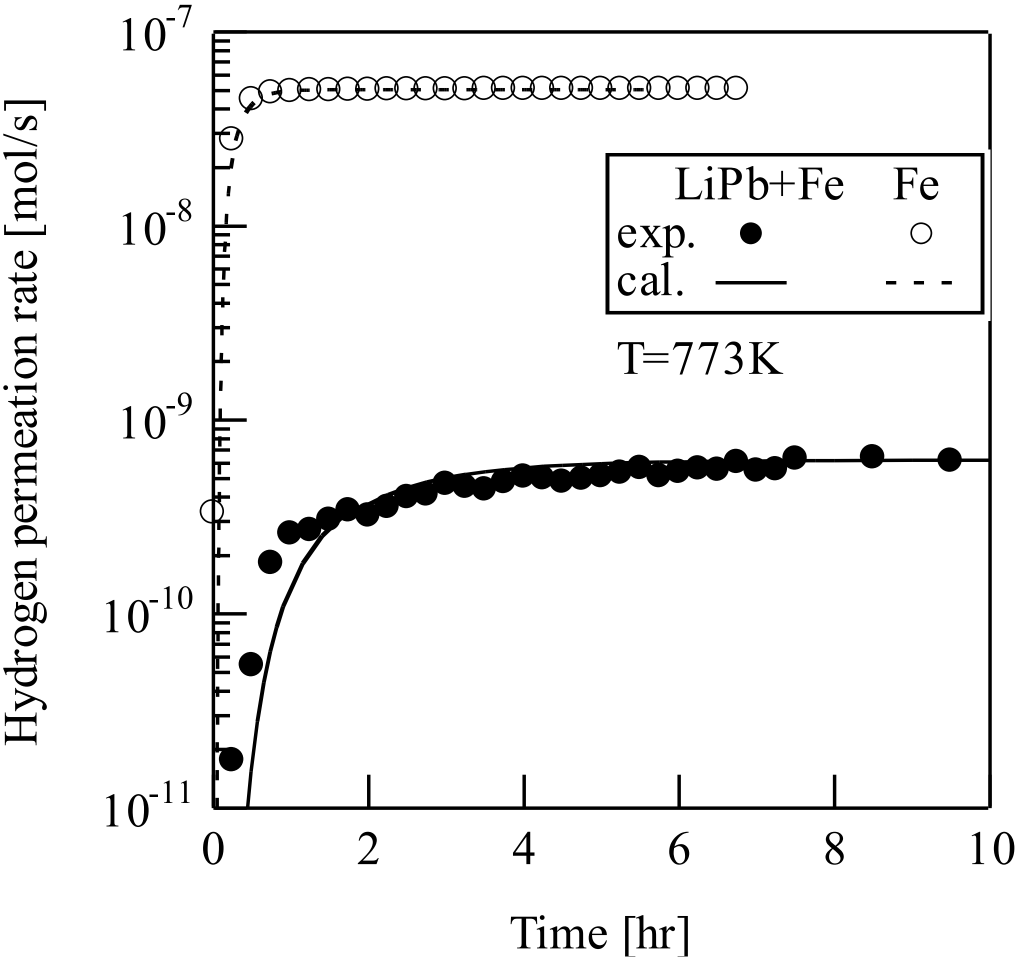
Figures Caption

Fig. 1 Comparison of experimental H_2 permeation rate through Li-Pb placed on α-Fe with calculation result

Fig. 2 Relationship among T permeation ratio of R_{perm}, permeation parameter of α (β=0.056) and T recovery efficiency of $E_{recovery}$

Fig. 3 Relationship between $R_{Q,LiPb\text{-}He}$ and N_{LiPb} as a function of N_{He} and γ

Fig. 4 Relationship between under-saturation ratio and concave curvature of crack



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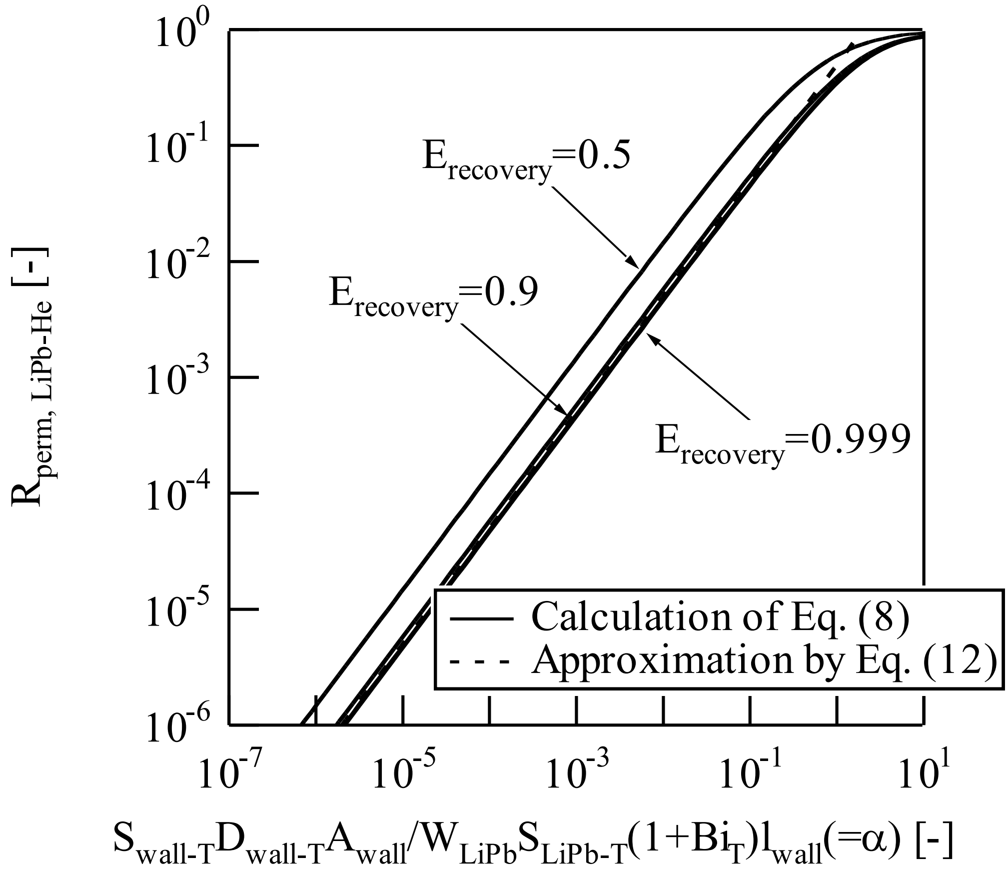

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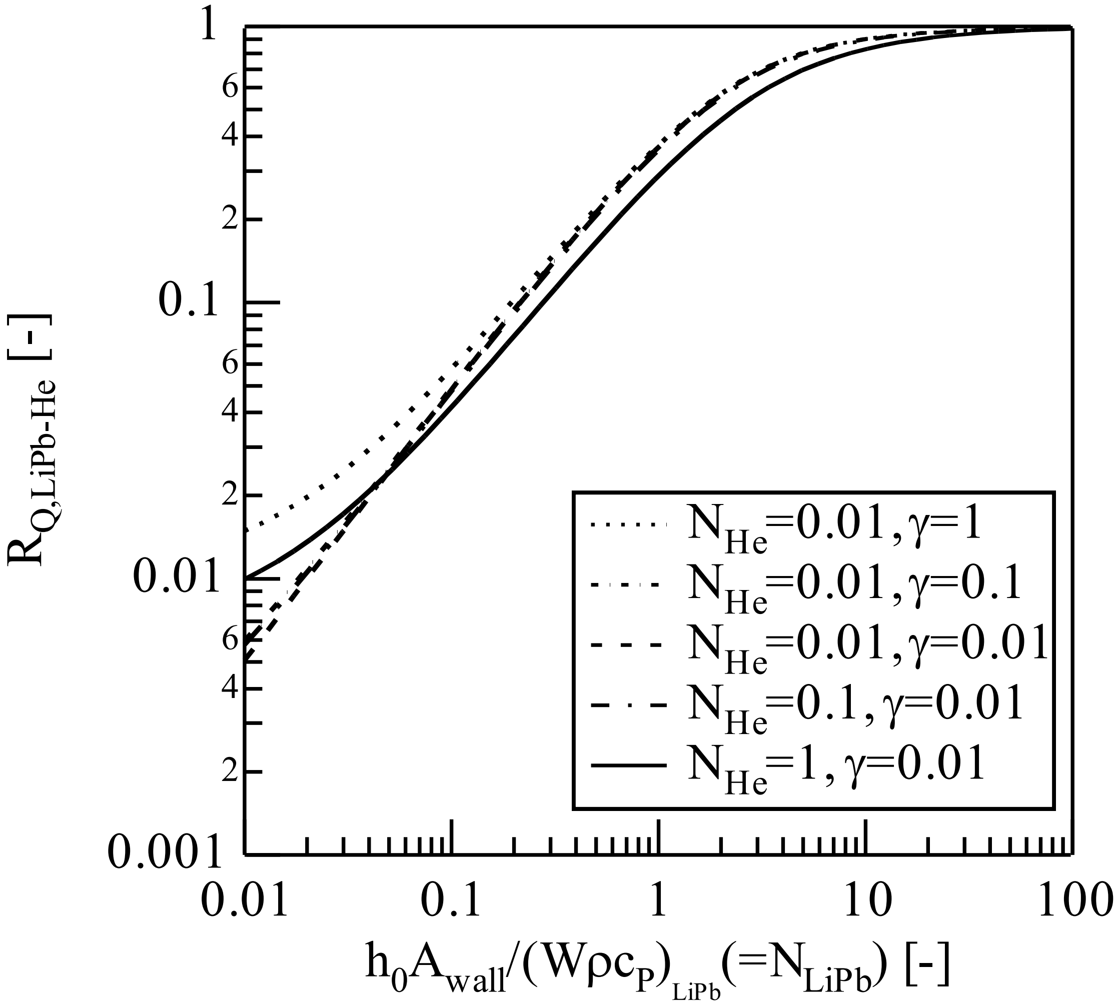

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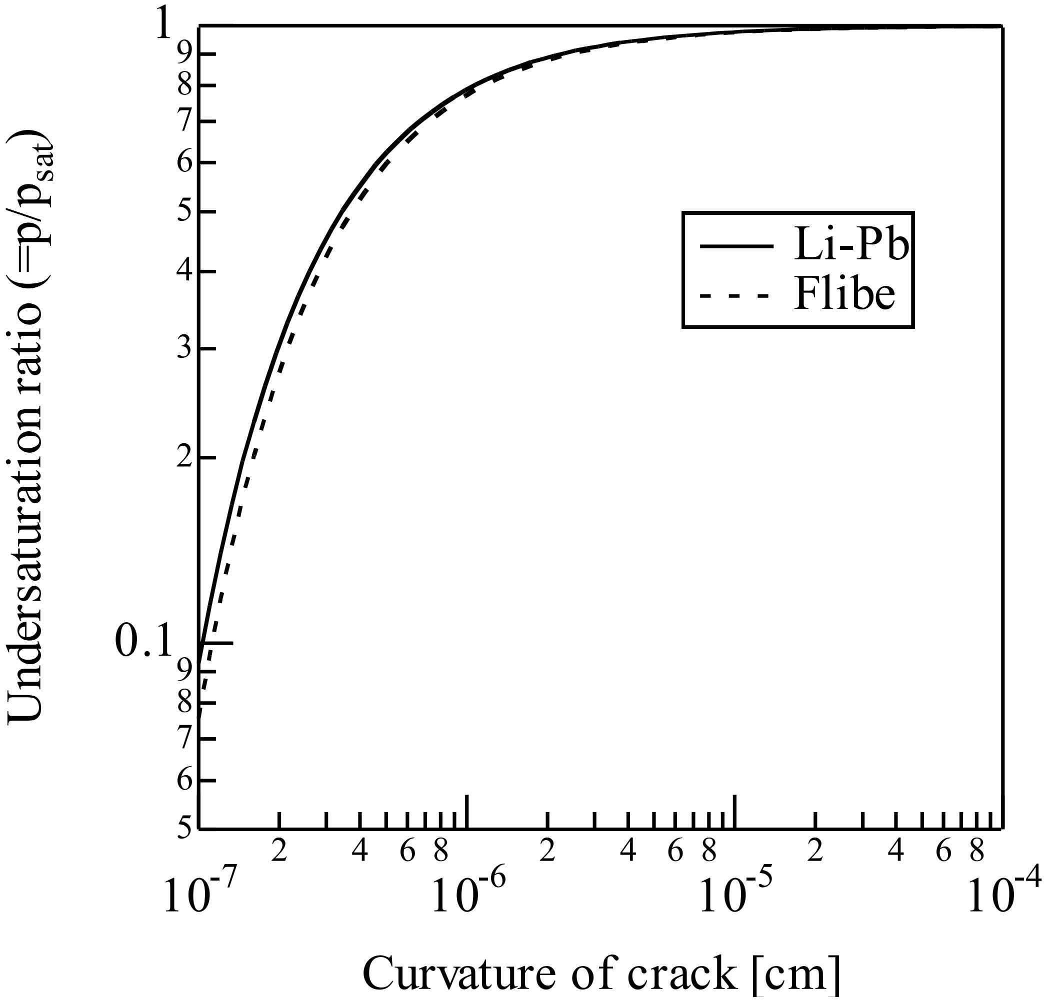

Fig. 4 Relationship between under-saturation ratio and concave curvature of crack

Table 1 Biot number of T transfer for combination of several blanket materials

Breeder	Structural material	Temperature	$S_{wall-T}D_{wall-T}$	$S_{breeder-T}D_{breeder-T}$	Bi_T
$Li_{17}Pb_{83}$	F82H8)	500°C	$6.93x10^{-11}$mol/msPa$^{0.5}$	$9.68x10^{-11}$mol/msPa$^{0.5}$	7.2/Sh
$Li_{17}Pb_{83}$	SiC9)	800°C	$4.06x10^{-8}$mol/ms*2)	$2.60x10^{-10}$mol/msPa$^{0.5}$	6.4/Sh
Flibe	V-4Cr-4Ti10)	500°C	$5.0x10^{-8}$mol/msPa$^{0.5}$	$4.50x10^{-13}$mol/msPa$^{0.5}$	$1.1x10^{6}$/Sh
Flibe	F82H8)	500°C	$6.93x10^{-11}$mol/msPa$^{0.5}$	$4.50x10^{-13}$mol/msPa$^{0.5}$	$1.1x10^{6}$/Sh

*1) l_{wall}=3mm, $de_{breeder}$=30mm, $Sh=de_{breeder}/l_{breeder}$ are assumed.

*2) Since the pressure dependence of permeation is different from the square-root rule, ($S_{SiC-H}D_{SiC-H}$) value at $p_{T2}=1x10^5$ Pa is used for the calculation of Bi_T.