An Innovative Concept of High Temperature Liquid Blanket for Hydrogen Production

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Abstract: Hydrogen is considered as the most potential energy carrier in the future, and the nuclear power would be used as a provider of high temperature heat for hydrogen production. An innovative concept of the high temperature lithium lead blanket with "multilayer flow channel inserts" has been presented in this paper. The maximum outlet temperature 1000 ^{o}C of lithium lead coolant could be achieved while assuring the temperature of the structural material well below the engineering limit of 550 ^{o}C for RAFM. The theoretical analyses and numerical calculations have been performed to validate the feasibility of this concept. Technology issues, such as tritium permeation and material corrosion on high temperature condition, are to be clarified for improvement of this innovative blanket concept.

Key words: Fusion power; High temperature lithium lead blanket; Hydrogen production

1. Introduction

Hydrogen is considered as the most potential energy carrier to meet the world's energy demand in the future. But scarcely hydrogen exists in the nature，hydrogen must be produced with huge thermal energy. A promising method for the hydrogen production is that nuclear power would be used as a provider of high-temperature heat, while fusion power is a candidate nuclear power due to clean, powerful, renewable, and environmentally benign. So the design of fusion blanket, the main component for the extraction of heat power, is the key issue for hydrogen production. Some points must be taken into consideration for this blanket design: First, blanket coolant outlet temperature must be high enough (e.g. up to 1000 ^{o}C) to satisfy the need of high efficiency production of hydrogen. Second, blanket structural material must be feasible for the high coolant temperature and should have good properties such as low irradiation, high thermal conductivity, high strength and stress and good fabrication and joining technology, etc. An innovative concept of the high temperature liquid lithium lead (LiPb) blanket has been proposed in this paper based on the current status of the blanket technology of the fusion power reactor.

2. Blanket concept description

To achieve a high temperature about 1000 ^{o}C for high efficiency production of hydrogen, one of the most challenging issues about the high temperature blanket is performance of the blanket structural material. Some materials with good temperature properties, such as SiC_f/SiC composite, V-alloy and W-alloy etc., are considered as the candidate structural materials for high temperature blanket **[1]**. But some issues for these materials limit their application in blanket design, including the unsolved fabrication and joining technology, rather low thermal conductivity and rather low strength and stress for SiC_f/SiC composite, the high induced radioactivity and afterheat for W-alloy, bad compatibility of V-alloy with coolant, etc. As a result, the development of high temperature blanket is limited by the current status of material technology.

An innovative concept of the high temperature LiPb blanket for hydrogen production has been presented in this paper. This innovative blanket design with “multilayer flow channel inserts (MFCIs)” is considered to obtain high temperature heat while using the relatively mature and most promising Reduced Activation Ferritic/Martensitic (RAFM) steel as structural material, refractory material with low thermal conductivity and high chemical compatibility with LiPb, such as SiC_f/SiC composite material or other composites as the functional material inserted in the flow channel (SiC_f/SiC composite is relatively feasible as FCI than as the structure due to different property requirement), and high pressure helium gas and LiPb as coolants. Helium gas is used to cool the RAFM structural material to keep it below the design limit of 550 ^{o}C, while LiPb is used to be self-coolant. Low temperature LiPb flows into the channel, then meanders through the multi-layer flow channel inserts. The temperature of the coolant LiPb is improved step by step, at last it is exported from the blanket in the high outlet temperature. Schematic layout of MFCIs structure and LiPb flow channel is shown in **Fig.1**.

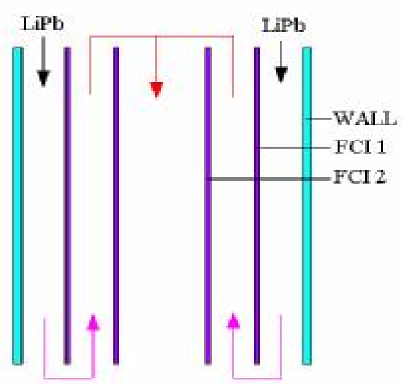

Fig.1 Schematic layout of MFCIs structure and LiPb flow circuit

Based on the innovative blanket concept design with MFCIs inserted in the LiPb flow channel, high temperature LiPb about 1000 ^{o}C (according with the allowable interface temperature of LiPb and SiC_f/SiC composite) can be obtained for assuring the temperature of the structural material well below the engineering limit of 550 ^{o}C for RAFM, and the thermal stress of the MFCIs far below the permissible limit due to the low temperature gradient across the MFCIs. This innovative concept is attractive for high temperature blanket design, First the outlet temperature of LiPb coolant is not limited by the maximum allowed operating temperature of the structure material. Second the conceptual design scheme easily comes ture due to relatively mature structural material and the FCI functional material.

3. Thermal-hydraulic and thermo-mechanical analyses

The preliminary thermal-hydraulic and thermo-mechanical analyses, which could evaluate the feasibility of this proposed blanket concept design, have been presented in this paper. The

ANSYS, a finite element computer code, is used to simulate structural temperature and stress distributions to assess the rationality of the blanket structure design and the feasibility of the multi-layer FCIs design. The surface heat flux of 0.7MW/m^2, the neutron wall load of 3.54MW/m^2, and the nuclear power density of the structure and LiPb multiplier can refer to the values in Refs.[2]. Material date of RAFM steel are taken from the ITER materials property handbook [3]. The maximum temperature limit is 550 ^{o}C and the interface temperature between LiPb flow and RAFM steel is limited to 500 ^{o}C. The SiC_f/SiC parameters and properties used in the analysis are consistent with the suggestion from the January 2000 International Town Meeting on SiC_f/SiC Design and Material Issues for Fusion Systems [4] and are summarized in **Table 1**. The coolant inlet/outlet temperature are assumed to be 300/420 ^{o}C and 350/1000 ^{o}C for 8MPa helium gas and 1MPa LiPb, respectively. The following detailed thermo-mechanical analyses are carried out with 2D calculation model.

Table 1 Suggested SiC_f/SiC parameters and properties

Density	~3000 kg/m^3
Porosity	~5%
Young's modulus	~200–300 GPa
Poisson's ratio	0.16–0.18
Thermal expansion coefficient	4×10^{-6} K^{-1}
Thermal conductivity	20W/m-k
Electrical conductivity	500$\Omega^{-1}m^{-1}$
Maximum allowable stress	190MPa
Max. allowable temperature	1000 ^{o}C
Maximum allowable SiC/LiPb interface temperature	1000 ^{o}C

Fig.2 shows the temperature and stress distributions of the structure and MFCIs. The maximum structural temperature 542 ^{o}C, the maximum FCI temperature 890 ^{o}C, the maximum interface temperature 475 ^{o}C between LiPb and structure, and the maximum structural stress 251MPa, the maximum FCI thermal stress 98MPa are well below the engineering limit of RAFM material and SiC_f/SiC FCI material.

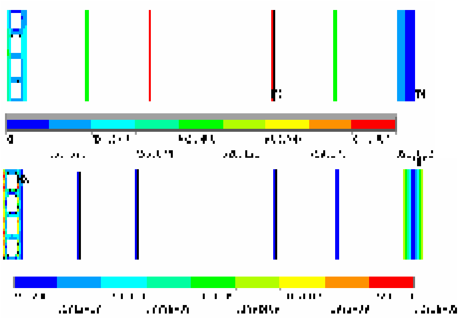

Fig.2 Temperature distribution (up) and stress distribution (down) of the structure and MFCIs

Furthermore, MHD pressure drop and flow features of complex LiPb flow are simulated with 3D mathematical model by fluid dynamic code FLUENT. The high magnetic field about 4.5T is assumed in the blanket region. **Fig.3** and **Fig.4** show the pressure distribution and the temperature distribution of LiPb flow in the flow channel with MFCIs. The MHD pressure drop is about 0.004MPa which is very small even if many turns in the flow. Such flow with multi-layer FCIs don't cause higher MHD pressure drop than the flow in a straight duct of the same average length. And the outlet temperature of LiPb is about 1000 ^{o}C which can meet the need of hydrogen production with this innovative concept design.

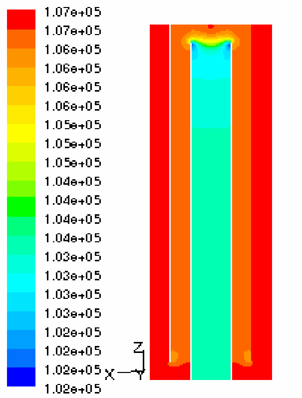

Fig.3 Pressure distribution of LiPb flow

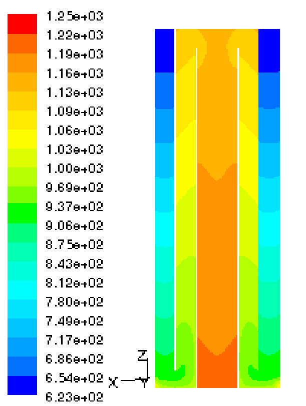

Fig.4 Temperature distribution of LiPb flow

3. Need of further R&D for the high temperature LiPb blanket

RAFM steel as structural material is relatively mature in fusion blanket design, but some issues should be concerned to the SiC_f/SiC FCI behavior and performance especially at high temperature and under irradiation, such as tritium permeation and chemical compatibility, etc.

3.1. Tritium permeation

Tritium permeation is a concern for the high temperature LiPb blanket and the tritium permeation barrier should be considered to reduce tritium permeation. SiC_f/SiC itself has very low hydrogen permeability, making it a candidate for tritium permeation barriers, but still to be further studied. SiC_f/SiC coating should be also considered to reduce tritium permeation in such high temperature blanket.

3.2. Chemical compatibility

The chemical compatibility of LiPb and SiC_f/SiC at high temperature is an area in need of R&D. Only limited data on the compatibility of SiC_f/SiC with LiPb are available. Some preliminary investigation suggested that static LiPb is compatible with SiC up to 850 ^{o}C **[5]**. Tests, for relevant LiPb velocity (up to 1 m/s), duration (10000 h), and high temperatures (about 1100 ^{o}C) have yet to be performed **[6]**. So the chemical compatibility with high velocity LiPb has to be measured for a relevant time length. Compatibility of LiPb with the joining material (brazing) has also to be checked.

4. Summary

This innovative high temperature blanket concept with “multilayer flow channel inserts” has been presented in this paper. Theoretical analyses and numerical calculation have show that it is feasible for LiPb to obtain high outlet temperature 1000 ^{o}C with this innovative concept design, and the MHD pressure drop of LiPb is small enough only about 0.004MPa, the maximum temperature 542 ^{o}C and 890 ^{o}C and the maximum stress 251MPa and 98MPa for the structure and FCI respectively, have been performed which can meet the engineering limits requirement of material and validate the feasibility and reliability of this concept. And technology issues such as tritium permeation and chemical compatibility, etc. on high temperature condition are to be considered for improvement of this innovative blanket concept.

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