A preliminary study on the feasible design of bionic blanket concept

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ABSTRACT

A bionic concept originating from the mechanism of gastric mucosa protecting a gastric wall from corrosion by gastric acid is creatively proposed, with the intention of finding a new way to reduce the corrosion of insulation coatings in liquid metal blankets. A compatible fluid barrier that mimics the function of gastric mucosa is used to prevent the flowing liquid metal from contacting the inner wall of a loop pipeline. The design of the bionic structure and the control of the barrier fluid are the most critical and difficult. A single-channel simulation is performed using Computational Fluid Dynamics (CFD) analysis to evaluate the effect of a compatible fluid barrier on separating the liquid lithium and insulation coating. The results show that the compatible fluid barrier can completely cover the inner wall of the pipeline within which the liquid metal is flowing, indicating that the bionic design can eliminate the corrosion of insulation coatings with flowing liquid lithium. Based on this, a compatible fluid barrier is investigated with multiple conditions, including the coverage area and film thickness, by changing the velocity ratio of the lithium to the barrier fluid, the shape of the inlet port, and the curvature radius of the bend pipes. In addition, an S-shaped pipe is confirmed to be completely corrosion free. This bionic concept is aimed at all corrosive liquid metals, and this work only starts with the extreme case of pure lithium. This work is expected to provide a preliminary feasibility basis for anti-corrosion design for a pipeline with dual fluids.

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1. Introduction

A blanket is one of the key components of a fusion reactor, and a blanket plays the role of neutron shielding, tritium breeding, and energy conversion in a reactor system. In a blanket, the breeder reacts with neutrons to produce tritium, while the coolant takes away the heat in the blanket and conducts it to the secondary cooling water. Most breeders need coolants such as water and helium to transfer heat. Liquid metal (including pure lithium and lithium alloys) has the functions of a breeder and a coolant at the same time (Akiba et al., 2010). Among the main types of blankets, solid breeder blankets are easy to implement with good control (Liu et al., 2014), but they have a relatively low thermal efficiency and a complicated refueling process. Thus, liquid metal breeder blankets have attracted increasing attention due to their advantages, including high heat conversion efficiency, good geometric adaptability, high tritium breeding ratio (TBR), and online tritium extraction (Sze & Mattas, 1997; Wong et al., 2006). Nevertheless, there are two main issues that greatly restrict the use of liquid metal blankets, especially when pure lithium is used. The first issue lies in the severe corrosion to the insulation coating caused by liquid lithium (Huang et al., 2010; Muroga & Pint, 2010), and the second issue is that magneto-hydrodynamic (MHD) effects will occur when magnetic fields are imposed on flowing liquid lithium without insulation coating adhering to the inner wall of the blanket pipe (Hulin et al., 2019; Smolentsev et al., 2010). There are many studies on the MHD effect (Chen et al., 2014; Mistrangelo & Bühler, 2016; Mistrangelo & Bühler, 2017; Yan et al., 2020; Zhang & Zikanov, 2015), but none of them can completely solve this problem. When using insulation coatings, the state-of-the-art solution is to deposit a thin film layer of a long-life insulation coating on the structural materials, such as Al₂O₃, Y₂O₃, and Hf₂O₃ (Muroga, 2012; Terai et al., 1996). These oxides have comparatively good chemical stability with liquid lithium, and to some extent, they are considered to achieve a dynamic equilibrium through the corrosion-redeposition process. Although this method can greatly reduce the MHD pressure drop, the dynamic balance of the corrosion-redeposition process will eventually break up, leading to a severe reduction in the operational...
lifetime of the insulation coatings. As long as the insulation coating is slightly damaged, the MHD pressure drop will increase significantly (Li et al., 2018; Pint et al., 2004). Up to the present, the Er₂O₃ coating has exhibited the most promising behaviors, with a maximum insulation lifetime of only about 1000 hours (Muroga et al., 2007; Suzuki et al., 2013). Another research direction is to use a sandwich structure of “metal layer-insulation coating-metal pipe wall” to protect the insulation coating (Hotta, 2000). This method uses the compatibility of liquid lithium and metal to isolate the insulation coating from the liquid lithium, thereby protecting the insulation coating from corrosion. However, the preparation of this structure is extremely difficult, and the service life of the surface metal layer is limited (Chopra & Smith, 1988; Vitkovsky et al., 2002).

There is a natural contradiction that inorganic compounds must be used as insulation coating, although they may undergo a strong corrosive effect in liquid lithium. As a result, determining how to deal with the contradiction requires careful consideration. Surprisingly, the answer to this contradiction can be found by studying the structure of an animal’s stomach. For example, the stomachs of humans and animals can digest a variety of foods within a short time, even including the stomachs of prey, but these stomachs are not self-digested by the acids. Although the gastric juice is acidic enough to corrode the stomach wall, the gastric mucosa can secrete bicarbonate and form a mucus-bicarbonate barrier that protects the gastric wall from gastric acid erosion (Evtikhin et al., 1992; Jensen, 1976). This principle provides a bionic model for the application of insulation coating in liquid metal breeder.

With the present research, there are the problems of corrosion and magnetic fluid effect, no matter what kind of liquid metal is used. The concepts developed in this work can solve or alleviate these two problems. Among the existing liquid breeders, lithium is the material with the strongest chemical reaction activity, and it is the material that is the easiest to obtain. This work starts with the most extreme pure lithium in order to make this concept have a wider scope of application. The intention of this work is to use a similar mechanism to create a liquid barrier between liquid lithium and the insulation coating, in which the liquid barrier is compatible with both the liquid lithium and the insulation coating. Since this is a preliminary study, the effect of magnetic fields is not being considered at this moment. By adopting a two-layer structure design, the barrier fluid is continuously injected from the outer pipe into the inner pipe (like a flow channel insert) via small channels on the inner pipe. In this way, the barrier fluid adheres to the surface of the insulation coating to form a liquid film, preventing liquid lithium from coming into contact with the insulation coating, and thereby obtaining anti-corrosion protection for the insulation coating. Moreover, the barrier fluid can be replenished as needed like the gastric mucosa, so that the liquid film can maintain dynamic stability, thereby ensuring long-term and stable protection of the insulation coating.

2. Research design

To achieve the anti-corrosion protection for the insulation coating, it is necessary to completely cover the insulation coating with a compatible fluid barrier by means of a thin film, thereby completely preventing the contact of liquid lithium with the insulation coating. As shown in Figures 1 and 2, a double-pipe structure is used to contain

![Figure 1. A schematic of the anti-corrosion structure design of a standpipe.](image-url)
the liquid lithium flowing in the inner pipe and the compatible barrier fluid flowing in the outer pipe. The wall of the inner pipe is decorated with small branch channels to connect the inner pipe and the outer pipe for the injection of barrier fluids.

In this design, when the barrier fluid flows in the outer pipe, the barrier fluid can be injected into the inner pipe through the elaborately arrayed branch channels. Under the pressure of liquid lithium, the barrier fluid is evenly spread on the wall of the inner pipe and extends down along the pipe to completely wrap the liquid lithium flow. From the center to the inner pipe wall, a “lithium-barrier fluid-inner wall of inner pipe” structure is formed, as shown in Figure 3.

As the flow distance increases, the barrier fluid may be diluted or consumed, resulting in poor barrier fluid coverage. Therefore, whether the barrier fluid from the branch channels can produce an effective liquid film, along with its coverage area and thickness, are the main concerns in this study.

In addition, as an extreme case of the bionic concept, lithium is a very chemically active liquid, and it is miscible with many fluids. Thus, it is difficult to find a compatible candidate for the liquid barrier fluid. Fortunately, according to existing phase diagrams (Predel & Landolt, 1993), at a specific composition ratio and temperature range, both selenium and tellurium can form two liquids with lithium that still possess fluidity. For the case of the high flow rate of liquid lithium, when the possible heat release is ignored, the two liquids can simply be regarded as the compatible barrier fluid. At the same time, due to the fact that the chemical activity of tellurium (melting point 452 °C, boiling point 1390°C) is slightly lower than that of selenium (Cunningham et al., 1971), the operating conditions of tellurium are preferentially introduced in this study, though it should be pointed out that the tellurium in the present work is only used to demonstrate the feasibility of a bionic design. In the future, it may be possible to target more suitable materials as the breeder and the barrier fluids that will have higher engineering application value.

In this study, the output Li and barrier fluids, as well as the chemical compounds due to possible reaction, need to be re-purified into pure Li and a pure barrier fluid again for recycling. An additional purification system or some improvement of the tritium extraction system could serve these purposes. The Argonne National Laboratory (ANL) showed that tritium (present as LiT) was preferentially exacted from liquid lithium by selected molten salts when the two liquids were in contact (Maroni et al., 1975). As a material with lower chemical activity than lithium, the affinity of barrier fluid to tritium is unlikely to be higher than that of lithium to tritium. Therefore, tritium in barrier fluid may be extracted in the same way. Hence, both the purification and tritium extraction can be solved with existing technologies, but
3. Model design and parameters

In order to verify the design of blanket pipeline, a single-channel model is used to study the influence of the velocity ratio and the radians of the branch channel on the coverage of the liquid film in the present work. The model structure is shown in Figures 4 and 5.

The model of the standpipe is a quarter single-channel model. Liquid lithium flows from the top to the bottom in the inner pipe, as shown in Figure 4, while barrier fluid flows into the inner pipe through a branch channel, and a liquid film starts forming from the outlet of the branch channel. Since no one has done similar bionic structure research so far, this study only considers the strength of pipes to a certain extent. One-eighth of the circumference is chosen as the branch channel width $a$ to ensure that pipes still have a certain strength, and $a$ is fixed as 15.31 mm. $\frac{b}{2}$ represents the radians of the branch channels, while $b$ is the height of the branch channel. The thickness of the branch channels is selected to be as small as possible to reduce the influence of the branch channels on the strength of the pipes. It is set at a fixed value of 2 mm with the length of 10 mm, and the included angle with the main flow channel is designed to be 30°. The outlet of the branch channel is 100 mm away from the inlet of the inner pipe to avoid the inlet effect of liquid lithium, and the flow velocity of the liquid lithium is 0.68 m s$^{-1}$ (Ni et al., 2015). Additionally, the gauge pressure at all outlets is 0 Pa.

The model of the bend pipe is a half model. Liquid lithium flows from the inlet on the left to the outlet on the right side, as shown in Figure 5, while the barrier fluid flows into the inner pipe through the branch channel. The flow velocity of the liquid lithium is 5.0 m s$^{-1}$ to ensure that the liquid lithium has enough pressure to press the barrier fluid against the wall of the pipe. According to the results of the standpipes, the velocity ratio is selected to be 8, which means that the inlet velocity of the barrier fluid is 0.625 m s$^{-1}$. The gauge pressure at all outlets is also 0 Pa. In order to simplify the model, a semi-annular branch channel is used to replace the sum of the branch channels for a certain pipe length.

Based on the research results of the standpipe model and the bend pipe model, a simple two-fluid loop model is constructed in this work. This model is in the shape of an S with two standpipes and two bend pipes. The inlet velocity of the liquid lithium is 4.1 m s$^{-1}$, so that when the liquid lithium reaches the entrance of the first bend pipe, its velocity can reach 5 m s$^{-1}$ to achieve full coverage of the liquid film on the inner wall of the bend pipes. In contrast, the velocity of the barrier fluid is selected to be 0.5125 m s$^{-1}$. Thus, the velocity ratio is 8, and the gauge
pressure at all outlets is $0$ Pa. The geometric parameters of the model are shown in Figure 6, and the pipe length of the model is $2.45$ m.

The boundary conditions at the interface between the barrier fluid and the pipes are the focus of this study (Ghalandari et al., 2019; Salih et al., 2019). It is assumed that there is no interaction between the two fluids. The tracking of the interface between the two fluids is accomplished by the solution of a continuity equation for the volume fraction of the two phases. For phase $q$, this equation has the following form:

$$
\frac{\partial (\rho_q \alpha_q)}{\partial t} + \nabla \cdot (\rho_q \alpha_q \vec{v}) = S_{\alpha_q} + \sum_{p=1}^{n} (m_{pq} - m_{qp}) \quad (1)
$$

where $\rho_q$ is the density of phase $q$; $\alpha_q$ is the volume fraction of phase $q$; $m_{pq}$ is the mass transfer from phase $p$ to phase $q$; and $m_{qp}$ is the mass transfer from phase $q$ to phase $p$. $S_{\alpha_q}$, the source term, contains contributions from radiation and the heat of reaction in the primary phase, and $S_{\alpha_q} = 0$ in this study (Fluent, 2013).

The wall of the pipe adopts a no-slip boundary. All of the models use unstructured hybrid grids composed of tetrahedrons and triangular columns. The boundary layer uses twelve layers of grids to capture the interface between the phases, as shown in Figure 7, and the innermost grid size is $0.0008$ mm. The number of grids for the standpipe model is about $1.8 \times 10^6$, and the number of grids for the bend pipe model is about $8 \times 10^6$.

For multiphase flow simulation (Bierbrauer & Zhu, 2008; Lamorgese et al., 2011; Lin & Jiang, 2020), grid accuracy has an important influence on the confidence of simulation results (Cloete et al., 2016; Feng & Tang, 2017). Therefore, studies have also been done on the grid independence of standpipes, obtained by examining the influence of the number of grids on two key result data types, as shown in Table 1. After the barrier fluid enters the inner pipe, there may be two situations where a liquid film cannot be formed or where the coverage area is limited although a liquid film is formed. $R_s$ is thus a very important type of result data that is defined as the ratio of the actual coverage area ($S$) of the barrier fluid on the pipe wall to the theoretical coverage area (width of branch channel $\times$ length of branch channel to outlet). The actual coverage area is obtained by measuring the area of liquid film consisting of $90\%$ barrier fluid and $10\%$ Li according to the Li-barrier fluid phase diagram. When $R_s$ is 1, it is considered that the liquid film formed by the barrier fluid achieves complete coverage on the wall of the inner pipes. In addition, the thickness of the liquid film is also a data type that needs to be paid attention to. Considering the $R_s$ and the thickness of the liquid film comprehensively, a grid accuracy with a grid number of approximately $1.8 \times 10^6$ is selected. The accuracy of the selected grid can save the calculation time when the result error is reasonable. The same mesh accuracy is also used for the bend pipes and the S-shaped pipe.

In this study, the Fluent module in Ansys software is used for simulation. In Fluent, the VOF model and the
Table 1. Results of grid independence test.

| The number of grids \((\times 10^6)\) | 0.66 | 1.19 | 1.46 | 1.87 | 2.42 |
|----------------------------------|-------|-------|-------|-------|-------|
| Rs                               | 0.61  | 0.67  | 0.83  | 0.96  | 0.97  |
| Thickness (mm)                   | 0.12  | 0.16  | 0.19  | 0.25  | 0.26  |

Eulerian model are used for the multiphase flow (Chen et al., 2019; Guerrero et al., 2017; Jiang et al., 2014). The VOF model is better than the Eulerian model in terms of the ability of interface capture, and it requires less calculation, so the VOF model is selected in this study. In order to better capture the shearing effect of the free surface in the boundary layer, and to consider the number of grids and calculation comprehensively, the standard \(k-\omega\) model is finally selected.

In the Volume of Fluid (VOF) model, the dynamic viscosity \(\eta\) of the fluid is the key parameter. Since there is no experimental data, \(\eta_{Li}\) is estimated according to the \(\eta = T\) empirical formula (Battezzati & Greer, 1989):

\[
\eta v^{\frac{1}{3}} = A \exp \left( \frac{C}{v T} \right) \tag{2}
\]

where \(v\) is the specific volume. At a fixed temperature, \(A\) and \(C\) are constant. Using experimental data for the selected barrier fluid from a handbook (Hicks & Chopey, 2012), \(\eta_{Li} = 3.04 \times 10^{-4}\) Pa · s can be obtained. The dynamic viscosity value of the barrier fluid \(\eta_{barrier\ fluid} = 1.49 \times 10^{-3}\) Pa · s is obtained from previous work by Sklyarchuk (Sklyarchuk et al., 2005).

4. Simulation results

4.1. Standpipes

The standpipe is the first to be studied since it is the simplest pipe structure. Its calculation results provide directions for the selection of the velocity ratio and the Reynolds number (Re) ratio, as well as branch channel design for subsequent research about bend pipes and S-shaped pipes.

When \(\frac{h}{a} = 0\), that is, when the shape of the branch channel is rectangular, the velocity ratio \(v_{Li}/v_{bf}\) has a significant effect on Rs, where \(v_{bf}\) stands for the velocity of the barrier fluid. Figure 8 shows the change of the Rs of the liquid film for different \(v_{Li}/v_{bf}\) and \(Re_{Li}/Re_{bf}\).

It can be obtained from Figure 9 that when the velocity ratio is too small, e.g., when \(v_{Li}/v_{bf} < 4\), the barrier fluid will directly rush into liquid lithium without forming a liquid film, failing to adhere to the inner pipe wall, which is also shown in Figure 9 (a–b). An optimal range of velocity ratio exists, satisfying \(5 \leq v_{Li}/v_{bf} \leq 68\), where Rs is equal to or close to unity (Figure 9 (d–h)). It should be noted that when \(32 \leq v_{Li}/v_{bf} \leq 68\) (Figure 9 (g–h)),

the backflow formed in the branch channel will cause liquid lithium to enter the outer pipe, while at \(5 \leq v_{Li}/v_{bf} \leq 16\), although liquid lithium will enter the branch channel due to the vortex, it is prohibited from entering the outer pipe because the pressure of the barrier fluid is sufficient to avoid the backflow (Figure 9 (d–f)).
From the ratio of Re at the inlets of the two fluids, it can be found that the Reynolds numbers of the two fluids have a huge gap. Among them, the barrier fluid is basically laminar flow, while liquid lithium is turbulent with high Reynolds number. The larger the Re ratio, the more favorable the stratification of the two fluids. Although the obvious interface between the two fluids can still be observed at a small Re ratio \((Re_{Li}/Re_{bf} \leq 95)\), it does not make the barrier fluid adhere to the tube wall to form an effective liquid film, as shown in Figure 9 (a–b). At the same time, a very high Re ratio \((Re_{Li}/Re_{bf} \geq 1018)\) will also make it difficult for barrier fluid to enter the inner pipe, as shown in Figure 9 (g–h).

In addition to the velocity ratio and the Re ratio, the shape of the branch channel also contributes to the coverage of the liquid film. With a fixed width, the height of the branch channel \((b)\) is adjusted to investigate the effect of the radians of the branch channel \((b/a)\) on the coverage of the liquid film. Figure 10 indicates that the optimal range of velocity ratio and Re ratio decreases with the increase of the radians of the branch channel.

As an important parameter used to characterize the stability of the liquid film, the thickness of the liquid film indicates how easy it is for the liquid film to remain intact when facing a rougher wall. A thicker liquid film is less sensitive to the effect of the roughness of the pipe wall, whereas the proportion of the liquid lithium in the inner pipe is reduced, which is not conducive to tritium breeding. As a result, pipe walls with different roughness require different thicknesses of liquid film, which should be determined case by case. This work only studies some influencing factors of the liquid film thickness. In stand-pipes, it can be observed that \(v_{Li}/v_{bf}, Re_{Li}/Re_{bf}\), and the radians of the branch channel \((b/a)\) affect the thickness of the liquid film, as shown in Figure 11.

It is clear that the thickness decreases with the increase of \(v_{Li}/v_{bf}\) and \(Re_{Li}/Re_{bf}\). Taking \(b/a = 0\) as an example, when \(5 \leq v_{Li}/v_{bf} \leq 8\) or \(159 \leq Re_{Li}/Re_{bf} \leq 254\), the thickness of the liquid film decreases sharply, while at \(v_{Li}/v_{bf} \geq 16\) or \(Re_{Li}/Re_{bf} \geq 509\), the thickness reaches the minimum value of 0.2 mm and stays almost unchanged with the further increase of the velocity ratio. Since the coverage area of the liquid film increases with the increasing velocity ratio, as has been indicated by Figure 8, together with the decrease of the barrier fluid flux, the thickness of the liquid film naturally decreases.

It also can be determined from Figure 11 that when the velocity ratio or the Re ratio is raised, the thickness of the liquid film decreases. In addition, at the lower velocity ratio or Re ratio, e.g., \(v_{Li}/v_{bf} \leq 5\) or \(Re_{Li}/Re_{bf} \leq 159\), the thickness of the liquid film varies by a large amount with different cross-section radians of the branch channel for a fixed velocity ratio, and the maximum value is 1.5 mm. When \(v_{Li}/v_{bf} \geq 8\) or \(Re_{Li}/Re_{bf} \geq 254\), the difference between each radian is much smaller with a maximum value of about 0.15 mm.

### 4.2. bend pipes

As an indispensable part of the liquid metal loop, the bend pipe is the key research object. This work focuses on the influence of the curvature radius of the bend pipes on the coverage result of the barrier fluid on the pipe wall.
In this design, only the case for which the barrier fluid completely covers the wall of the inner pipe, or in other words, for which $R_s$ equals 1, meets the demand for corrosion protection. It can be found from Figure 12 that when the curvature radius is 750 mm, 700 mm, or 600 mm, the covering result of liquid film is not perfect. When the curvature radius is less than or equal to 500 mm, the liquid film can completely cover the wall of the inner pipe. Considering the structural strength of the inner pipe, the bend pipe with a curvature radius of 100 mm uses fewer branch channels. In this case, full coverage of the inner pipe wall with the barrier fluid can still be achieved.

Due to the inertia of the barrier fluid, the thickness distribution of liquid film on the inner wall of bend pipes is not uniform. As shown in Figure 13, the part closer to the outer fillet of the bend pipe gains a greater thickness of liquid film. The thickness of the liquid film near the outlet of the bend pipes is measured. The results are shown in Figure 13.

It can be found from Figure 14 that the minimum thickness of the liquid film formed in the bend pipes with different curvature radii is less than 0.5 mm, while no obvious trend can be found for the maximum thickness. It should be noted that the maximum thickness of the liquid film in a bend pipe with a curvature radius of 100 mm and fewer branch channels is significantly reduced. It can be speculated that the flux of the barrier fluid in the inner pipe can affect the maximum liquid film thickness in the bend pipes.

### 4.3. S-shaped pipe

The S-shape is a classic pipe shape in the liquid loop, so in this work, a tentative simulation of an S-shape pipe is carried out. The S-shaped pipe is designed to fit into the existing liquid blanket module. At the same time, in order to ensure the full coverage of the barrier fluid in the upward pipe, the number of branch channels is increased. The simulation result is shown in Figure 15.

As shown in Figure 15, under the preset conditions, complete coverage of the barrier fluid on the wall of the S-shaped pipe can be achieved. The thickness of the liquid film near the outlet of the S-shaped pipe is also tested. The S-shaped pipe has the most branch channels, the total flux...
of the barrier fluid is the largest, and the maximum liquid film thickness is also the largest. This result verifies to a certain extent that the previously inferred maximum liquid film thickness is positively correlated with the flux of the barrier fluid, or, in other words, the number of branch channels in this work.

5. Conclusions

This research focuses on the feasibility of a bionic concept for designing the pipe structure in the liquid metal blankets of fusion reactors. The detailed mechanism of the design mimics the process of a gastric wall secreting protective fluids to prevent gastric acid from corroding mucosa. Numerical simulation methods are used to illustrate the feasibility of this idea. Through the layout of the double-pipe structure, a compatible barrier fluid is formed to isolate the liquid lithium from the insulation coating. To demonstrate the application of this design, this work has also investigated the influence of the branch channel and velocity field of the barrier fluid on the coverage of the inner pipe wall.

(1) The use of a barrier fluid in this bionic design can prevent liquid lithium from corroding the insulation coating, no matter whether the pipe is a standpipe or a bend pipe.

(2) The coverage of the inner pipe wall by a barrier fluid is related to the velocity ratio of the two fluids, the shape of the branch channel, and the curvature radius of the bend pipes.

(3) The numerical simulation results of the single channel model show that the velocity ratio of the two fluids and the curvature radius of the bend pipes can dominate the Rs and the thickness of the liquid film. The positive results show that $5 \leq v_{Li}/v_{bf} \leq 16$ or $159 \leq Re_{Li}/Re_{bf} \leq 509$ and $b/a = 0$ are better choices for the standpipes. In such design, the Rs (ratio of coverage area) stabilizes at 1, the barrier fluid can achieve full coverage of the inner pipe wall without flowing backward to the outer pipe, and the liquid film is more stable and has less divergence.

(4) For the case of bent pipes, the curvature radius of less than or equal to 500 mm is more conducive to full coverage of the barrier fluid on the wall of the inner pipes.

In conclusion, this exemplary Liquid Te-Li system has preliminarily proved the feasibility of the bionic two-liquid flow design. Thus far, this work has only been a study of single inner pipes, and there is still a long way to go for a real liquid metal loop. The study of the structural design of the inner and outer double pipes, the mechanical properties and the heat dissipation of pipes, the study of the liquid metal in a pipe in a magnetic field environment, and the recovery of the liquid metal and barrier fluid still need to be completed in the follow-up work.

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