MHD and Heat Transfer Issues and Characteristics for Li Free Surface Flows under NSTX Conditions

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ABSTRACT

In the APEX study, one of the tasks focuses on the exploration and identification of the attractive options and issues for flowing liquid lithium walls in the NSTX device. In addition to constraints imposed by the machine, the operating conditions of the flowing liquid walls along the center stack and divertor areas are guided by MHD and heat removal requirements. In this paper, we present important MHD and heat removal issues and analysis for the proposed free surface lithium flows under NSTX conditions. It is shown that of all MHD effects, the one caused by the normal magnetic field is the most important. The flow over the center stack area is not affected by MHD interaction significantly, whereas flow over the inboard divertor undergoes strong MHD drag resulting in flow thickening by several times. The flow over the outboard divertor is essentially stopped. The analysis shows that a flow with an inlet velocity of 2 m/s and film thickness of about 4 mm can be established to provide surface temperature less than 400° C for the center stack under a projected NSTX total heating power of 10 MW operation.

I. INTRODUCTION

There appears a noticeable interest in pursuing the potential physics and technology benefits of lithium walls on fusion reactors. Lithium surface at the plasma edge is believed to improve plasma performance by reducing recycling and improving edge control. Furthermore, it seems capable of allowing stable tokamak operation with increased elongation under reactor conditions. Modeling results indicate that the magnitude of improvement can be large, with up to a factor of three improvements in stable beta (from 5-7% to 20-22%) at aspect ratio 4 and 3, respectively[1,2]. Flowing walls with magnetic Reynolds number >1 would potentially stabilize resistive wall modes as well allow for higher beta steady state equilibrium with very hollow current profiles. From the technology viewpoint, a flowing lithium wall helps reduce the thermal stress and consequent failure rates of the first solid wall. These physics and technology benefits provide incentives for exploring flowing liquid lithium walls. In the APEX[2] study, one of the tasks focuses on the exploration and identification of the attractive options and issues for flowing liquid lithium walls in the NSTX device.

The primary role of a flowing liquid wall test in a major operating plasma confinement device (e.g. NSTX) will be to provide integrated operational experience for liquid walls and to understand and quantify the effects of lithium walls on plasma performance and liquid wall responses to various plasma operational conditions. While NSTX operating conditions, such as magnetic field strength, may not resemble reactor conditions, NSTX results will be useful in guiding designs for more exhaustive environmental conditions. NSTX tests will also play a significant role in integrating technology elements for a flowing lithium wall. Furthermore, extensive comparisons between experimental measurements and code predictions will be possible.

Several flowing liquid wall options are possible in NSTX. A straightforward option is an axi-symmetric flowing annular liquid film on the surface of the center stack, which forms a natural inboard divertor as the flow approaches the bottom of the center stack. An addition to this is a flowing liquid wall at the outboard divertor using a separated inlet manifold system as shown in Figure 1. The main focus of this paper is to define the MHD and heat transfer characteristics of these flowing lithium film flows. MHD analysis is performed for an axis-symmetric flow on top of an isolated backing plate, while the impact of conducting back plate is discussed in section III. D. Specifically, the lithium flow operating conditions are guided by integrating the program needs with the system (e.g. heat flux values) and performance requirements (e.g. surface temperatures) in addition to the constraints imposed by the machine. Certainly, other flow options for NSTX applications including droplet and flows through perforated channels ("soaker hose" concept) may be possible. However, their MHD and heat transfer properties are not yet characterized, and the experimental and theoretical data on the behavior of droplets in a non-uniform magnetic field are scarce[3]. This makes design very uncertain.

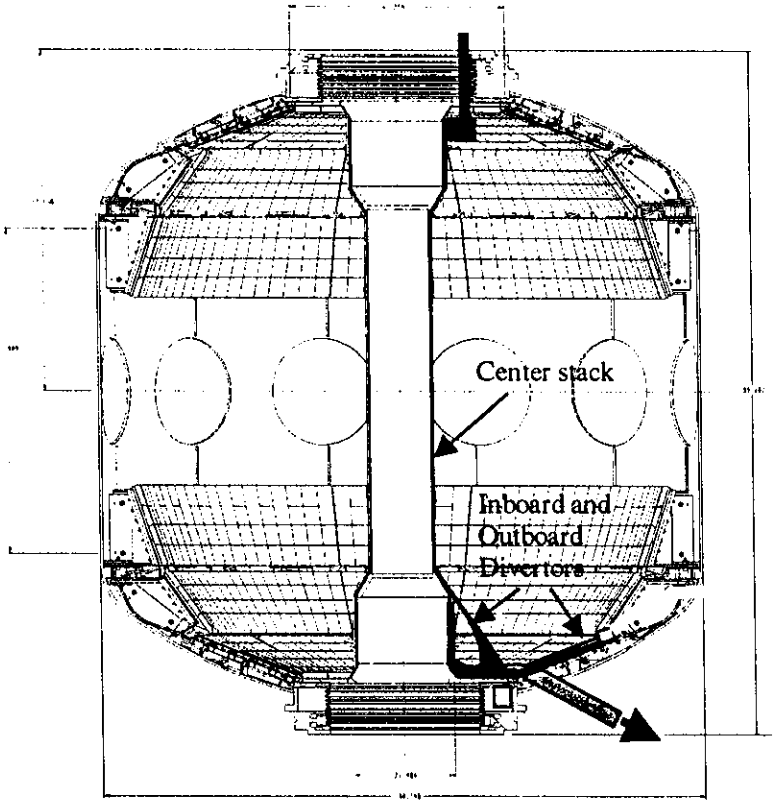

Figure 1 Example of Flowing Lithium Walls in NSTX Device in APEX Exploration Study

II. NSTX MAGNETIC FIELD CHARACTERISTICS AND THEIR IMPACT ON MHD

The issue of establishing a viable NSTX lithium flow configuration deals with MHD interaction. The feasibility of liquid metal walls in particular is very sensitive to the variation in strength and orientation of the fields. A 3-D magnetic field profile, which corresponds to a discharge with β=10%, along the inner boundary of the NSTX device is shown in Figure 2. The distinct features of this magnetic configuration include: (1) a uniform toroidal magnetic field accompanied with a small radial field along the center stack; (2) a relatively strong magnetic field perpendicular to the inboard and outboard divertor resulting from a combined vertical and radial field components; and (3) a non-uniformity like the 1/R dependence of the toroidal field on the major radius.

The most important effect associated with the magnetic field is the drag force caused either by the toroidal magnetic field gradient or by the wall-normal magnetic flux. This results in a MHD drag force and a reduced flow velocity due to the induced toroidal electric current. If this opposing drag force is strong enough the flow may become unstable or even cease. Moreover, a spiral motion can develop due to a combined effect of the gradient toroidal magnetic field and the wall-normal magnetic field and cause centrifugal instability. On the other hand, without toroidal axi-symmetry of the flow and field, reliable insulator coatings may be required on all surfaces in contact with the LM layer. Eddy current forces perpendicular to the surface can pull the LM off the surface, even when a complete axi-symmetry is assumed in the toroidal direction. Additional pumping is required to push the liquid against the MHD opposing force when extracting Li from the chamber. More complicated MHD issues include poloidal fields effects, effects of injecting poloidal current on flow stability, effects of temporal magnetic field variations on flow stability and motions, and effects of non-axisymmetry.

Our near-term goal is to define schemes for establishing and maintaining stable flowing lithium walls in spatially varying magnetic fields and evacuating fluids away from the chamber without causing unacceptable flow degradation.

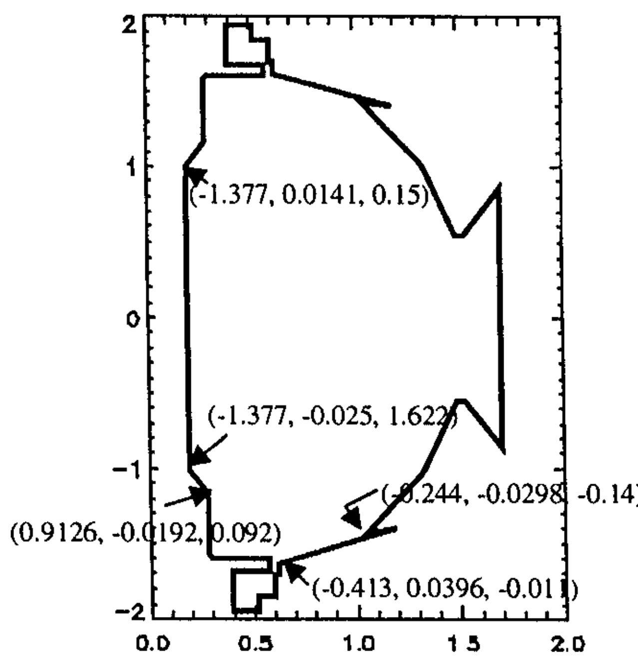

Figure 2 NSTX Boundary Magnetic Field Strength for a Discharge with Beta of 10%. Values are field strengths for B_t, B_r, B_v in tesla.

III. MHD ANALYSIS

Among the issues that are being analyzed are the impact of the wall-normal magnetic flux, effect of the toroidal field gradient on the flow, and the effect of the multi-component magnetic field. These issues are addressed separately for the center stack with the inboard divertor area, and the outboard divertor region.

A. Mathematics Model

The problems associated with a complicated MHD flow can be simplified, taking into account that (1) the flow is laminarized due to a strong magnetic field and, (2) as for an axially symmetric flow there is no azimuthal or toroidal variation of the flow being considered. Furthermore, because the flow thickness is much smaller than the flow path, only streamwise changes of the external magnetic field are important (changes in the applied magnetic field in the normal direction are neglected). Besides that, the model assumes the boundary layer approximation in which diffusion transport in the flow direction is negligible compared to the convective one in the same direction. The third assumption was based on the inductionless approximation. The estimations carried out for the center stack and the divertor show that under NSTX conditions the magnetic Reynolds number is smaller then 1. Consequently, the induced magnetic field is much weaker than the external one and can be neglected where they appear together.

Based on this MHD model a finite-difference computer code has been developed[4]. The code uses the velocity, the pressure, and the magnetic field as the independent variables. The governing equations were formulated in terms of the boundary fitted coordinates. In what follows "x" and "y" are used for the streamwise coordinate and the wall-normal coordinate respectively. A mapping technique has been applied for tracking the free surface. Non-uniform meshes with the grids concentrating near the boundaries were used. The ADI method[5] was applied for solving the elliptic problem for the induced magnetic field used as a stream function of current, while the Blottner-type method[6] was used for solving parabolic equations for the velocity components.

The model includes all 3 components of the applied magnetic field and all 3 velocity components. It allows space (in the main flow direction only) and temporal variations of the external magnetic field. Different effects associated with the magnetic field gradients and with the applied electric currents can be analyzed. At present the model can not be applied to flows with non-axisymmetry, nor with large magnetic Reynolds number. Multi-surface flows with droplet formation or splashing as well as reverse or stagnant flows can not be analyzed either. Further steps leading to more general formulations will be considered in the future.

In addition, considering that the MHD drag can be viewed as an additional source term of body force in an axi-symetric flow configuration, a commercial CFD code (FLOW-3D) has been modified to study the effect of MHD on the surface characteristics based on volume of a fluid free surface tracking algorithm[7]. The modified code was used to analyze flow over the inboard divertor region.

B. Lithium Flows Along the Center Stack and Inboard Divertor

There are two mechanisms leading to MHD drag. First, if a toroidal field gradient along the flow direction exists, induced currents will appear, resulting in the opposing Lorentz force. There are no streamwise changes of the toroidal field over the center stack region, but changes take place in the inboard divertor area. An example of such currents is given in Fig.3.

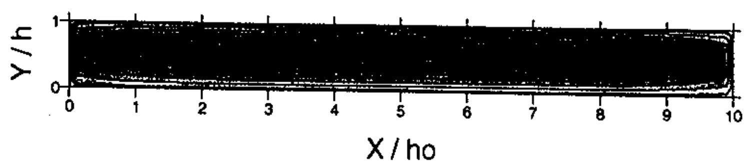

Figure 3 Induced current distribution inside the lithium (x: streamwise, y: wall normal, h: film thickness)

Another factor leading to MHD drag is the toroidal electric current, $j_t=\sigma U B_\perp$, where $B_\perp$ is the wall-normal component of the magnetic field and U is the streamwise velocity component. The opposing MHD force is a result of MHD interaction between j_t and $B_\perp$, so that MHD drag~ $(\sigma U B_\perp)\times B_\perp$. Both effects are considered in the analysis, although, as the analysis shows, the second effect is more significant for NSTX-type fields. The calculated flow thickness evolutions for different inlet conditions are shown in Figure 3 (Noted that the result of the inboard flow characteristics as shown is calculated based on the outlet velocity at the center stack. Neither momentum nor MHD loss was taken into account changing flow direction). For all cases the inlet velocity is set at 2 m/s. As shown, the gravitational force has been subdued by the MHD drag, which then results in a fairly uniform flow over the center stack region. Furthermore, as the flow approaches the inboard divertor region, the film has thickened considerably. Meanwhile velocity has been substantially reduced, due to a significant increase in

MHD drag. The heat transfer capability of such a reduced velocity flow becomes a concern with regard to the removal of the inboard divertor heat fluxes. Thus, if an integrated center stack and inboard divertor flow is favored due to its mechanical design simplicity, the inboard divertor heat flux becomes the dominating factor in determining the inlet flow characteristics. The goal is to identify a flow operating condition such that not only the surface heat can be adequately removed, but also without generating too many lithium vapors and, at the same time, keeping the lithium inventory to a minimum.

In addition, streamwise electric currents, which are induced by the space varying toroidal magnetic field, interacting with the normal magnetic field create a toroidal MHD force in the inboard divertor region. This force causes a spiral-type toroidal flow around the machine axis. Due to its toroidal motion, a centrifugal force appears. At its strong magnitude (if this force is not balanced by counteracting MHD or gravitational forces) the flow may lead to a centrifugal instability and provoke splashing or other unstable flow circumstances. Present analysis shows that the toroidal force is rather small under NSTX parameters and, at its first order approximation the centrifugal instability does not jeopardize the flow.

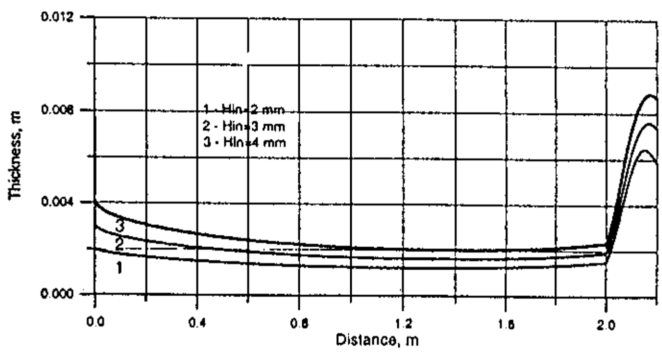

Figure 4 Flowing Lithium Film Thickness Evolution as Lithium Proceeds From the Top of the Center Stack Towards Inboard Divertor for Different Inlet Film Thickness (Inlet velocity = 2 m/s)

Analysis was performed to look into the details of lithium free surface characteristics under a wall-normal field and field gradient based on the aforementioned modified FLOW-3D code. As shown in Figure 5, lithium flow has thickened significantly over the NSTX inboard divertor region due to the MHD drag caused by a normal field gradient changing from 0.06 T to 0.03 T over a distance of 20 cm. However, if the wall normal field increases slightly (e.g. wall normal field varies from 0.08 T to 0.045 T over a 20cm long flow path) the flow becomes unstable as the lithium proceeds downstream. Droplets splashed away from the lithium surface are found due to the MHD opposing force (as shown in Figure 6). A simple analysis shows that as the normal field greater than ~ 0.08 T the MHD induced opposing force is much greater than the gravitational force (more than 5 times), which may be the reason to cause this unstable effect. Further increase in wall-normal magnetic field results in a complete stop of the flow. Qualitatively, the modified FLOW-3D results agree with that of finite difference 3D-MHD code based on a mapping technique (see Figure 4). The accuracy of both analyses presented in this paper remain to be checked by the experimental results.

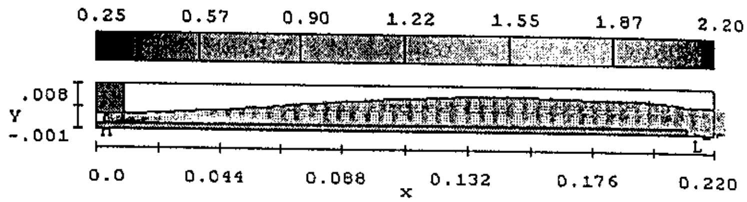

Figure 5 Streamwise velocity evolution as lithium proceeds over the NSTX inboard divertor under a linearly varying wall-normal field from 0.06 T to 0.03 T (velocity magnitude: meter per second, streamwise and normal lengths: m)

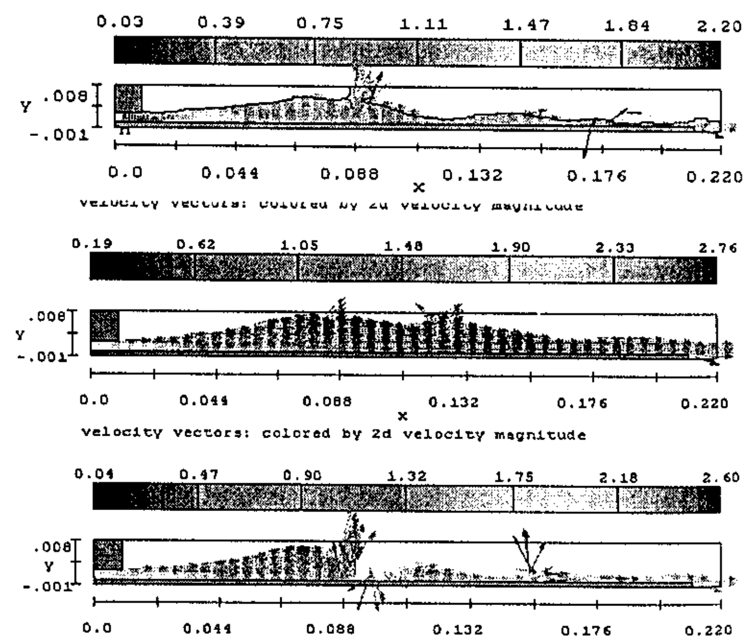

Figure 6 Lithium flow becomes unstable as the normal field increases. 2D X-Y plane streamwise flow velocity vectors under a high normal wall magnetic field (wall-normal field varying from 0.08 T at x=0 to 0.046 T at x=0.2m) at different travelling time = 0.6, 0.8, 1.0 seconds, respectively.

C. Outboard Divertor Flow

In this region, there exists a much larger wall-normal field (resulting from a combined vertical and radial field components) which leads to a significant MHD drag force to damp the flow. Also, the divertor inclination angle is quite shallow. Even though the initial velocity is as high as 10 m/s, the inertia and the gravitation are not enough to overcome the MHD drag. Also, no numerical solution has been found because there appears to be no driving force (source term) in the momentum equation. The MHD drag may be overcome by magnetic propulsion, a scheme proposed by L.Zakharov[8], through an applied external current in the lithium. The applied external current creates an acceleration pumping force, which then drives the flow (as shown in Figure 7). The calculations show that a current flux of 4 kA/m^2 is enough to overcome the opposing drag created by a field gradient of 4.5 T/m. However, to utilize this technique meaningfully it requires that the lithium flow from a higher field (near the axis) to a lower field (near the outer boundary). This is beacuse if the lithium flows from the outside inward, a strong normal force directed outward is expected to lift lithium off the solid substrate. Whether the space would become a problem at the bottom of the chamber for such a flow scheme remains to be studied.

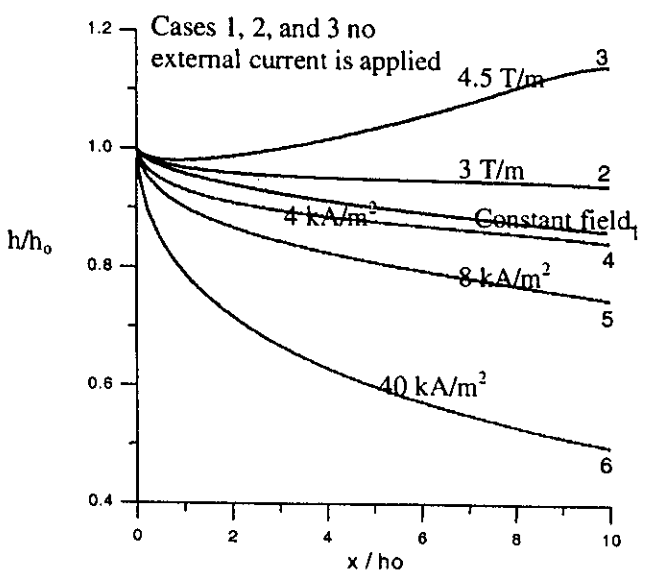

Figure 7 The MHD drag form the field gradient is overcome by a magnetic pumping effect from the applied external current. Cases shown the external current is applied to case 3 with a field gradient of 4.5 T/m. (h_0 = 2 mm)

On the other hand, instead of flowing toroidally continuously, it may be desired to subdivide the flow into several sections by means of obstacle partitions. Such a segmented flow design will reduce the toroidal current and hence reduce the drag. However, due to the existence of the partitions, new MHD effects appear. This includes a Hartmann effect at the walls perpendicular to the toroidal magnetic field if electrically isolated partition walls are used. The formation of a Hartmann layer is expected to cause an additional MHD drag. Further quantification of this MHD force is needed to justify the effectiveness of the proposed scheme. If an electrically conducting partition wall is used, MHD drag caused by the toroidal field becomes higher since the wall is less electrically resistive than that of the Hartmann layer. Again, further quantification of such an additional force is needed to justify the concept and determine whether an insulator is needed for lithium film flows at the outboard divertor region.

D. Effect of Conducting Substrates

It should be noted that the degree to which MHD effects manifest themselves depends on the structural wall electrical conductivity. For example, the flow damping force caused by the toroidal field gradient will be higher if the structural wall is electrically conducting, since the resistance of the wall shunts resistance of the liquid layer. As shown in Figure 8, due to the adjacent solid conducting wall, the induced current profile near the wall region has been modified significantly as compared to that of Figure 2.

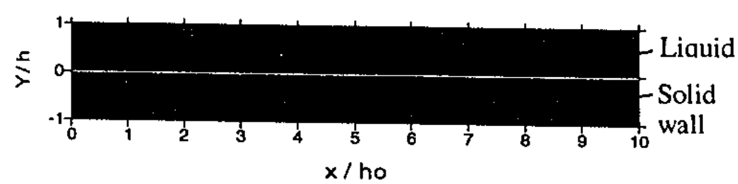

Figure 8 Effect of the electrically conducting solid wall on the induced electric current distribution among the lithium and solid wall

In the calculation, for the sake of simplicity, the electrical conductivity of liquid was assumed to be equal to that of the wall. Since the effect of the toroidal field gradient is much weaker than that caused by the wall-normal component, the additional MHD drag caused by the electrically conducting substrate solid wall is insignificant to degrade the flow under NSTX parameters. However, the conductivity of the wall should be taken into account for estimation of how much external current is needed to provide sufficient flow pumping. This is because the current that leaks to the wall cannot accelerate the flow.

IV. HEAT TRANSFER ANALYSIS

A projected NSTX surface heat load on the center stack under a total heating power of 11 MW is shown in Figure 9. The peak heat load is about 2.5 MW/m^2 and located at 0.35 m above and below the mid-plane (about 1 m away from the midplane is the top of the center stack = 0 m). To understand the heat transfer characteristics and temperature profile, the previously calculated velocity distributions are used in the heat transfer analysis.

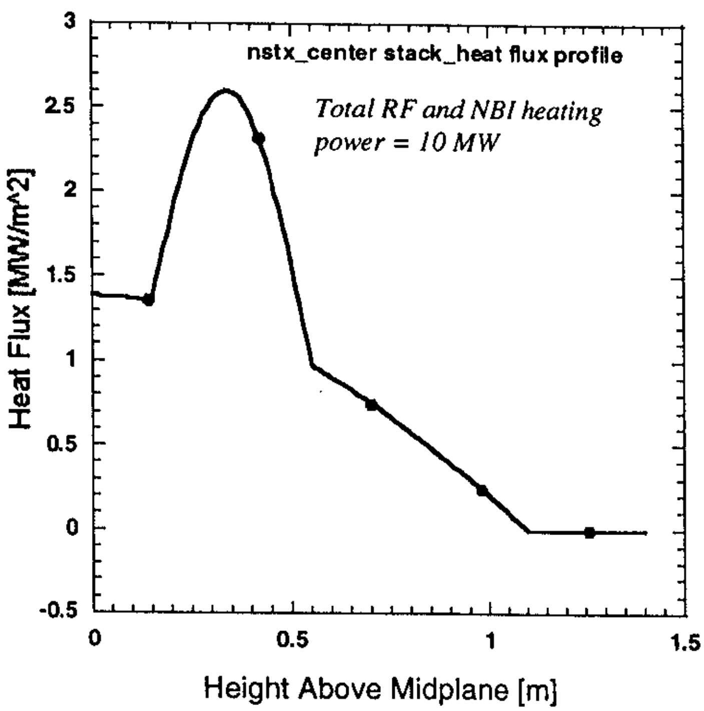

Figure 9 Projected surface heat load distribution on the center stack for a total heating power of 10 MW.

The calculated lithium free surface temperature profiles for different inlet film thicknesses as the flow proceeds from the top of the center stack down to the bottom of the center stack are shown in Figure 10. As shown, the lithium temperature increases gradually and reaches the first peak at about 0.35 m above the mid-plane. It decreases slightly due to a reduced surface heat flux and axial conduction. The same pattern repeats as the lithium proceeds downstream. The lithium surface temperature can be maintained below 400 °C assuming an inlet temperature of 220 °C for the inlet film thickness of 4 mm and velocity of 2 m/s. This set of operating conditions corresponds to a volumetric flow rate of 11 l/s, while 55 liters of lithium is needed for a 5-second operation. Since the surface temperature is tied closely with the velocity and surface heat load distributions, no definite fluid operating condition can be drawn at present for divertor heat removal. The temperature calculations in the inboard divertor area can be conducted once the spatial surface heat flux distribution in this area becomes available. However, the flow scheme for the outboard divertor region has to be identified first.

V. CONCLUDING REMARKS

The results of the on-going NSTX flowing lithium wall exploration study under the APEX program have been presented in this paper. The goal of this study is to identify flowing lithium wall configurations and associated operating conditions that would help achieve NSTX physics objectives and to characterize what the engineering requirements are. To meet this objective, MHD and heat transfer analyses have been performed for flowing lithium walls on the center stack, and inboard and outboard divertors for a projected surface heat load distribution with a NSTX magnetic field configuration at a discharge with beta of 10%. The analyses will further be combined with experimental investigations using a toroidal MHD facility (and others) before the employment of flowing lithium walls in the NSTX can be realized.

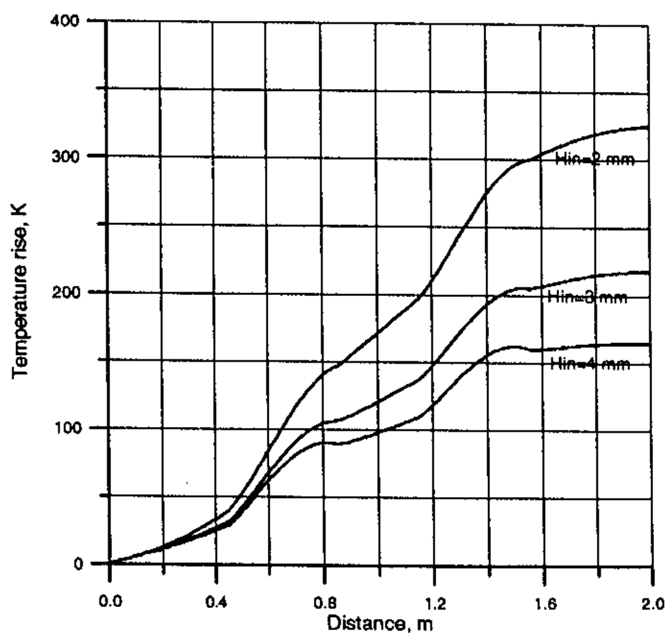

Figure 10 Surface temperature rises as lithium proceeds to the bottom of the center stack for different inlet film thickness. Lithium inlet velocity = 2 m/s.

In the center stack region the lithium is driven by the gravitational force opposed by a relatively weak MHD force caused by the wall-normal component of the magnetic field. The analysis show that a flow with an inlet velocity of 2 m/s and film thickness of about 4 mm can be established to provide a surface temperature less than 400° C. This set of operating conditions corresponds to a flow rate of 11 l/s. The maximum allowable lithium inventory in the NSTX is expected to adjust the flow condition as well as to define proper flow loop configurations. In addition, the calculation detects a small amount of toroidal force in the flow, which may lead to a non-dangerous centrifugal instability.

In the inboard divertor region, the MHD drag caused by the wall-normal magnetic field significantly slows down the flow (about 2 times). The exact flow condition can be established once the surface heat load distribution is available. As a means to mitigate excessive flow thickening and heat transfer degradation, either different central column geometry or the magnetic propulsion effect could be used.

The film flow down the outboard divertor is essentially stopped because of the strong MHD interaction between the induced toroidal current and the wall-normal field component. The magnetic propulsion is not applicable to this flow orientation since the applied current causes a strong normal force directed outward to lift the flow. It is possible to reduce the MHD drag by segmenting the continuously toroidal flow into several sectors. Yet, analysis is needed to evaluate the effectiveness and determine whether an insulator is needed. On the other hand, the magnetic propulsion technique is applicable if the liquid flows from inside outward (from a higher field to a lower field). However, the required streamwise current flux might be rather high. Different heat removal schemes such as droplet or jet curtains will also be considered in the future.

NOMENCLATURE

B: magnetic field strength
h (H): film thickness
x: streamwise coordinate
y: normal coordinate
U: streamwise velocity

Greek
σ: electrical conductivity

Sub and super-scripts
0: inlet
t: toroidal
r: radial
v: vertical
⊥: wall normal

ACKNOWLEDGEMENTS

This work was performed under U. S. Department of Energy Contract DE-FG-03-86ER-52123. NSTX boundary field strength was provided by Dr. D. S. Darrow of the Princeton Plasma Physics Laboratory.

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