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Review Article

A Review of Liquid Metal Technologies for Fusion Energy Systems

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KEYWORDS

ABSTRACT

Nuclear fusion offers the potential for an almost limitless and clean energy source, yet achieving a sustainable and commercially viable fusion reactor remains a formidable challenge. A key obstacle is the thermal limitations of Plasma Facing Components (PFCs) utilized in tokamaks. While solid Plasma Facing Materials (PFMs) have been extensively researched, their limitations in tolerating the harsh conditions of fusion environments have led to increasing interest in liquid metal PFMs. Among these, liquid lithium stands out as a highly promising candidate due to its low atomic number and excellent thermal properties. This review traces the evolution of liquid lithium PFC concepts, with particular emphasis on the Lithium Metal Infused Trench (LiMIT) system. It explores the interaction between liquid lithium and magnetic fields, highlighting the resulting magnetohydrodynamic (MHD) effects and thermoelectric magnetohydrodynamic (TEMHD) phenomena. Experimental and computational investigations underscore both the potential and challenges of liquid lithium systems, such as the occurrence of dryout under high heat flux conditions and the necessity for optimized channel designs. This review provides a detailed overview of the tokamak liquid metal technology and pinpoint critical areas for future development, with the goal of enabling the practical application of liquid lithium-based PFCs in fusion reactors.

1. Introduction

The pursuit of a sustainable and clean energy source has positioned nuclear fusion as a leading alternative to conventional energy generation methods. Unlike nuclear fission, fusion has the potential

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to offer a nearly limitless energy supply without the long-term radioactive waste. Despite considerable progress in fusion research over the past few decades, achieving a stable and self-sustaining fusion reaction under terrestrial conditions remains a significant challenge.

A major barrier to the realization of a functional fusion reactor is the development of materials capable of enduring the extreme conditions produced by fusion plasmas. PFCs serve as the first line of defense, exposed directly to the intense heat and particle flux generated during fusion. Historically, solid PFMs such as tungsten and carbon have been extensively studied due to their high melting points and ability to withstand considerable thermal loads. However, these materials face significant drawbacks, including sputtering, erosion, and the introduction of high atomic number impurities into the plasma, which can degrade plasma performance and reduce fusion efficiency.

In recent years, liquid metal based PFUs have been recognized as viable alternative to solid materials mainly due to their unique properties, including self-repairing capabilities, high thermal conductivity, and their capacity to absorb and release large quantities of energy through phase transitions. Liquid lithium, in particular, has emerged as a strong candidate because of its low atomic number, which minimizes radiation losses, and its efficient trapping of hydrogen isotopes, which enhances fuel recycling and reduces plasma contamination. The use of liquid metal as PFM has provided the foundation for the development of novel designs, such as the Lithium Metal Infused Trench (LiMIT) system, where liquid lithium is circulated by thermoelectric magnetohydrodynamic (TEMHD) forces.

This review provides a detailed overview of the tokamak liquid metal technology, emphasizing the fundamental principles, experimental results, and computational models that have advanced our understanding of these systems. It addresses the challenges inherent to liquid lithium, including dryout under high heat flux conditions and the complex interactions between liquid metals and magnetic fields. Additionally, this review highlights key gaps in existing research and outlines potential areas for future investigation, aiming to facilitate the successful integration of liquid lithium PFCs into next-generation fusion reactors.

2. REVIEW

Nuclear fusion has been studied for more than half a century, yet the realization of sustainable nuclear fusion seems far-fetched. In the recent decades one of the major problems that has limited the nuclear fusion devices to research facilities is the choice of material for PFCs [1-4]. Previously much effort has been devoted to the selection of the most suitable solid Plasma Facing Material (PFM). In this regard a number of high and low atomic number (Z) elements have been studied and tested [5-8]. One of the key factors contributing to the choice is based on the recycling phenomenon in Tokamak [9-12]. Recycling is a process in which the plasma particles escape the high temperature core plasma and move to a much lower edge plasma where they interact with the PFC's or the wall of vacuum vessel, transfer their energy and get absorbed or deposited in the form of monolayers on the corresponding surfaces. Now as a result of plasma bombardment these atoms i.e., mostly hydrogen can be dislodged from the surface and are re-ionized by the plasma. Thus, recycling helps to maintain the plasma density with the downside being the energy lost in the process [13-16]. Now alongside hydrogen, the atoms of PFC's are also dislodged and enter the plasma as impurities. Now the low-Z impurities arising from utilization of low-Z PFM are easily ionized by plasma thus less energy is lost. Whereas high-Z impurities other than requiring large amount of energy for ionization also contribute towards bremsstrahlung radiation where the plasma ions are deflected in by nuclei of atom through which they pass thus releasing energy in the process. On the other hand, however, the melting temperature of low-Z metals is much less as compared to high-Z metals [17-21].

The requirement of enhanced structural integrity along with benefits of low-Z PFM has led to the utilization of liquid metals as PFM. Liquid metal PFU's have enhanced thermal handling capabilities mainly because of conductive, convective and evaporative heat transfer mechanisms, improved structural integrity against surface damage due to surface tension aided self-healing capabilities and easier maintenance [22-24]. A number of studied on low-Z metals carried out in the past decade have suggested lithium to be the most suitable candidate based on effective hydrogen isotope trapping efficiency which helps in controlling the plasma purity and fuel dilution, high latent heat of vaporization which helps in sustain the thermal loads from higher heat fluxes by phase change, higher heat capacity which causes higher heat to be absorbed without excessively increasing the temperature, reduction of common residual gases i.e., oxygen and water vapors used in tokamak vacuum system which can then be easily removed and widely compatible temperature range of lithium with steel [25-29].

Liquid metals when employed in the tokamaks are affected by the interaction of magnetic field and the charged particles of metal [30-32]. The motion of these charged particles (electrons) within a magnetic field generates induced electric currents [33-35]. These currents then interact with the applied magnetic field, producing a Lorentz force that propels liquid metal. Other than the interaction of magnetic field, an additional Lorentz force is also generated as a result of Seebeck or thermo-electric effect. Under this effect, when a thermal gradient is applied across the interface of two different metals electrons diffuse from hotter region of each body to cooler region thereby accumulating at the lithium side and depleting from the heat sink side of the interface. This creates an electric field resulting in flow of electric current. The induced electric current interacts with the external magnetic field, producing an additional Lorentz force that drives the movement of liquid lithium[36-40].

In the past decade, a number of concepts implementing liquid lithium concept have been proposed and tested. One of the prominent names among them is LiMIT developed in 2011 at the University of Illinois at Urban Champaign (UIUC) [41]. This design features an open trench PFU wetted with liquid lithium. Liquid lithium is contained as well as actively cooled by stainless steel heat sink and closure. The plasma facing side of the device contains narrow open channels similar to a heat sink used in electronic equipment while the bottom side has wider channels encases in SS closure. Liquid lithium is driven in such channels not by pressure gradient but by Lorentz force as mentioned above. A resistance heater is incorporated to maintain the liquid lithium at a temperature above its melting point on the cooler side. For the safe operation of such PFU, it is required that the solid stainless steel must not be exposed to direct heat flux for extended period of time called dryout. One of the causes of dryout has been identified as excessive evaporation at high temperatures which typically occurs at higher heat fluxes. However, even at lower heat flux, localized acceleration at the region where heat flux is greatest can lead to depression and pileup of lithium in the channel. This depression when reaches the walls of trench leads to dryout [42-45].

Afterwards the development of LiMIT, this concept has been tested in various facilities. P. Fiflis et al., [46] studied the thermal performance of LiMIT in Magnum PSI linear plasma simulator. The PFU consists of air-cooled stainless-steel trenches having dimensions of 1 x 2 mm and 5 cm length carrying liquid lithium. The PFU is subjected to an absorbed heat flux of up to 3MW/m^2 on the open side of trench. A resistive heater is also placed on the closed side of trench to increase the temperature of lithium returning to the open side of trench to 475 C. Other than keeping the minimum temperature of liquid lithium above melting temperature, it also provides thermal gradient necessary to drive lithium to the inlet of open channel [41, 47-49]. The corresponding velocities and surface temperatures are measured. It is observed that a heat flux of 3MW/m2 causes the local lithium depression and pileup, as a result of which stainless steel trench gets exposed and damaged. The author further extends the analysis to the case when dryout is mitigated by changing the geometry of channel or introducing a wire mesh. For this purpose, half of the trench is modeled in ANSYS fluent, with fixed wall and slip boundary condition at the free surface. While other walls of trench have no slip condition, and a heat flux is applied to induce the effect of resistive heater. The heat transfer coefficient within the channel is regulated in such a way that the temperature of liquid lithium above 230 ^{0}C without applying heat flux at the open surface. The results indicated that in the absence of dryout the maximum temperature of steel reaches 435 ^{0}C, which is less than melting temperature under 3 MW/m^2 heat flux.

M. Szott at al., [50] determined the dryout conditions in the open surface trench by performing 2D simulation coupled with moving mesh module of COMSOL. The bottom surface utilizes no slip boundary condition. The driving force resulting from TEMHD was determined from 3D analysis of trench with fixed top surface. The resulting volumetric force was applied to the 2D domain in the form of gaussian distribution. The author further optimized the ledge height as a means of mitigating the dryout.

In summary, despite decades of research, the development of sustainable nuclear fusion remains a complex challenge, with the selection of PFCs playing a critical role in advancing the field. The limitations of solid PFMs, including their susceptibility to surface damage and contamination, have driven the exploration of liquid metals as a promising alternative. Liquid lithium has emerged as a prime candidate due to its exceptional thermal properties, effective hydrogen isotope retention, and self-regenerating capabilities. Recent innovations, LiMIT system, have shown considerable advancements in addressing challenges like dryout and enhancing thermal regulation under extreme heat flux conditions. While challenges remain, particularly regarding the interaction of liquid metals with magnetic fields and the risk of dryout, ongoing research and simulations offer promising solutions to these obstacles. These innovations are essential for enhancing the performance and longevity of PFCs, moving the field closer to achieving practical, long-term nuclear fusion.

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