Forefront of liquid metal technologies for fusion reactors

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Abstract. Fusion reactor is an innovative power plant, which is necessary for a sustainable society. The important issue is the development of key components, i.e. tritium breeding blanket and divertor. Liquid metal Li and Pb-16Li are candidate tritium breeders, which also function as a reactor coolant. Liquid Sn is a promising coolant of liquid surface divertor, which is responsible for power exhaust and impurity removal through guided plasma exhaust in magnetic plasma confinement fusion reactors. The design studies on the liquid breeder blanket and the liquid surface divertor are being conducted toward fusion DEMO reactor. The chemical behaviours of liquid metals have been studied to improve the tritium transfer and the material compatibility. This paper reviews recent studies on the liquid metal technologies for the fusion reactors.

1. Introduction
Fusion reactor is an innovative power plant, which is necessary for a sustainable society. The important issue is the development of key components, i.e. tritium (T) breeder blanket and divertor. The blanket is essential component being in charge of T breeding and energy conversion. Liquid metals lithium (Li) and lead lithium alloy (Pb-16Li) are candidate T breeders. Liquid surface divertor has been proposed to overcome the large heat load on the divertor surface. Self-cooling liquid blanket concepts have been studied both for magnetic confinement fusion reactors [1] and inertial fusion reactors [2, 3], since the blanket structure can be simplified according to their multi-function such as a T breeder, a T transporter, a reactor coolant and a shielding material. The divertor is responsible for power exhaust and impurity removal through guided plasma exhaust in magnetic confinement fusion reactors. Liquid tin (Sn) is a promising coolant of the liquid surface divertor. The design study on the liquid blanket and liquid surface divertor are being conducted toward fusion demonstration (DEMO) reactor.

The chemical behaviours of the liquid metals have been studied to clarify and improve T transfer and material compatibility. Table 1 presents major thermophysical properties of liquid metal Li, Pb-16Li and Sn [4-7]. The excellent heat transfer characteristics of the liquid metals are strong advantage. However, the electrical conductivity induces large pressure drop by magnetohydrodynamic (MHD) effect under magnetic field [4]. The use of ceramic materials as electrical insulation can mitigate the MHD effect. The chemical compatibility of structural steels and ceramic materials with the liquid metals is important issue. In the present paper, recent studies on the liquid metal technologies for the fusion reactors are reviewed.

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2. Liquid breeder blanket

Figure 1 shows a schematic diagram of liquid breeder blanket of fusion reactors and mass balance of T fuel cycle under a steady-state operation. High energy neutrons are produced through deuterium-tritium (D-T) fusion nuclear reaction expressed as;

\[ D + T \rightarrow He + n \]  \hspace{1cm} (1)

The number of T atom supplied for the fusion reaction is given as “S [1/s]” in Fig. 1. The quantity of T consumed by its burning in the fusion reaction is then given as “D [1/s]”, and the burning ratio “D/S” is known as approximately 5%. The remaining T is exhausted with He through the divertor. Neutrons produced by fusion reaction are captured by Li installed in the blanket, and T is then produced. Natural Li consists of two stable isotopes: Li-6 (\(^{6}\)Li) and Li-7 (\(^{7}\)Li). The T production by \(^{6}\)Li and \(^{7}\)Li is expressed as;

\[ ^{6}\text{Li} + n \rightarrow He + ^{3}\text{H} \]  \hspace{1cm} (2)

\[ ^{7}\text{Li} + n \rightarrow He + ^{3}\text{H} + n' \]  \hspace{1cm} (3)

High concentration of \(^{6}\)Li in Li promotes the T breeding. The T breeding by Pb-16Li is also good, since Pb functions as a neutron multiplier. T produced in the liquid blanket are transferred in the blanket loop and recovered in the T recovery system. In this paper, tritium breeding ratio (TBR: B) of the blanket and tritium recovery ratio (R) are defined as;

\[ B = \frac{T \text{ produced by blanket}}{T \text{ consumed by fusion reaction}} \]  \hspace{1cm} (4)

\[ R = \frac{T \text{ recovered from blanket loop}}{T \text{ produced in blanket}} \]  \hspace{1cm} (5)

The coverage of the blanket around plasma is given as “C”. The quantity of T produced in the blanket is then expressed as “CBD [1/s]”. The recovery of T from liquid Li is not easy since the chemical affinity between Li and T is large. The T recovery from liquid Pb-16Li is easier than that from liquid Li due to the chemical activity of Li is small in the alloy. The ratio of T loss in the fuel cycle is given as “L”. T escape from the reactor system and the accumulation in the reactor materials are the reason for the loss of T. However, the loss can be controlled by the use of ceramic materials as a T permeation barrier [8]. The T self-sufficiency can be achieved at the condition expressed as;

\[ S=1-L(S-D+RCBD) \]  \hspace{1cm} (6)

Table 1. Major thermophysical properties of liquid metal Li, Pb-16Li and Sn [4-7].

|         | Melting point [K] | Density [kg/m³] | Thermal conductivity [W/mK] | Viscosity [mPas] | Pr number |
|---------|------------------|-----------------|----------------------------|-----------------|----------|
| Li [5]  | 453              | 481 at 800K     | 53.7 at 800K                | 0.344 at 800K   | 0.027 at 800K |
| Pb-16Li | 508              | 9170 at 773K    | 15.1 at 673K [6], 26.8 at 773K [7] | 1.29 at 773K [6] |
| Sn      | 505.1            | 6761 at 800K    | 33 at 800K                  | 0.0094 at 800K  |
In the T fuel cycle, D and Li are depleted. However, these elements are practically unlimited energy sources, since they can be recovered from seawater. The abundance of D in seawater is 0.015 mol%, and it is recovered by means of isotopic separation from seawater [9]. The abundance of Li in seawater is 0.17 mg/L, and it can be recovered by adsorbent [11] or electrodialysis [10]. Thermal energy generated in the liquid blanket is transferred to the secondary loop through the heat exchanger, and is finally used to generate electricity by the steam turbine.

### 3. Important function of liquid surface divertor

The divertor is responsible for power exhaust and impurity removal through guided plasma exhaust in magnetic plasma confinement systems. The divertor is exposed to high-energy neutron and large heat load about 5 to 10 MW/m² [12]. The critical issue for the divertor development is to mitigate the damage of its structural material by large heat load. The design study on solid divertor is being conducted for the development of fusion DEMO reactors [12]. The liquid surface divertor, in which the surface of the structural material is covered and protected by the liquid metal coolant, is also being proposed [13]. In this concept, the recycling of plasma particles may be suppressed due to their adsorption and transport by the flowing liquid metal coolant. Therefore, the plasma performance is also improved. Thus, the liquid divertor concepts have some strong advantages, which can achieve longer lifetime of the divertor material and better plasma performance.
The vapour pressure of liquid metal is an important factor as the coolant of liquid surface divertor, since the metal vapour degrades the plasma performance. The vapour pressure of Li and Sn is expressed as follows [14]:

\[ P_{v, Li} = 10.75 \times 10^9 e^{-\frac{153,800}{RT}} \quad (455-1500K) \] (7)

\[ P_{v, Sn} = 65.42 \times 10^9 e^{-\frac{309,200}{RT}} \quad (1424-1638K) \] (8)

The vapour pressure of Pb-16Li was also obtained in the literature [14]. Figure 3 shows the vapour pressure of these liquid metals at the temperature of divertor operation. The vapour pressure of liquid Sn is much lower than that of Li and Pb-16Li. Therefore, liquid Sn is a promising coolant of the liquid divertor, since its vapour pressure is extremely low.

4. Chemical compatibility issue on liquid metal system

4.1. Liquid Li blanket

Reduced activation ferritic martensitic (RAFM) steel (e.g. F82H [15], JLF-1 [16] and Eurofer97 [17]) is the candidate structural material of the liquid breeder blanket and the liquid surface divertor. Table 2 presents the chemical compositions of some RAFM steels.

|                | Cr | W  | C   | Mn | V   | Ta | Fe  | Ref. |
|----------------|----|----|-----|----|-----|----|-----|------|
| F82H (IEA HEAT)| 7.65| 2  | 0.09| 0.16| 0.16| 0.02| Bal. | 15   |
| JLF-1 (JOYO-HEAT)| 9  | 1.94| 0.09| 0.49| 0.2 |     | Bal. | 16   |
| Eurofer97      | 9  | 1.1 | 0.11| 0.4 | 0.15-0.25| 0.06-0.09| Bal. | 17   |

It is known that the corrosion of steels in liquid metal is caused via dissolution of steel compositions such as Fe and Cr [18]. The corrosion of RAFM steels in liquid Li is negligibly small when the purity of liquid Li is high, since the solubility of Fe and Cr in high-purity liquid Li is quite small. However, non-metal impurities such as nitrogen and oxygen promote the corrosion [19, 20]. The corrosion is promoted according to the formation of unstable chemical compounds as;
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\[ 2\text{Li}_3\text{N} + \text{Fe} \rightarrow \text{Li}_9\text{FeN}_2 + 3\text{Li} \]  \hspace{1cm} (9)

\[ 5\text{Li}_3\text{N} + \text{Cr} \rightarrow \text{Li}_9\text{CrN}_5 + 3\text{Li} \]  \hspace{1cm} (10)

\[ 4\text{Li}_2\text{O} + \text{Fe} \rightarrow \text{Li}_9\text{FeO}_4 + 3\text{Li} \]  \hspace{1cm} (11)

\[ 2\text{Li}_2\text{O} + \text{Cr} \rightarrow \text{LiCrO}_2 + 3\text{Li} \]  \hspace{1cm} (12)

These chemical reactions are caused on the steel surface, and Fe and Cr are depleted from the steel surface. The steel surface then reveals a porous structure. The erosion occurrence on the corroded surface is then induced at flowing condition. This behavior is called as “corrosion-erosion” [18]. The chemical potential of carbon in liquid Li is also important parameter, since the steel surface is decarburized in liquid Li when the carbon potential is extremely low [21]. Thus, the corrosion of RAFM steel in liquid Li can be mitigated by the chemical control of non-metal impurities.

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**Figure. 3** Vapour pressure of Li, Pb-16Li and Sn.
4.2. Liquid Pb-16Li blanket

The corrosion of RAFM steels in liquid Pb-16Li is caused by the dissolution of the steel compositions (i.e., Fe and Cr) as the same as other heavy liquid metals such as Pb and Pb-Bi [18]. The solubility of the metals in liquid Pb-Li is explained as;

\[ C_{S,M}^{\text{Pb-Li alloy}} = (1-x)C_{S,M}^{\text{Pb}} + xC_{S,M}^{\text{Li}} \]  

(13)

where \( x \) is the chemical activity of Li in the alloy, which is determined by the Li concentration. \( C_{S,M}^{\text{Pb-Li alloy}} \), \( C_{S,M}^{\text{Pb}} \) and \( C_{S,M}^{\text{Li}} \) are the solubility of metals in the liquid Pb-Li, liquid Pb and liquid Li, respectively. It is known that the solubility of metals in the Pb composition, \( C_{S,M}^{\text{Pb}} \), is not promoted by the non-metal impurities. However, the solubility of metal in the Li composition, \( C_{S,M}^{\text{Li}} \), can be larger, when the concentration of non-metal impurities in the alloy is higher as explained by the equations (9-12) in the section 4.1. Therefore, the corrosion is promoted by nitrogen and oxygen dissolved in the alloy [22]. The corroded surface then reveals a porous structure. The porous surface is mechanically eroded by the corrosion-erosion in flowing Pb-16Li little by little [23]. The dissolution corrosion in Pb-16Li can be mitigated by the use of anticorrosion layer described in section 4.4.

4.3. Liquid Sn divertor

The corrosion of RAFM steels in liquid Sn is caused by the formation of intermetallic compounds [24, 25]. Figure 4 shows the cross-sectional surface SEM image of RAFM steel JLF-1 (Fe-9Cr-2w-0.1C) and the results of EDX analysis after exposure to liquid Sn at 773 K for 262 h. The steel surface was covered by the intermetallic compounds as shown in Figure 4(a). The intermetallic compounds consist of Fe and Sn as shown in Figure 4(b). The layer can be classified into two layers (i.e., Sn-rich outer layer and Fe-rich inner layer). The outer layer must be formed by the precipitation of FeSn. The inner layer is formed by the corrosion and called as reaction layer [24]. The reaction layer had the thickness of approximately 20 \( \mu \)m. The thickness of the layer after the exposure to liquid Sn for 250 h at 873 K was approximately 100 \( \mu \)m [24]. These results indicate that the corrosion intensity is strongly influenced by the temperature of liquid Sn. The corrosion of RAFM steel in liquid Sn can be mitigated by the use of anticorrosion layer described in the next section.

![Figure 4](image)

**Figure 4.** Results of corrosion test of RAFM steel JLF-1 in liquid Sn at 773 K for 262 h (a) cross sectional SEM image and (b) results of EDX analysis on intermetallic compound layer.
4.4. Anticorrosion layer

The corrosion of RA FM steels in liquid metals Pb-16Li and Sn can be mitigated by the use of anticorrosion layer, since the direct interaction between the liquid metals and the steels is suppressed by the layer. Therefore, oxide layers and oxide ceramic coatings, which can function as the anticorrosion layer in the liquid metals, have been explored. The chemical stability of these materials in the liquid metals are theoretically evaluated by the thermodynamic calculations. The chemical potentials of oxygen in liquid metal Pb-16Li is expressed as follows;

\[
\phi_{O,Pb-16Li} = \Delta G_{f, Li_2O} - 2\Delta G_{f,(Pb-17Li)} + RT\ln\left(\frac{C}{C_s}\right) \quad [kJ/mol] \tag{14}
\]

\[
\frac{G_{Li(Pb-17Li)}}{kJ/mol} = -60.122 + \frac{1778.2}{T} \quad (713<T[K]<1013) \tag{15}
\]

where \( C \) is the oxygen concentration, \( C_s \) is the oxygen solubility, \( R \) is the gas constant, \( T \) is the temperature, \( \Delta G_{f, Li_2O} \) is the Gibbs free energy for formation of \( Li_2O \) and \( \Delta G_{f,(Pb-17Li)} \) is the excess Gibbs energy of mixing Li into Pb-17Li [10]. In the same way, the oxygen potential in liquid Sn is expressed as follows;

\[
\phi_{O,Sn} = \frac{1}{2} \Delta G_{f, SnO_2} + RT\ln\left(\frac{C}{C_s}\right) \quad [kJ/mol] \tag{16}
\]

where \( \Delta G_{f, SnO_2} \) is the Gibbs free energy for formation of \( SnO_2 \). Figure 5 shows the Gibbs free energy for formation of various oxides and the oxygen potential of liquid metals when \( C/Cs \) in equations (14) and (16) is 0.01. The oxygen potential of liquid Pb-16Li is rather low. Therefore, limited types of oxides can survive in liquid Pb-16Li. It is known that \( Al_2O_3 \) layer survive in liquid Pb-16Li and function as the anticorrosion layer [26]. It is also recently demonstrated that the corrosion of steels in liquid Sn can be mitigated by the \( Al_2O_3 \) layer [27].

![Figure 5. Oxygen potential of liquid Pb-16Li and Sn and Gibbs free energy for formation of oxides.](image-url)
5. Conclusions
Major conclusions are follows; (1) The liquid breeder blanket is the key component for tritium breeding and energy conversion of fusion reactors. Liquid metal Li and Pb-16Li are candidate tritium breeders. Their thermophysical properties and chemical behaviors were reviewed in this paper. The material compatibility of liquid Li with RAFM steel JLF-1 is good, though the chemical control of non-metal impurities such as nitrogen and oxygen dissolved in liquid Li is necessary. The corrosion in liquid Pb-16Li is caused by the dissolution of steel’s compositions such as Fe and Cr. The corroded surface is mechanically eroded by flowing Pb-16Li. (2) The liquid surface divertor is proposed to overcome large heat load on the divertor surface. Liquid Sn is a promising coolant of the liquid surface divertor due to its extremely low vapour pressure. The important issue of the liquid Sn divertor is the corrosion of structural materials. The corrosion of RAFM steel is caused by the formation of intermetallic compounds. The alloying corrosion is strongly influenced by the temperature. (3) The chemical stability of oxides in liquid metals was reviewed in this paper. Excellent corrosion resistance of Al2O3 in liquid Pb-16Li and liquid Sn was introduced.

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