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ABSTRACT

The magnetohydrodynamic (MHD) effects can present a feasibility issue for a self-cooled liquid metal blanket of magnetically confined fusion reactors, especially inboard regime of a tokamak. This pressure drop can be significantly reduced by using insulated wall structure. A self-healing insulating coating has been identified, which will reduce the pressure drop by more than a factor of 10. The future research direction to further quantify the performance of this coating is also outlined.

I. INTRODUCTION

A self-cooled lithium blanket uses the liquid lithium as both the coolant and the breeding material. Thus, all the nuclear energy is deposited directly inside the coolant. Therefore, the first wall becomes the only heat transfer surface and the pressure containing boundary. For this reason, the self-cooled lithium blanket is inherently simple and reliable. Also, lithium has excellent neutronics properties, and tritium breeding for a lithium blanket is not an important issue. Those are some of the reasons that a self-cooled lithium blanket has obtained the most attention in fusion reactor design studies^{1,2,3} and was top rated in BCSS⁴.

A key concern about a self-cooled lithium blanket has been the MHD pressure drop. The interaction of the velocity of the liquid metal and the magnetic field results in induced electromotive force, which drives current through both the wall and the liquid metal and result in large body forces opposing the motion of the liquid metal. To counter this force, a large pressure drop is required to move the metal. This pressure will increase the stress of the structure and increase the pumping power. If the magnetic field is too high, the pressure required will

be too large that the stress may exceed the design limit.

It has been known for some time that the MHD pressure drop can be significantly reduced if an insulated layer is used to reduce the flow of the eddy current to the structure. However, the effect of radiation, lithium corrosion to the reliability of the coating is uncertain.

The paper presented here summarizes some recent developments in this area. The parameters of ARIES-II reactor design will be used to assess the need of the insulator for a tokamak. Some candidates for the insulator material will be discussed and a reference material will be selected. The electrical resistance on the coating has been measured. The effect of the insulator coating to the MHD effect will be addressed. Future R&D needed will also be discussed here.

II. MHD PRESSURE DROP LIMITATIONS

The pressure in a blanket has to be larger than that of the pressure drop so that there will be enough pressure head in the blanket to push the coolant through the reactor. This pressure may cause large hoop stress in the blanket. The limiting case would be that this hoop stress become larger than the allowable stress of the structure material. If that is the case, methods to reduce that pressure has to be incorporated into the blanket design. One of the possible methods is to use an insulated wall. Therefore, we will first assess the parameter regime within which a self-cooled lithium blanket can be used without an insulated wall. The assessment here only addresses the inboard (IB) blanket of a tokamak. Also, only problem associated with heat transport is assessed. Detailed design to accommodate first wall heat transfer, and the entrance and exit effects of the coolant will further reduce this parameter regime.

The coolant is assumed to enter the IB blanket from the top of the torus, and exit from the bottom. The other configuration is

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to enter from the top of the torus, turn around at the middle of the IB blanket, and exit from the top. These two configurations are shown in Fig. 1. If heat transport is the only concern, the pressure drop of the two configurations are the same, since both the velocity and the flow length are the same.

The thermal energy received by one linear unit on the toroidal direction is

$$Q = Q^* l$$

The coolant velocity is

$$v = \frac{Q}{\delta \rho C_p \Delta T}$$

and the MHD pressure drop for bare walls is

$$\Delta p = v l B^2 \frac{\sigma_w t_w}{a}$$

Since the allowable stress has to be larger than the hoop stress

$$S \geq \Delta p \frac{a}{t_w}$$

Therefore

$$v l B^2 \sigma_w \leq S$$

or

$$\frac{Q^* l^2 B^2 \sigma_w}{\delta \rho C_p \Delta T} \leq S$$

In which

- Q^* is the total thermal loading*
- l is the IB length (6 m for ARIES-II)
- B is the local magnetic field
- σ_w is the wall electrical conductivity ($1.8 \times 10^6 \frac{1}{\Omega \cdot m}$)
- δ is the IB breeding zone thickness (.2 m)
- ρ is the density of the coolant (500 kg/m³)
- C_p is the specific heat of the coolant ($4.2 \times 10^{-3} \frac{MJ}{kg}$)
- ΔT is the coolant temp. rise (200°C)
- S is the allowable stress

For ARIES-II $Q^* B^2 < 130$

* Defined as the total energy deposited in the blanket per unit first wall area.

Figure 2 shows the operating regime of ARIES-II and the MHD pressure drop limitations. It is clear that, with ARIES-II's parameters, an insulated wall is required.

For TPSS², the δ is 0.35 m and the l is only 4 m (high aspect ratio reduces the minor radius), and

$$Q^* B^2 < 512$$

Figure 3 shows the MHD limit and the TPSS IB regime. It is clear that a non-insulated wall is not excluded for TPSS. Fig. 3 also shows that, even with TPSS geometry, a non-insulated wall will not work with ARIES magnetic field.

It has to be emphasized that the design limitations shown in Figs. 2 and 3 are necessary but not sufficient conditions. Only the dominate component of the MHD pressure drop is included in this evaluation. Also, only the hoop stress is included in determining the stress limitations. However, even with this limited evaluation, it is clear that MHD pressure drop in the IB of the tokamak may cause feasibility problems with a non-insulated wall. An insulated wall development program is thus critically important in the liquid metal technology in fusion applications.

III. INSULATING COATING

Based on preliminary survey of more than 15 oxides and nitrides, four ceramic materials (CaO, MgO, Y₂O₃, and BN) were identified⁶ as candidates for insulator coating development. These compounds were fabricated by a variety of techniques and exposed to flowing lithium at 400°C to assess chemical compatibility^{7,8,9}. Yttrium oxide exhibited excellent corrosion resistance in flowing liquid Li at 400°C; its corrosion rate was measured to be 0.042 $\mu\text{m/yr}$. Resistivity measurements were taken before and after Li exposure to determine the effects of Li on the electrical properties of Y₂O₃. No deterioration in the resistivity could be measured; in both cases the resistivity was $>10^{12} \Omega\text{m}$. Boron nitride coatings on V-20Ti substrates were fabricated by the newly developed ion-beam-assisted-deposition process. These coatings are expected to exhibit better compatibility with liquid Li than the previously rf-sputtered coatings. Preliminary measurements of the resistivity of in-situ-formed (V,Ti)_xN reaction product layers on various V-base alloys including V-7Cr-5Ti, V-2.5Ti-1Si, and V-20Ti have been made.

A. Indication of the Existence of the Coating

For the complex geometries and high-temperature operating environments of interest

Figure 1. Inboard blanket flow path.

Figure 2. TITAN MHD pressure drop limit.

Figure 3. TPSS MHD pressure drop limit.

and the required high reliability, in-situ-formed self-healing coatings appear to offer the most reasonable solution. Excellent-quality diffusion coatings on metals and alloys have been obtained when the diffusion element has been introduced via a liquid metal, e.g., lithium.

A candidate of the in-situ-formed, self-coating coating is the (V-Ti)N coating formed from the nitrogen in lithium reacting with the Ti in the V-alloy. Formation of the nitride (V-Ti)N on V-base alloys has been observed in various experiments (Table I). This nitride surface layer has been associated with reduced diffusion of nonmetallic impurities^{10,11} in the liquid lithium/structural materials systems; more specifically, a retarded carbon transfer phenomena¹⁰ was observed in V-20Ti alloys. Adelhelm, et. al.¹² observed that corrosion rates of V-3Ti-1Si were minimized with 30 wppm nitrogen in liquid lithium and attributed this to the protective effect of a (V,Ti)_xN reaction layer with $x = 1.55-1.67$. The thickness of this layer was dependent on nitrogen concentration, not time. Chopra and Smith¹¹ also observed a nitride layer on V-base alloys exposed to liquid lithium. Although no uniform scale was observed in alloys with a low titanium content (<5%), a uniform, mixed nitride layer formed on V-(15,20)Ti. The thickness increased with temperature, not time, with values of about 1.5, 2.5, and 6.0 μm at 427, 482, and 583°C, respectively. However, the layer was brittle

and could spall under thermal stresses. Votinov, et. al.¹³ found that titanium, being a more reactive element, caused nitrides to form closer to the surface, and these nitrides limited further diffusion. Similar reaction products were also found in other lithium compatibility studies¹⁴⁻¹⁷.

Ongoing experiments focus on characterization of the nitride layer on the V-20Ti and titanium specimens exposed to flowing lithium at Argonne National Laboratory and on measurements of electrical conductivity to quantify insulation properties.

B. Measurement of Resistance of Coating

Specimen Preparation Specimen surfaces were cleaned in several solutions in an ultrasonic cleaner. The first solution was soap water, second was acetone, and last was methanol. A circular coating of silver was sputtered onto the front and back surface of the foil. The part of the sample that was not supposed to be coated was protected using a metal shield. The diameter of the silver coatings were ~3 mm and the thickness was ~0.1-0.2 μm .

A Pt wire electrode was attached to each sputtered silver coating using silver paint. The specimen was suspended in a furnace by the electrodes to obtain high temperature resistivity measurements.

TABLE I
Summary of Reported Observations of Reaction Product Layer Formed
on V-base Alloys after Li Exposure^a

Observed Reaction Product	V-base Alloy Substrate	Test Conditions		Lithium Impurities (wppm)			Thickness (μm)	Surface Layer Characterization
		Temp. (°C)	Time (h)	N	O	C		Observations ^b
V ₃ N, VN, Li ₇ VN ₄	V	--	--	--	--	--	--	-- ¹³
VN	V	477	--	140	--	--	--	Reaction products insoluble in Li ¹⁴
Li ₇ VN ₄	V	477	--	23,400	--	--	--	Reaction products insoluble in Li ¹⁴
Mixed nitrides	V-(15,20)Ti	427-538	>700	20-50	--	8-12	1.5-6.0 ^c	Uniform brittle scale ¹⁰
TiN	V-(15,20)Ti	482	>1600	20-50	--	8-12	10	Decreased N diffusion, increased hardness ¹⁰
Nitrides	V-(5-30)Ti	700	500	3633	580	19,000	20	Dense scale, restricted impurity diffusion ¹²
Nitrides	V-(5-30)Ti	700	500	13,524	1400	35,000	15-40	Dense scale, restricted impurity diffusion ¹²
(V,Ti) _x N ^d	V-3Ti-1Si	533-550	>362	8-64	--	0.3-2	2-5	Density of scale a N content ^{11,15}
Fe, Cr, Ni enriched	V	800	1000	200-2000	<250	<50	10	Film formed in V/Fe system in static Li ¹⁶

^a Limited to open literature; more observations are reported verbally or in informal documents.

^b More information is given in the cited references.

^c Surface layer thickness increased with temperature and did not form on alloys with 5% Ti or less.

^d Where $1.55 < x < 1.67$.

Equipment The furnace used consisted of heating coils, a Variac power controller, a ceramic test chamber, thermocouple, and argon supply. Resistance was measured using a Hewlett-Packard Digital Multimeter model #HP 3465A.

Testing High purity Argon (99.999% pure) was flowed at atmospheric pressure through the ceramic tube during the tests. The temperature was raised to 600°C for one hour to anneal the silver paint. After cooling the resistance was measured at 50°C intervals.

Contact resistance was measured by connecting the two Pt electrodes with silver paint and no sample in between. The contact resistance of ~0.12 Ω is acceptable for coatings with a resistance >10 Ω .

Calculations The resistivity of the coating was determined by the following equation:

$$\rho_c = [(R - R_0) \cdot A / 2t_c] - (\rho_s \cdot t_s / A)$$

where R is the measured resistance through the sample, R_0 is the contact resistance, A is the area of the silver sputtered surface, t_c is the thickness of the coating, ρ_s is the resistivity of the substrate, and t_s is the thickness of the substrate.

Initial measurements suggest that the electrical resistivity of the coating is many orders of magnitude higher than the base V-20Ti. The resistance of the coating is measured at $10^{-5} \Omega\text{-m}^2$.

IV. EFFECT OF INSULATED COATING TO MHD PRESSURE DROP

The ratio of fully developed pressure drops for insulating and bare wall coolant ducts, p, is given by:

$$p = (1/cM) + 1/(1+\alpha cM)$$

where, c is the wall conductance ratio of the bare wall duct, M is the Hartmann number, and α is the ratio of the product of the resistivity and thickness of the insulating layer to the expression $2bM/\sigma_f$; 2b is the radial dimension of the duct and σ_f is the fluid electrical conductivity. The derivation of this equation is shown in Appendix A.

For a duct of 5 cm x 5 cm in a 10 Tesla field, the above parameters have the following values:

$M = 2.5 \times 10^4$, $2bM/\sigma_f = 4 \times 10^{-4}$, $c = 0.02$ (for 1 mm wall) and, therefore:

$$p = 0.002 + 1/(1 + 1.25 \times 10^6 p_{ins} \cdot t_{ins})$$

The pressure reduction factor is plotted in Fig. 4. For the ARIES condition, a pressure reduction factor in excess of 10 can be expected.

The pressure reduction factor reported here is only for the Hartman flow in the uniform magnetic field regime. The real blanket configuration includes the entrance, exit and turning effects, etc. Therefore, this pressure reduction factor does not necessarily represent the reduction in pressure that can be achieved in a real blanket design.

Figure 4. Effect of insulated wall to MHD pressure drop.

V. FUTURE DIRECTIONS

The future directions of liquid metal blankets will be the parallel development paths of blanket channels with insulator coatings or bare wall. Insulator coatings offer a greater operating parameter space in terms of allowable magnetic field, heat deposition rate, and geometry, but they bring the additional complexity of another material in the blanket system. Key issues for insulator coatings are fabrication, baseline properties, and lifetime performance in a chemical and neutron environment. Bare wall systems offer greater engineering simplicity where the blanket lifetime is dependent on only a single material - the structural material. The

operating parameter space for bare wall systems is more restricted, so that the primary goal of the development of bare wall systems is to find the means for expanding the range. This involves utilizing MHD related forces and thermal hydraulic effects to enhance heat transfer capability.

The two paths investigate considerably different phenomenon. With insulator coatings, the primary emphasis is materials performance under severe fusion conditions including liquid metal corrosion and neutron damage effects. The MHD considerations, although still significant, are of a less importance, and include mainly thermal hydraulic optimization. With bare walls, the primary emphasis is on MHD effects on flow behavior, and particularly on combined MHD heat/transfer behavior. The influence of flow instabilities on enhancing heat transfer rates is the most important near term issue.

In the near term, both insulated walls and bare walls should continue to be investigated to determine which approach is more attractive. The near term emphasis on insulator coatings is to select leading candidate coatings and to determine their stability in liquid metals. The objective of this work is to find a coating which can reform or repair itself in-situ if the original coating cracks or flakes. It will probably be necessary to add other constituents to the liquid metal/coating/structure system to insure in-situ repair of the coating. Successful development of a corrosion resistant coating would then lead to in-reactor tests to determine neutron radiation resistance. Since insulators as a group are expected to have shorter radiation lifetimes than structural metals, it is very desirable that the coatings be repairable in-situ. The final test will be an integrated test with a lithium loop in a neutron and magnetic environment. The pressure drop measurement over a long time period will provide the information of the stability of the coating.

The near-term work for bare wall systems is in the area of MHD-heat transfer effects to determine the influence of flow instabilities on heat transfer. If heat transfer is enhanced substantially, then the operating space for bare wall systems would be increased and could be considered for advanced fusion systems.

In the longer term, larger design specific blanket sections would be tested. As the test systems become larger and more geometrically complex, larger test systems will be required. A new test facility, ALEX-II, has been proposed which utilizes an existing dipole superconducting magnet with a field of ~6 T and a test volume of ~3m³. The facility would be adequate for testing thermal hydraulic

of large liquid metal blanket systems prior to being tested in the fusion environment.

VI. CONCLUSIONS

The MHD problem in the inboard region of a tokamak presents a serious problem. The magnetic field is highest, and the space is limited. For a reactor with parameters similar to those of the ARIES-II design, the pressure drop is so high that the internal pressure in the blanket causes the stress in the structure to exceed the design limit. Therefore, for such design, bare walled structure is not acceptable unless a thicker blanket is used. A (V, Ti)N coating has been identified which can provide an insulating effect to eddy currents. This insulating effect will reduce the MHD pressure drop by more than a factor of 10. This coating is self-generated from the interaction of the nitrogen in the lithium and Ti in the V-alloy. Therefore, the system is simple and the coating is expected to be reliable.

Future research plan is outlined here to further quantify the reliability of this coating under irradiation and lithium corrosion environment.

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APPENDIX A. MHD PRESSURE DROP CALCULATION FOR A PARTIALLY INSULATED WALL DUCT

Induced EMF = $2bUB$

Equivalent circuit for current

$$R_w = \frac{1}{\sigma_w} \frac{2b}{t_w}, R_{ins} = \frac{\rho_{ins} t_{ins}}{a} = \frac{\alpha 2bM}{a\sigma}$$

$$R_{hl} = \frac{1}{\sigma} \frac{2b}{t_{hl}}, R_{lm} = \frac{2b}{\sigma a}$$

$$\text{where } \alpha = \frac{\rho_{ins} t_{ins}}{2bM/\sigma}$$

All resistances are per unit length.

$$R_{total} = R_{lm} + \frac{R_{hl} (R_w + R_{ins})}{R_{hl} + R_w + R_{ins}}$$

$$R = \frac{2b}{\sigma a} + \frac{\frac{2bM}{\sigma a} \left(\frac{2b}{\sigma_w t_w} + \frac{2baM}{a\sigma} \right)}{\frac{2bM}{\sigma a} + \frac{2b}{\sigma_w t_w} + \frac{2baM}{a\sigma}}$$

$$R = \frac{2b}{\sigma a} \left[1 + \frac{\frac{a\sigma}{\sigma_w t_w} + \alpha M}{1 + \frac{1}{M} \frac{a\sigma}{\sigma_w t_w} + \alpha} \right]$$

$$= \frac{2b}{\sigma a} \left[1 + \frac{\alpha M + 1/C}{1 + \alpha + 1/MC} \right]$$

$$\text{Current per unit length} = \frac{\text{EMF}}{R_{\text{total}}}$$

$$= \sigma U B a \frac{1}{1 + \frac{\alpha M + 1/C}{1 + \alpha + 1/MC}}$$

$$\text{Current density} = \text{current}/a$$

$$= \sigma U B \frac{1}{1 + \frac{\alpha M + 1/C}{1 + \alpha + 1/MC}}$$

$$\text{Pressure gradient} = \text{current density} \times B$$

$$= \sigma U B^2 \frac{1 + \alpha + 1/MC}{1 + \alpha + 1/MC + \alpha M + 1/C}$$

For all practical purposes $MC \gg 1$, $M \gg 1$

$$\therefore (\Delta p)_{\text{ins}} = \sigma U B^2 \frac{1 + \alpha}{1 + \alpha M + 1/C}$$

$$(\Delta p)_{\text{no ins}} = (\Delta p)_{\alpha=0} = \frac{\sigma U B^2}{1 + 1/C} = \frac{C}{1 + C} \sigma U B^2$$

$$\therefore \frac{(\Delta p)_{\text{ins}}}{(\Delta p)_{\text{no ins}}} = \frac{1 + \alpha}{1 + \frac{\alpha MC}{1 + C}}$$

$$\text{Limits: } \alpha = 0 \quad \frac{(\Delta p)_{\text{ins}}}{(\Delta p)_{\text{no ins}}} = 1$$

$$\alpha \gg 1 \quad 1 + \alpha \approx \alpha$$

$$1 + \frac{\alpha MC}{1 + C} \approx \alpha MC$$

$$\text{and } \frac{(\Delta p)_{\text{ins}}}{(\Delta p)_{\text{no ins}}} = \frac{\alpha}{\alpha MC} = \frac{1}{MC}$$

In general,

$$\boxed{\frac{(\Delta p)_{\text{ins}}}{(\Delta p)_{\text{no ins}}} = \frac{1 + \alpha}{1 + \frac{\alpha MC}{1 + C}}}$$

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