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LETTER

Lithium–metal infused trenches (LiMIT) for heat removal in fusion devices

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Abstract

Observation of liquid lithium flow in metal trenches has been made using a lithium–metal infused trench (LiMIT) tile and is reported here. The flow is self-pumping and uses thermoelectric magnetohydrodynamics to remove heated lithium and replenish it at a lower temperature. Flow velocities have been measured and compared with theoretical predictions.

(Some figures in this article are in colour only in the electronic version)

One of the top issues facing a fusion power reactor is how to handle the heat load at the plasma–material interface. An alternative path to the current solid materials is that of using flowing liquid metals. Previously, it has been shown that lithium is a promising liquid metal for this application with experiments in CDX-U handling a heat spot of 60 MW m^{-2} [1] without any noticeable evaporation. The thermoelectric effect between Li and stainless steel was shown to cause flows in the liquid Li [2] and with the addition of a magnetic field thermoelectric magnetohydrodynamics (TEMHD) [3] can be used to stir the liquid metal.

This letter describes a method utilizing TEMHD to remove a high-heat flux with metal tiles having a series of trenches in the radial direction allowing the radial flow of lithium across the separatrix strike point as shown in figure 1. The thermoelectric effect causes a current to develop between a liquid metal and container wall when a temperature gradient is present along the interface between them. If an external magnetic field is applied with a component perpendicular to the interface, then a Lorentz force results in a net body force on the liquid resulting in a TEMHD flow [4].

Figure 2 shows the concept of how a TEMHD-driven lithium divertor could work. As the divertor heat stripe hits the Lithium–metal infused trenches (LiMIT) it causes the temperature on the top surface to increase. This temperature gradient produces a thermo-electric current in the lithium in the vertical direction. Since the toroidal magnetic field is primarily perpendicular to the trench direction there will be a force on the lithium in the radial direction along the trenches.

While initial designs would not be actively cooled, forced cooling illustrates how the LiMIT concept could be expanded to a Fusion Nuclear Science Test Facility (FNSTF), as is shown in figure 2. Even without the cooling channels, the temperature gradient will still be established during the shot due to thermal inertia. A key aspect of this approach is that it is self-limiting; the higher the temperature gradient is the faster the lithium flows, which in turn cools the structure. With no heat flux the lithium is stationary.

LiMIT has been built at the University of Illinois and tested in the Solid/Liquid Divertor Experiment (SLiDE) [5]. A focused electron beam stripe hits the centre of trenches within a 60° angle from normal mimicking a divertor or limiter heat-flux profile. At the same direction of the e-beam a magnetic field is kept to provide a driven force for the lithium.

The stainless-steel trenches have a width of 2 mm, a length of 90 mm and a depth of 10 mm. Overall there are 20 trenches for the lithium to flow through. The trench structure sits in a mount that is hollowed out around the sides and underneath so that the lithium can flow out of one end, down around the back of the trenches and then back into the trenches through the other side.

The flow in the trenches is observed and measured by dropping Li_2O particles onto the flowing lithium surface and tracking the movement of these particles with digital camera. Surface temperature is measured by an Inframetrics 760 IR camera.

Figure 3 shows four frames of a movie taken from the top observation port showing a Li_2O particle flowing with the lithium along a trench. The electron beam power was $P = 1.5$ kW corresponding to an overall heat flux $\Phi = 3$ MW m^{-2}. The magnetic field perpendicular to the trench

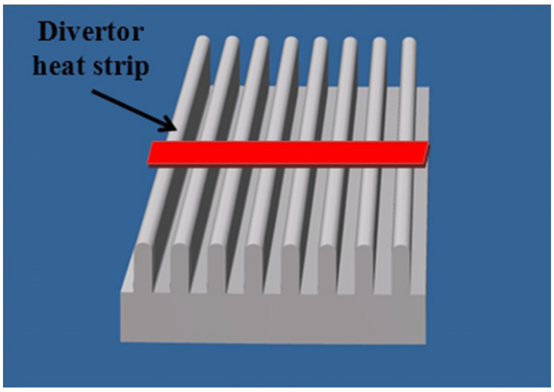

Figure 1. The LiMIT concept: metal tiles with radial trenches containing lithium. The trenches run in the radial (poloidal) direction such that they lie primarily perpendicular to the toroidal magnetic field and the divertor heat stripe.

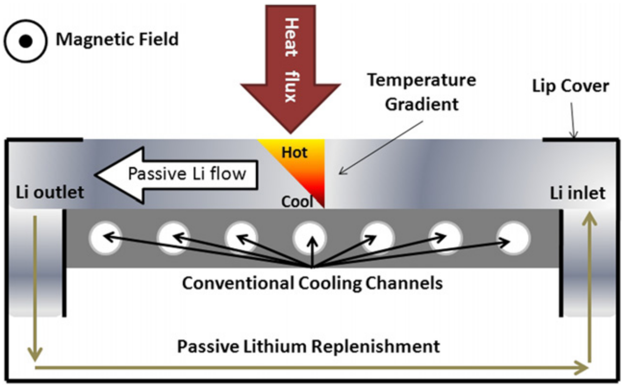

Figure 2. Concept for heat removal using TEMHD. The Li flows in the slots of the metal plate powered by the vertical temperature gradient.

was $B = 0.0589$ T. The average measured velocity of the flow was $v_{\text{Li}} = 0.22 \pm 0.03\,\text{m}\,\text{s}^{-1}$. Multiple movies were made showing movement of such a particle.

Figure 4 shows the temperature increase of the trench surface during 20 s heating period. Two measurements were taken before and after the heating so that the difference can reveal the temperature increase. The emissivity of lithium is assumed to be 0.05 which was measured before for a pool of lithium. Figure 4 shows the asymmetric temperature distribution along the flowing direction.

From the IR measurement, the average flowing velocity can be estimated by $u = \frac{q}{\rho C_P h w (\Delta \frac{T}{2})}$ assuming the heat from the beam is transferred out of the trench through the convection and the temperature at the bottom interface is near zero. Therefore, the average temperature increase in a single channel is half the surface temperature increase. Here q is the power absorbed by a single trench. ρ is the density of lithium. C_P is the heat capacity of lithium. h is the height of the trench and w is the width of the trench. ΔT is the temperature difference between the inlet and outlet temperatures were measured in ten trenches and the resulting velocity is $0.15 \pm 0.07\,\text{m}\,\text{s}^{-1}$. The large error and some hot spots in figure 4 are mainly due to the impurity layer in the trench which alters the surface emissivity and can cause saturation.

A theoretical model has been derived based on the following assumptions: the average velocity only has z component (along the direction of the flow) and is constant in both regions; after the heating point the temperature gradient along the y direction will exist but will become zero after the lithium flows back to the right inlet; the pressure is continuous and the pressure changes linearly in each region (figure 5). The pressure at the interface between both regions is zero and the pressure at the outlet and inlet is P. The length of the left region is assumed to be L_1 and that of the right region is L_2. The magnetic field is along the x direction.

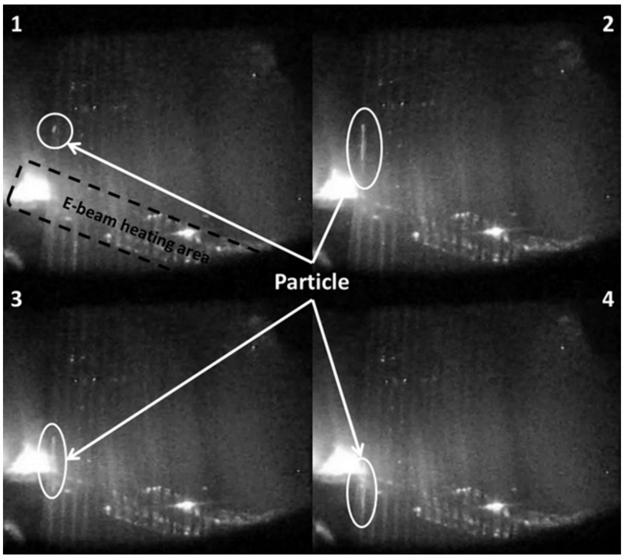

Figure 3. Flow measurements of the lithium using a Canon SX200IS movie camera with a frame rate of 25 frames per second. The heat stripe is perpendicular to the trenches as shown in the first frame. These four frames show a particle flowing along one of the trenches. The elongation of the track is due to the movement during the exposure of each frame.

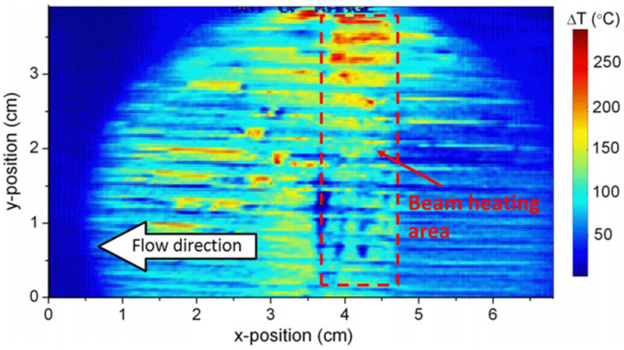

Figure 4. IR temperature measurement of the temperature increase during 20 s heating period. The initial temperature distribution has been subtracted and the lithium emissivity is assumed to be 0.05. Some of the hot and apparently cold spots are due to saturation of the camera from stationary impurities.

Following the method from Shercliff [3] and applying the current conservation and Kirchhoff's law, the mean velocity in the left hot region is

$$\overline{u_{\text{left}}} = \frac{Ha - \tanh(Ha)}{(Ha + C\tanh(Ha))}\left(\frac{S}{B}\frac{\mathrm{d}T}{\mathrm{d}y} - \frac{1+C}{\sigma B^2}\frac{\mathrm{d}P}{\mathrm{d}z}\right). \qquad (1)$$

Here $C = w\sigma/t\sigma_w$, $\mathrm{d}P/\mathrm{d}z = P/L_1$ and Ha is the Hartmann number which is $Ha = Bw\sqrt{\sigma/\mu}$ representing the ratio of

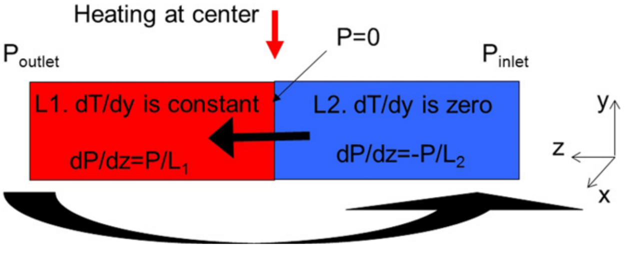

Figure 5. Set-up of the 2D model. The heat flux hits at the boundary between the two model regions. The left-hand boundary and the right-hand boundary are treated as continuous.

electromagnetic force to viscous force. w is the thickness of lithium trench, t is the thickness of the stainless-steel wall, σ_w is the electric conductivity of stainless steel, σ is the electric conductivity of lithium. S is the Seebeck coefficient of lithium and its value is 25 μV K^{-1} [6].

In the right region a similar mean velocity can be derived as

$$\overline{u_{\text{right}}} = -\frac{1}{(\sigma B^2)\left(\frac{\mathrm{d}P}{\mathrm{d}z}\right)\left(1-\frac{\tanh(Ha)}{Ha}\right)} \qquad (2)$$

where $\mathrm{d}P/\mathrm{d}z = -(P/L_2)$. The continuity of velocity requires $\overline{u_{\text{left}}} = \overline{u_{\text{right}}} = \bar{u}$ we can obtain the mean velocity from equations (1) and (2)

$$\bar{u} = \frac{\frac{S}{B}\frac{\mathrm{d}T}{\mathrm{d}y}}{\frac{Ha+C\tanh(Ha)}{Ha} + \frac{(1+C)L_2}{L_1}\left(1-\frac{\tanh(Ha)}{Ha}\right)}. \qquad (3)$$

Based on the assumption that the absorbed energy could transfer in two ways: 1D heat conduction along the y direction in the left region and 1D-convection along the z direction, a power balance equation can be written as

$$q = k\frac{\mathrm{d}T}{\mathrm{d}y}L_1 w + \rho C_P\left(\frac{1}{2}\frac{\mathrm{d}T}{\mathrm{d}y}h\right)\bar{u}hw. \qquad (4)$$

The LHS is the power that is absorbed by the trench and the first term of RHS is the heat conduction term. The second term in RHS is the convection term and $\frac{1}{2}(\mathrm{d}T/\mathrm{d}y)h$ is assumed to be the mean temperature rise in the trench.

After substituting the average velocity into the above equation we can obtain an equation of $\mathrm{d}T/\mathrm{d}y$:

$$\frac{1}{2}\rho C_P h^2 w \frac{\frac{S}{B}\left(1-\frac{\tanh(Ha)}{Ha}\right)}{\frac{Ha+C\tanh(Ha)}{Ha}+\frac{(1+C)L_2}{L_1}}\left(\frac{\mathrm{d}T}{\mathrm{d}y}\right)^2 + kL_1 w\frac{\mathrm{d}T}{\mathrm{d}y} = q. \qquad (5)$$

In our experiment the heating power is 1500 W and since there are 20 trenches in the tray the energy absorbed by each trench (q) is 75 W. The transverse magnetic field B is 0.0589 and $w = 0.002$mso the corresponding Ha is 9.86. L_1 is assumed to be half of the trench length so L_1 is 0.05 m and L_2 is also 0.05 m. ρ is the density of lithium, C_P is the heat capacity of lithium and k is the heat conductivity of lithium.

Resulting $\mathrm{d}T/\mathrm{d}y$ from equation (5) is 1940 K m^{-1} and with this temperature gradient the average velocity is 0.15 m s^{-1} which is similar to the velocity from the IR measurement and is within the uncertainty of the measured velocity via the particle tracking method.

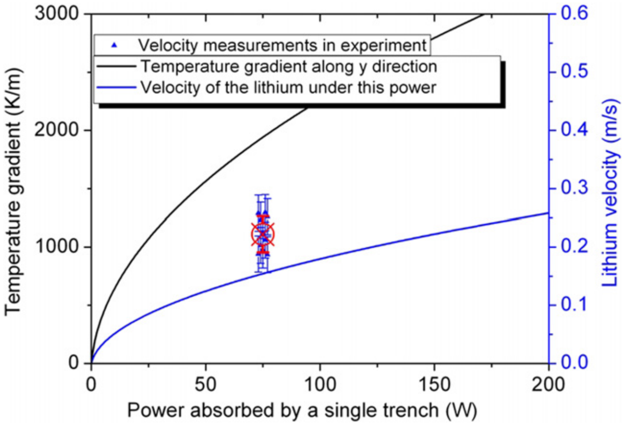

Figure 6. Plot of equations (3) and (5) versus the power absorbed by a trench. Experimental measurements of velocity from the particle tracking method and their mean (red circle) are also shown.

Figure 6 shows the temperature gradient and the velocity of lithium surface increase with the power absorbed by a single trench. When the power is low, the temperature gradient increases quickly since at this time the heat conduction is dominant. But when the power is high the flowing lithium will efficiently bring the heat away leading to a decreasing slope of the temperature gradient, which illustrates the heat transfer ability of flowing lithium.

One limit of this concept to remove heat is the thermoelectric current in the radial direction due to the heat-flux profile perpendicular to the strike point [7]. The resulting $J \times B$ force could eject the lithium. The current along the trench can be calculated from

$$j_{\text{TEMHD}\parallel} = \frac{1}{1+C}\sigma S\frac{\mathrm{d}T}{\mathrm{d}z}. \qquad (6)$$

For $\Delta T_{\parallel} = 100$ K, $\mathrm{d}T/\mathrm{d}z = 2000$ K m^{-1}, and C and S from earlier, the $j_{\text{TEMHD}\parallel} = 8.9 \times 10^4$ A m^{-2}. Total current along the Li trench is then 0.45 A and the force from the TEMHD is 0.045 N. The capillary force is $2\Sigma L$ and $\Sigma = 0.3$ N m^{-1} at 300 °C. So the capillary force which constrains ejection is about 0.06 N. This force is not altered by a change in the thermoelectric power so while there could be a net force upwards, it can be balanced by choosing the width of the trenches. The ability of LiMIT to remove heat is limited primarily by the surface temperature of the lithium and the solid trench. The balance between the cooling efficiency and the heat power is the key to find out the maximum heat flux the trench can withstand before the temperature goes too high.

In summary, utilizing TEMHD, self-flowing molten lithium has been shown to be able to remove a peak heat flux of 3 MW m^{-2} with the potential possibly to remove up to 20 MW m^{-2} with stainless trenches and this geometry, or more with Mo and different trench widths and heights under high magnetic field. A 2D theoretical model based on the Navier–Stokes equation coupled with heat conduction and convection model predicts the observed velocity within 25%.

Future work will quantify the heat removal capacity more precisely, test differing geometries, quantify the IR temperature profiles in more detail and investigate the performance under high magnetic field.

Acknowledgment

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