ROLE OF THERMOELECTROMAGNETIC FORCES IN CAPILLARY POROUS SYSTEMS PROPOSED FOR LIQUID METAL COOLING OF FUSION REACTOR COMPONENTS

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Abstract: Protection of plasma facing components against thermal and corpuscular overloads remains as one of the most important tasks in fusion related research. The interest in liquid metals is connected with the opportunity to create movable and renewable contact surface with plasma. Today as one of the most promising solutions is the Capillary Porous System (CPS). In this work SS/Li CPS has been analyzed focusing on positive and negative aspects caused by thermoelectromagnetic (TEM) forces. The absolute thermoelectric power of liquid Li is extremely high compared to other metals (20 μV/K). Thermoelectric current, interacting with the strong, plasma confining magnetic field (up to 5T) creates force on liquid metal, which might have a significant impact on device performance.

1. Introduction

Thermoelectromagnetic convection (TEMC) recently is of a particular interest in the field of crystal growth and solidification of metallic alloys [1]. This convection emerges as a result of thermoelectric current and applied magnetic field interaction, and may play significant role in solute and mass transport near solidification interface and in the mushy zone [2]. A high TE current density is defined by a high differential thermoelectric power, good electrical conductivity and high temperature gradient. Ability for a pair of materials to generate TE current is characterized by figure of merit which has dimension of [A/W]

$$Z_{TE} = \frac{\sigma \cdot \Delta S}{\lambda} \tag{1}$$

Electric potential and current distribution in continuous media is governed by Ohm's law eq. (2). In some circumstances thermoelectric term can be dominant source of electric current in the material.

$$\vec{\nabla} V = -S(T)\vec{\nabla} T - \vec{j} / \sigma \tag{2}$$

The computing technique developed for metallurgical applications is applied to a quite different field, to fusion technologies in this work. In liquid lithium cooling system thermoelectric current may create force which may drive a liquid convection or alter pressure distribution in the liquid lithium. Low density of Li allows TEM forces to induce significant liquid lithium flow easily. Idea to use thermoelectric pumping effect to remove heat from a divertor has been explored in last few years by Ruzic [3]. It has been shown that in such a way an intense enough free surface flow can be generated in a system of parallel grooves. No outer power source is needed and flow is driven conditionally by the heat flux itself.

2. Presentation of the problem

We are considering another version of divertor design when the thermoelectric flow is generated in a capillary porous system containing of stainless steel mesh surrounded by liquid lithium. As a base for the calculation of TEM forces a traditional schematic CPS version [4] has been chosen. As an outer coolant instead of water liquid Ga is proposed, which is more effective and can sustain higher temperature. The behaviour of a CPS (Liquid lithium/Stainless steel mesh) subjected to homogeneous and inhomogeneous heat flux from plasma has been analyzed numerically. It is demonstrated that local heat pulse from plasma may cause forces which pushes lithium into plasma and away from hottest place. These forces may exceed gravity and capillarity and be dominant force to determine lithium flow in the divertor. Order of magnitude estimations has been carried out to compare different physical effects.

Table 1. Properties of liquid lithium, stainless steel and 2/3 SS+1/3 Li by volume porous media used in numerical simulations and force density estimations.

Property	**Symbol**	**Lithium**	**Stainless steel**	**Porous media**	**Unit**
Thermal conductivity	λ	44	16	26	W/m*K
Heat capacity	C	4350	500	1800	J/kg*K
Electrical conductivity	σ	$3.6\cdot10^6$	$1.3\cdot10^6$	$2\cdot10^6$	Sim/m
Absolute thermoelectric power	S	20	0	7	μV/K
Density	ρ	500	7500	5000	Kg/m^3
Surface tension	γ	0.32			N/m
Viscosity	μ	$6\cdot10^{-4}$			Pa*s
Thermoelectric figure of merit	Z_{TE}	1.64	0	0.54	

The CPS under consideration contains a of 7 mm thick SS mesh layer with characteristic structure size of 0.5 mm. Inside this layer 2/3 of the volume is SS mesh and 1/3 is liquid Li. Liquid lithium is fed from the thin layer at the bottom of the CPS and brought to the contacting surface by capillary forces and pressure difference. Li flow in the device is shown in Fig.1. The deposited power is removed from the bottom of CPS layer by a liquid gallium flow contained between 4 mm stainless steel walls. The application of Ga allows to increase a maximum working temperature to 400^{0}C. At temperatures over 400^{0}C the SS walls would loss their corrosion- resistance with regard to Ga which may lead to other problems during prolonged exploitation of the system. TE current is generated at the interface between two media with different absolute thermoelectric powers if temperature gradient is parallel to interface, but TE current is also generated in the volume of the material if S is function of temperature. Macroscale TE current circulation is generated at the surface between CPS and SS wall, while small scale TE current flow is generated within the CPS. In CPS current path length is comparable to mesh structure size and magnitude can vary depending on CPS geometry, temperature gradient and other parameters. In this work we analyze only on large scale TE current. Principal scheme of the 200x200 mm divertor panel is given in Fig.2.

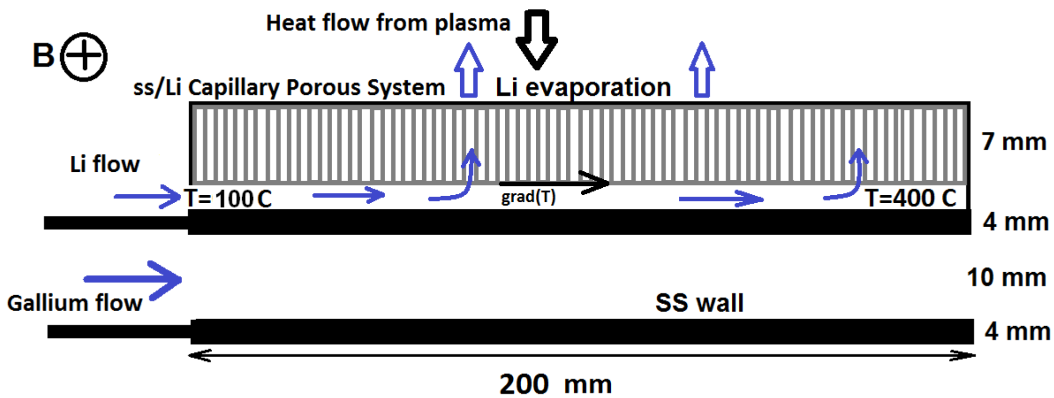

Figure 1: Li flow in the divertor. CPS here is depicted as array of the vertical stainless steel capillaries.

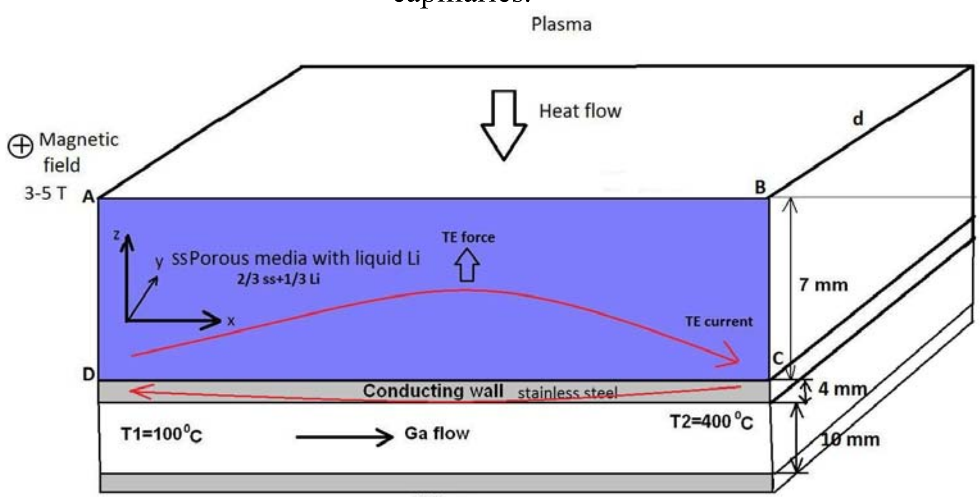

Figure 2: Schematic picture of 200x200 mm divertor plate. Thermoelectric current flow and Lorentz force are indicated with arrows.

Numerical models have been developed to calculate TE current density and TEM force if constant and inhomogeneous heat flux is applied perpendicular to the plasma/CPS surface. If homogeneous heat flux is applied to divertor plate depicted in Fig.2, then TE current flows in one direction through the CPS and in opposite through SS wall. Direction of the current is defined by the direction of temperature gradient and sign of differential thermoelectric power. Calculated TE current density in the case when a constant heat flux is applied and temperature gradient is perpendicular to CPS/SS surface is shown in Fig.3. In this case if heat flow is inhomogeneous, then situation is more complicated and current density and force distribution is difficult to predict. If Gaussian shape heat pulse is applied to plasma/CPS surface is numerically analyzed and results are shown and compared to homogeneous case in Fig.4. Temperature and current distribution are calculated Fig. 4b,c. Fig. 4d and Fig.4e compare TE force densities acting on CPS. Homogeneous heat flow creates almost uniform force perpendicular to plasma/CPS surface, while force density caused by inhomogeneous heat flow also creates force component parallel to CPS/plasma surface, thus may cause surface deformation and push Li out of the SS mesh in some places.

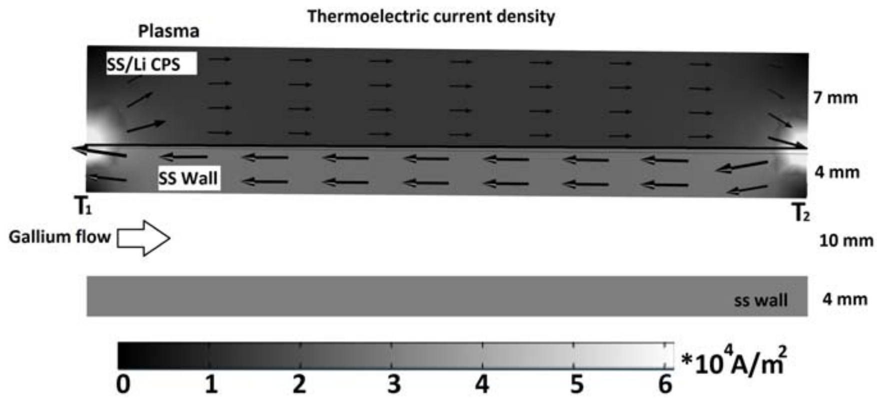

Figure 3. Thermoelectric current density in CPS region and in SS wall if constant heat flow is applied from the plasma zone.

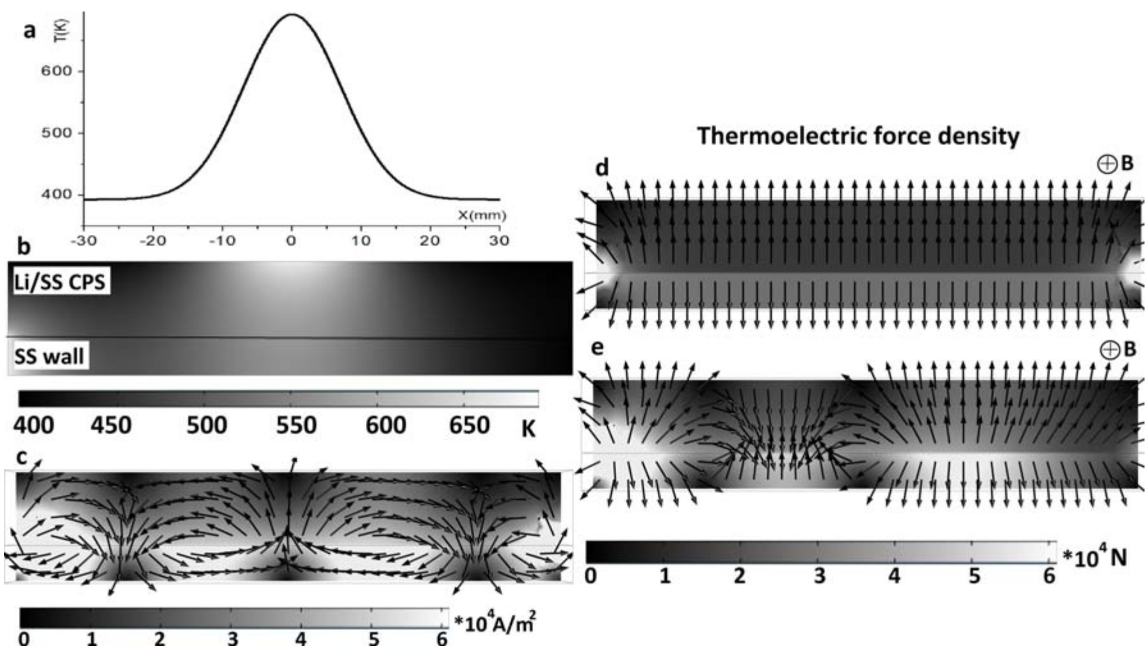

Figure 4. Thermoelectric current density if a non-homogeneous heat flux is applied. a - temperature profile along plasma/CPS surface, b - temperature distribution in the divertor plate, c - calculated thermoelectric current density. Thermoelectric force distribution in case of: d - homogeneous, e - inhomogeneous heat flow. Only CPS and SS wall are shown in this picture.

The following quantities are used in numerical models and force estimations: d = 0.5 mm-capillary characteristic length, L = 7 mm - CPS layer thickness, θ = 15 K/cm - temperature gradient along the CPS/SS interface, B = 1 T - magnetic field induction, u = 2 cm/s - characteristic Li flow velocity. Force order of magnitude estimations is given in Table 2.

Table 2. Force density estimation acting on CPS in macroscale

Force	Equation	Characteristic force density
Capillary force	$F_c = 4\frac{\gamma}{dL}$	55 kN/m^3
Gravity force	$F_g = \rho g$	70 kN/m^3
Viscosity	$F_v = \frac{32\mu u}{d^2}$	31 kN/m^3
MHD braking force [7]	$F_e = \sigma u B^2$	40 kN/m^3
TEM force [8]	$F_{TE} = \sigma \Delta S \theta B$	50 kN/m^3

3. Conclusion

It is demonstrated that TE current may create force which has significant effect on the liquid Li flow within CPS. It is found that liquid metal surface can be deformed and liquid metal can be pushed away from the hot zone by TEM forces. This force has to be taken into account during design of the system. If an inhomogeneous heat flow is applied than temperature gradient in the CPS has all three components and TEM force is present in CPS regardless of magnetic field orientation. In case of Gaussian shape heat impulse from plasma zone and constant magnetic field along the surface, liquid Lithium is pushed away from hot zone as demonstrated by numerical models. Force density estimations indicate that TEM force can exceed all other forces under certain conditions, thus the influence of thermoelectric phenomena in Li CPS has to be carefully analyzed and taken into account during design of divertor for fusion reactors. This phenomena needs to be deeper evaluated and understood for better usage of it and to avoid negative effects of TEMC.

4. References

[1] Li, X.; Fautrelle, Y.: Influence of thermoelectric effects on the solid-liquid interface shape and cellular morphology in the mushy zone during the directional solidification of Al-Cu alloys under a magnetic field. Acta Materialia, vol. 55 (2007), iss. 11, pp. 690-704.

[2] Kaldre, I; Fautrelle, Y; Etay, J; Bojarevics, A; Buligins, L: Thermoelectric current and magnetic field interaction influence on the structure of directionally solidified Sn-10%wt.Pb alloy. Journal of Alloys and Compounds, vol. 571 (2013), pp. 50-55.

[3] Ruzic, D.N.: Lithium Walls: The Ultimate Technology. Illinois: Center for Plasma-Material Interactions, 2010.

[4] Mironov, S.V.; Evtikhin V.A.: The tests of liquid metals (Ga, Li) as plasma facing components in T-3M and T-11M tokamaks. Fusion Engineering and Design, vol. 81 (2006), p. 113-119.

[5] Shercliff, J. Thermoelectric magnetohydrodynamics. J. Fluid Mechanics, vol. 91 (1979), part 2, pp. 231-251.

[6] S.J. Zinkle. Summary of physical properties for lithium, Pb-17Li, and (LiF)n*BeF2 coolants. APEX Study Meeting Sandia National Lab, July 27-28, (1998).

[7] Davoust, L., Bertrand, F., Moreau, R., Tanguy, P., & Bolcato, R. Recent results on MHD damped convection in the horizontal Brigman configuration. Magnetohydrodynamics, vol.33 (1997), no. 4, pp. 319-327.

[8] Wang, J., Fautrelle, Y., Ren, Z., Li,X., Nguyen-Thi, H., Mangelinck-Noel, N., Salloum Abou Jaoude, G., Zhong, Y., Kaldre, I., Bojarevics, A., Buligins, L.: Thermoelectric magnetic force acting on the solid during directional solidification under static magnetic field. Applied Physics Letters, vol. 101 (2012), iss. 25, 251904.