# Concept Description and Thermalhydraulics of Liquid Surface FW/Blankets for High Power Density Reactors

**A. Ying, N. Morley, K. Gulec, B. Nelson[1], M. Youssef, and M. Abdou**

**Mechanical and Aerospace Engineering Department, UCLA**
**405 Hilgard Avenue**
**Los Angeles, CA 90095-1597**

**[1] Oak Ridge National Laboratory**
**Oak Ridge, TN 37831-8218**

## ABSTRACT

The attractive features and scientific challenges offered by the liquid wall systems render them strong candidates for investigation in the APEX project[1]. In particular, their high power density capabilities make the fusion reactors economically competitive. In this paper, as part of evolving a practical design based on this evolutionary idea, issues concerning thermalhydraulics of liquid surface first wall/blankets were analyzed. Design approaches as presently envisioned include both liquid films over the solid surface and gravity driven thick liquid jets using lithium and flibe as working fluids. The analyses involved defining liquid systems operating conditions, such as velocity and inlet/outlet temperatures, as well as to calculate free surface temperature so that the evaporation rate from the free surface would not jeopardize plasma operation while maintaining the liquid temperature within the operating windows for high thermal efficiencies. All analyses were performed for a neutron wall load of 10 $MW/m^2$ and its corresponding surface heat flux of 2 $MW/m^2$. The results indicated that high velocities, hard x-ray spectra and turbulent heat transfer enhancement were necessary conditions for keeping flibe first wall temperature low. On the other hand, at velocities of 20 m/s or higher, it appears possible to maintain lithium film evaporation rate below $10^{20}\#/m^2s$ in an ARIES-RS type configuration. Nevertheless, present analyses have not uncovered any basic flaws or major shortcomings in the underlying scientific or technical arguments for the concepts. Yet, engineering innovations of how to maintain and control the flow and the associated analyses are still needed.

## INTRODUCTION

Free liquid surfaces appear to be suitable for handling the high neutron wall load and high surface heat flux in future high power density fusion reactors. The general liquid wall approach has some very obvious attractive features including the reduction of radiation effect in structural material, the elimination (or reduction) of FW thermal stresses, the elimination of thick plasma facing armor materials, and a possibly significant reduction of the replacement time. Design ideas as presently envisioned for magnetic fusion devices include both fast moving, thin liquid films flowing over the FW solid surface, and thick liquid jets acting as both FW and blanket flow. The thick liquid wall concept was first proposed for an FRC device in the late 1960s, where the plasma volume were surrounded by a 75cm thick, free surface lithium blanket flowing at 30 m/s [2]. The concept was recently extended to a tokamak configuration in which a slug flow, straight through inboard and two counter rotating outboard sections were introduced [3]. In contrast to that the jet flows without any structure or container, the liquid film adheres to the surface by the centrifugal force. The FW liquid is injected into the vacuum chamber at a rate great enough to actively convect away surface heat and initial high intensity neutron energy deposition. The liquid could then be used as a free surface divertor and recirculated as coolant through the blanket to heat it to efficient power conversion temperatures as shown in Figure 1.

The amount of hot liquid in the vacuum environment raises concerns regarding plasma contamination by evaporated liquids. There are also fundamental questions regarding the adaptation of liquid flows to the topological constraints of toroidal plasma devices including penetrations. MHD issues will need to be investigated in order to validate the possibility that such films can indeed be created and sustained along their required flow length when the fluid is an electrical conductor.

In this paper, thermalhydraulics aspects of the flow characteristics and the associated hydrodynamic stability issues as well as of the heat transfer capabilities are analyzed for both lithium and flibe as working liquid. Flibe is the favored liquid from the viewpoints of the shielding, pumping and safety characteristics. However, lithium is a low Z material and may be more compatible with plasma operation. Utilization of lithium will have to deal with the MHD effects, not just in the surface flows, but in supply lines and feed systems, and so may still require electrical insulating coatings. It is believed that an understanding of the basic thermal-hydrauilcs performance of the free surface liquid flows is imperative for the ultimate development of a practical design.

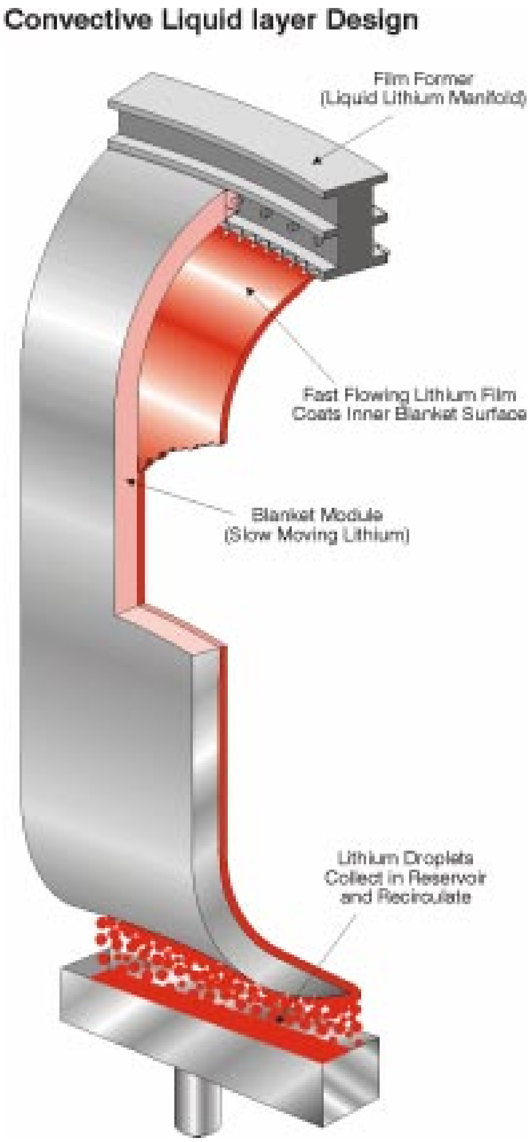



**Figure 1 Schematic View of Convective Liquid Wall Design**

**THIN FILM FLOWS W/O MHD EFFECTS**

One of the difficulties involving the use of free surface films for fusion reactors relates to the flow on a concave surface. To ensure a compact flow trajectory along the plasma contour lines and yet not to interfere with plasma operation, the flow has to carry adequate centrifugal inertia against the gravity, friction and MHD forces. The hydraulics of a thin flow on a typical plasma topological surface is predicted using the simplified conservation equations for mass and momentum in cylindrical coordinates (see figure 2).

$$\frac{d\left(hV_\theta\right)}{d\theta} = 0 \quad \text{(continuity)} \tag{1}$$

$$\frac{V_\theta^2}{R} = \frac{1}{\rho}\frac{dp}{dr} + g\cos\theta \quad \text{(r - mom)} \tag{2}$$

$$\frac{V_\theta}{R}\frac{dV_\theta}{d\theta} = -\frac{1}{\rho R}\frac{dp}{d\theta} + g\sin\theta - F_{friction} \quad (\theta\text{ - mom}) \tag{3}$$

The conservation equations can be manipulated into the following form by making the assumption that the film is thin (h/R << 1).

$$V_\theta = q_o/h \tag{4}$$

$$p(R,\theta) = \left( V^2/R - g\rho\cos\theta\right)\cdot h \tag{5}$$

$$\frac{dh}{d\theta} = \frac{-Rgh^3\sin\theta + Rh^3F_{friction}}{gh^3\cos\theta + q_o^2} \tag{6}$$

The equations can then be solved to produce profiles of $V_\theta$, h and p as a function of location on the arc. The quantity p is an indicator of the adherence of the film, and is always positive for attached flows. The equilibrium height can be determined by setting the numerator of the equation for h equal to zero. This is the point where friction balances gravitational acceleration. The equations are thus very sensitive to the definition of the friction term.

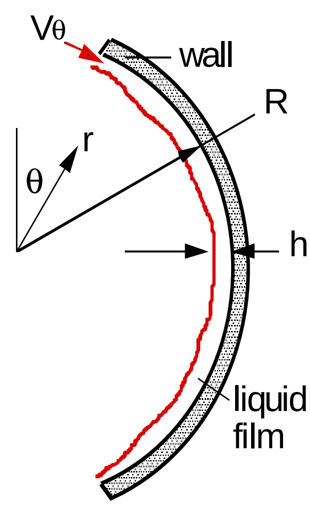



**Figure 2 Simplified cylindrical geometry for hydraulics calculations of thin films**

The appropriate friction term is determined by the type of flow. For an electrical semi-conductor like flibe, the flow is turbulent and the friction is estimated from the

Darcy-Weisbach formula applied to open channels using the appropriate friction factor, *f*

$$F_{friction} = \frac{f q_0^2}{8h^3} \tag{7}$$

For an electrical conductor like lithium, the flow is most likely laminarized, depending on the flow velocity, and the friction is estimated using the fully-developed Hartmann flow profile to determine the shear at any sidewalls (due to the toroidal field) and the back plate (due to any radial field component).

$$F_{friction} = \left( \frac{2B_T}{hw} + \frac{B_R}{h^2} \right) q_o \sqrt{\sigma v / \rho} \tag{8}$$

It should be noted that this formula assumes the all wall to be electrically insulated from the flow, and that electrical currents behave as in fully-developed flows. Developing MHD flows will require a much more sophisticated treatment than that given here.

In the event that either of these terms are smaller than the parabolic velocity profile shear stress (*e.g.* $B_R \Rightarrow 0$), then the parabolic shear stress is applied instead.

$$F_{friction} = \frac{3 v q_o}{h^3} \tag{9}$$

Hydraulic calculations indicate that flow depth equilibria in the range of 2 cm can be achieved for both lithium and flibe flows at their respective speeds (see figures 3 and 4). A thicker/faster film leads to a high volumetric flow

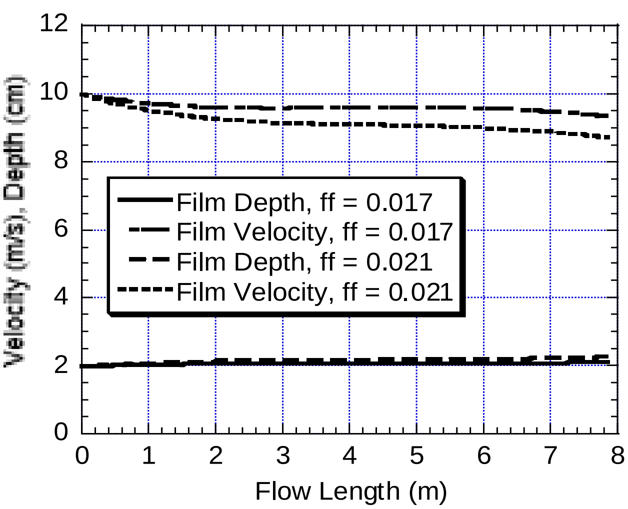



**Figure 3: Flow Profiles for Flibe film on an 8 m arc cylindrical surface (θ = 45° to 135°). The friction factors of 0.017 and 0.021 are used for smooth and rough surfaces, respectively.**

rate inside the chamber in which a large pumping power is needed to drive the flow. The depth equilibrium for the turbulent flibe flow is not extremely sensitive to the exact value of the friction factor. A 25% increase in the smooth pipe friction factor, which is likely due to Taylor-Gortler boundary layer instabilities resulting from flow on a curved plate, does not significantly change the hydraulic results. The flow is still very near the inlet conditions in this case. The lithium flow, however, is sensitive to the selection of the strength and orientation of the magnetic field. The presence of a small radial field component, $B_R$ = 0.25 T, causes a significant reduction in the velocity of the film flow over the 8 m flow length. The slower/thicker lithium flow will remain in contact with the plasma for a longer time than desired, and the surface temperature rise may be too high.

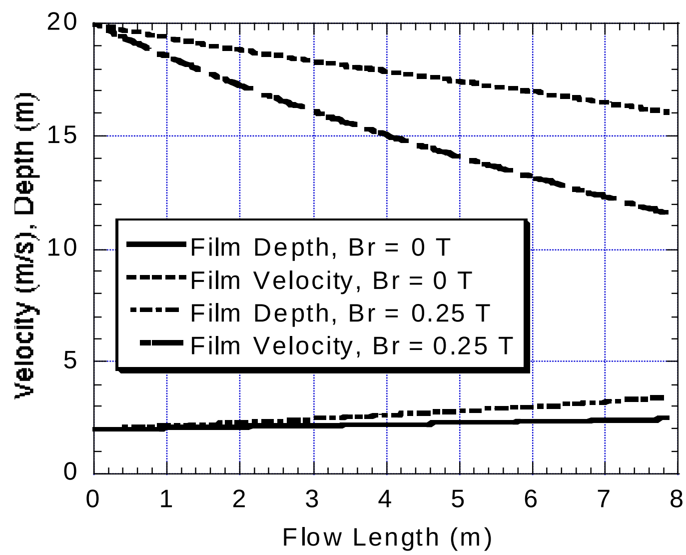



**Figure 4 Flow Profiles for Lithium films on an 8 m arc cylindrical surface (θ = 45° to 135°). Lithium flow has a 7 T tordoidal field, a width of 1 m, and shows significant retarding effect of a relatively small radial field normal to the surface.**

## THERMAL ANALYSIS OF THE FW LIQUID SURFACES

A key issue of liquid first walls is whether or not the evaporated liquid can be removed without critically contaminating the plasma. This quantity is generally proportional to the amount of vapor evaporated out of the first wall surface which is a function of liquid surface temperature. Without detailed edge plasma calculations, the simplest way to answer this question is to examine what magnitudes of the liquid FW surface temperatures can be achieved under the specified heat load conditions.

The temperature profile of the liquid FW is calculated using a three-dimensional finite difference heat transfer code for a combined surface heat load of 2 MW/m$^2$ and neutron wall load of 10 MW/m$^2$. The code takes the velocity profile as an input parameter and solves the energy equation:

$$\rho Cp\left[Vx\frac{\partial T}{\partial x}+Vy\frac{\partial T}{\partial y}+Vz\frac{\partial T}{\partial z}\right]=k\nabla^2 T+q''' \quad (10)$$

The volumetric heating due to both neutron and x-ray interactions are accounted in the source term, $q'''$. Details of the neutronics analysis are included in paper in ref. [4]. In cases where x-ray penetration is insignificant, the surface heat flux is accounted for as a boundary condition. To adequately simulate the sharp heat deposition gradient, finer meshes are required in the first 1 cm of the liquid wall close to the plasma side.

The surface and bulk temperature distributions as fluids proceed downstream are shown in Figures 5 and 6 for lithium and flibe slug jets, respectively; while temperature profiles into the jets at about 2.0 m downstream are shown in Figure 7. As shown, accounting for x-ray penetration significantly reduces the jet surface temperature, particularly in the case where

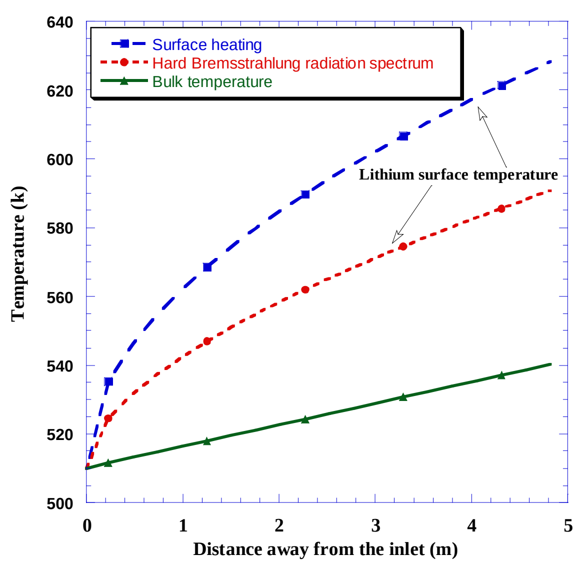



**Figure 5 Lithium jet surface and bulk temperatures as jet proceeds downstream (For a surface heat load of 2 MW/m$^2$ combined with a neutron wall load of 10 MW/m$^2$ and jet velocity = 20 m/s)**

Flibe surface is exposed to a hard Bremsstrahlung radiation spectrum (for example as the case shown: a classical Bremsstrahlung radiation spectrum corresponding to an average $T_e$ of 10 KeV). Nevertheless, most of the Bremsstrahlung radiation is deposited within the 1$^{st}$ cm of the jet. Furthermore, being a low thermal-conductivitymedium, the amount of heat conducted into the jet is insignificant which results in a much sharper temperature gradient across the flibe jet as compared to that of lithium jet [Figure 7]. The peak surface temperatures as shown for 1 cm thick lithium and Flibe jets under the hard Bremsstrahlung radiation heating for the coolant velocity of 20 m/s are 327 and 743 $^0$C, respectively. The corresponding evaporation rates for the aforementioned temperatures are 10$^{19}$ and 10$^{23}$ atoms/m$^2$s, respectively. The maximum lithium surface temperature increases to 375 $^0$C if lithium flows at a lower velocity of 10 m/s.

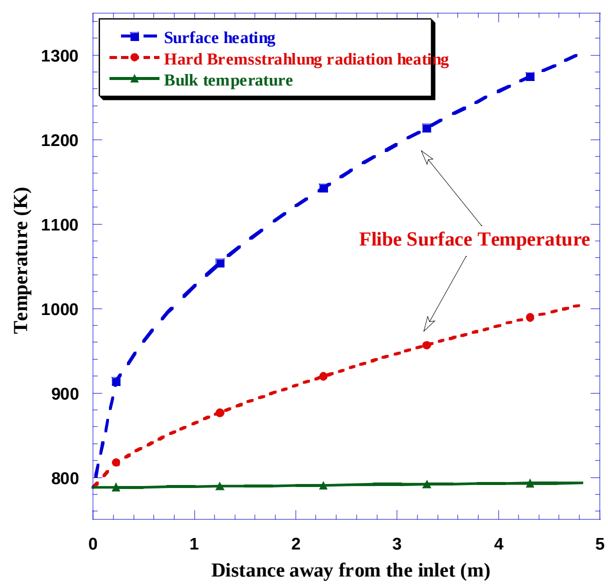



**Figure 6 Flibe jet surface and bulk temperatures as jet proceeds downstream (For a surface heat load = 2 MW/m2 combined with a neutron wall load = 10 MW/m2 and jet velocity = 20 m/s)**

For the preceding 2 cm Flibe film flowing at 10 m/s, the maximum surface temperature exposed to a hard Bremsstrahlung radiation of the same heating condition reaches 862 $^0$C with an average exit temperature of 534 $^0$C which is about 19 $^0$C higher than the inlet temperature. These results indicate that some amount of heat transfer enhancement is needed to reduce the flibe FW surface temperature. Since the jet is highly turbulent, the existences of eddies/pockets are expected to help achieve this goal.

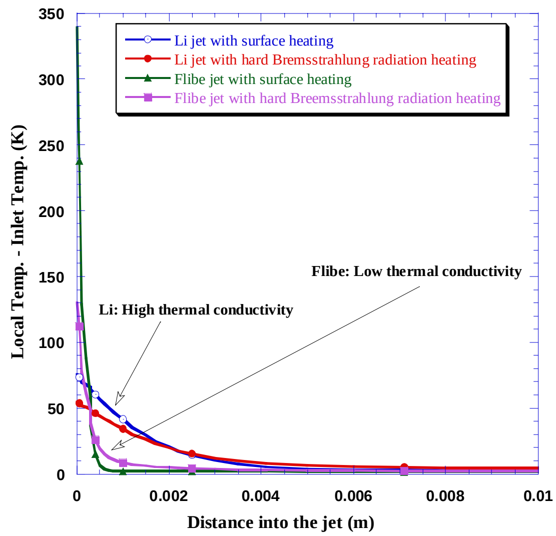


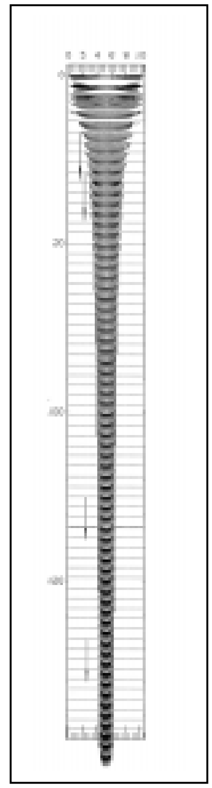

**Figure 7 Temperature increases inside the jets at about 2 m downstream under different heating conditions (jet velocity =20 m/s, 1 cm thick jet)**

## LIQUID BLANKET DESIGN: GRVITY-DRIVEN JETS

Behind the first wall, the simplest way to form a thick liquid is to drive the liquid jet using gravity force in contrast with the mechanical force driven rotating flow as proposed in [5]. Such a type of jet flow is modeled with RIPPLE; a 2-D, incompressible, free-surface, transient computer code developed at LANL including surface tension effects. The RIPPLE solution of Figure 8 shows that free thick liquid jet tends to be thinned due to the acceleration of gravity. More specifically, the jet thickness is rapidly reduced from 10 cm to 3 cm and stays at around 2 cm for the bottom part of the plasma core if the jet is injected at 1 m/s (Figure 9). The jet thinning effect can be overcome by increasing the initial jet velocity; and a uniform thick liquid jet can be obtained throughout the plasma core if the jet is injected at 7 m/s or above. However, with the flow rate increases the pumping power increases even more significantly as shown in Figure 10.

The thinning reduces liquid's potential for radiation protection of solid first walls behind the liquid. Furthermore, the high heat capacity of the liquid results in an unnoticeable temperature rise of less than 20 C even severely heated by a neutron wall load of 10 MW/m$^2$. Although a fairly uniform liquid temperature could be a favorable condition for the thermal cycle, the blanket liquid needs to operate at high temperatures to achieve a high thermal conversion efficiency. This implies that a thick liquid wall concept would comprise

**Figure 8 RIPPLE result of Flibe slab jet configurtion with initial jet velocity and thickness of 0.5 m/s and 10 cm, respectively(travelling distance = 2m, final jet thickness= 2 cm)**



multiple slab jets including a high-speed jet facing the plasma having a lowest surface temperature to avoid jeopardizing plasma operation. It is conceivable that, to combat thinning and achieve an appreciable amount of radiation shielding, one could recirculate and subsequently re-inject the fluid at different vertical heights/radial positions. To the extent of having the lifetime structure behind the liquid, a thick liquid wall approach could involve the use of flow reflectors to help restrain the liquid inside a pocket structure. The fast moving jet in front of the pocket provides resistive forces for preventing the liquid entering the plasma core. The fluid temperature inside the pocket is maintained by continuously circulating a small amount of liquid in and out of the pocket. These specially designed reflectors that protect the liquid entering the

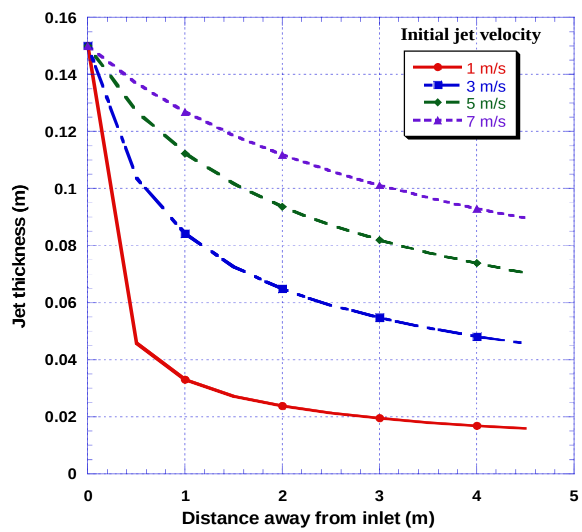



**Figure 9 Flibe Jet thickness reduces as jet proceeds downstream due to the gravitational force**

plasma core have to be periodically replaced. More analyses are planned to help proceed with a realistic design based on this approach.

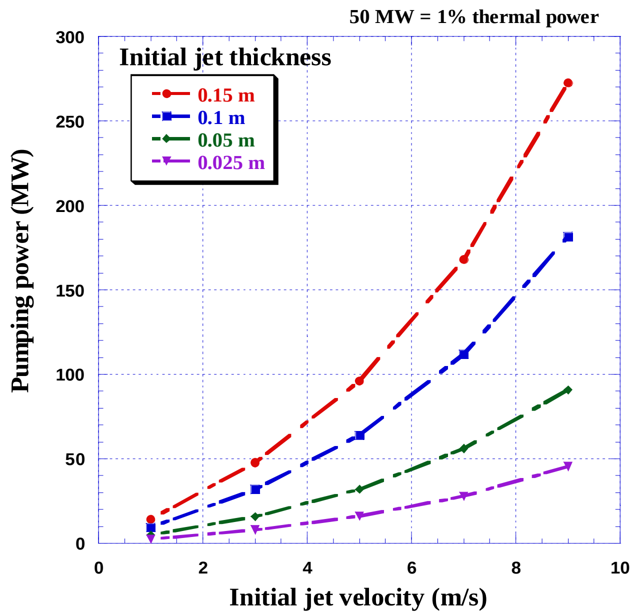



**Figure 10 Pumping power requirement increases significantly for high speed thick Flibe blanket jets**

## HYDRODYNAMICS STABILITY OF FLIBE FW FILM

The fluid dynamic behavior of the liquid first-wall system is an important issue in addressing the feasibility of the liquid first wall concepts. The stability of the liquid first wall should be maintained for efficient heat extraction from high neutron and surface heat loads while satisfying safe and reliable operation for the fusion power system. It should be noted that the stability of the liquid first wall is not only effected by liquid first wall operation and geometry parameters but also by the existence of the components in the liquid first wall system such as flow straightener, contraction nozzle, back plate geometry and drain system.

The mechanisms affecting the dynamic behavior of the liquid first-wall over a concave surface may be related to: (a) Taylor-Gortler vorticity formations in the liquid first wall boundary layer along the concave surface, (b) boundary layer relaxation on the liquid wall surface as it leaves the nozzle exit, (c) hydraulic jump, (d) eddy generation due to high velocity gradients in the boundary layers along the nozzle inner walls, (e) inviscid shear-layer instabilities (Kelvin-Helmholtz). Considering the neutron wall loading, charged particle and radiation energy deposition in the liquid first wall, the dynamic behavior of the first wall may further be affected by: (f) stratification (Rayleigh-Taylor), (g) charged particle liquid first wall momentum interaction (h) thermal relaxation of the liquid first wall. The mechanisms stated here may introduce or enhance the turbulence in the first-wall flow and at its free surface. An increase in the turbulence intensity at the free surface may increase convective heat transfer rate. This condition may decrease the required minimum liquid wall velocity so that uniform and more heat deposition in the first wall can be assured while maintaining the evaporation rate within the constraint limits [6]. Therefore, any of those mechanism should not be eliminated unless it destabilizes the first wall flow completely or increases mass loss in the first wall due to evaporation or splashing.

A case with a first wall operating condition of 10 m/s average velocity, 0.02 m of thickness flowing over a 4 m radius of concave surface is investigated using flibe as a working fluid at an operating temperature of 600 °C

**Table 1:** Operating condition and non-dimensional flow parameter of the case

| Avg. Vel. m/s | Liq. Wall $\delta$(m) | Re ($10^5$) | Fr= $U^2$/ ($g.\delta$) | Fr* | We ($10^5$) | ($U^2$/R) /g |
|---|---|---|---|---|---|---|
| 10 | 0.02 | 0.579 | 510 | 200 | 0.21 | 2.5 |

Characteristic length is taken as liquid first wall thickness ($\delta$).

As seen in Table 1, the flow regime is expected to be turbulent since Reynolds number (Re) is higher than 2000. Furthermore, the modified Froude (Fr*) number (ratio of inertia forces to centripetal forces ($U^2$/R)) is much greater than one. Therefore flow regime is expected to be supercritical (any disturbance on the first wall surface will not propagate upstream) and a hydraulic jump may occur. Hydraulic jump may cause an increase in the first wall thickness. An increase in the first wall thickness results in a smaller modified Froude number. Therefore there is a stabilizing mechanism for hydraulic jump. Also, there is a component of gravitational acceleration in the flow direction that may minimize the possibility of hydraulic jump. But it should be noted that any transient change in the first wall thickness may be a source of perturbation to the liquid first-wall surface.

Waves may form on the first wall surface due to the relaxation of the boundary layer leaving the nozzle exit from no-slip boundary condition to free-shear boundary condition [7]. Momentum thickness of the liquid wall on the upper wall of the nozzle is a function of pressure distribution (nozzle contraction ratio, upper wall surface curvature) in the nozzle as well as operating parameters. Momentum thickness of the liquid wall on the upper wall of the nozzle is estimated using nozzle design data developed for FMIT [8]. Surface waves are expected when the momentum thickness ($\delta_m$ : 5.8 $10^{-5}$ m) and Reynolds number based on momentum thickness of the present case ($Re_{\delta m}$: 168) is compared to the experimental results obtained by Brennen [9], Hoyt et al. [10] and Hassberger [8]. The average wavelengths of surface waves is expected to be 0.21 cm. The inverse Weber number based on momentum thickness of the boundary layer on the first wall surface ($\sigma/(\delta_m \rho V_\infty^2)$: 1.7 $10^{-2}$) is more than experimentally obtained values $10^{-4}$ [11,8] therefore, surface waves are expected to be stable.

The flow field of a boundary layer on a concave wall is unstable when [11]

$$\frac{r}{\delta_m} \le \left( \frac{\rho \delta_m V_\infty}{\mu} \right)^2 \qquad (11)$$

It should be noted that stability mechanism is inviscid and viscosity only damps the motion. Assuming that liquid flows over a meter of flat surface in the nozzle before it reaches to the concave back plate region, the momentum thickness of the liquid first wall flow system is determined using the momentum thickness relationship for turbulent boundary layer over a flat plate [13]. The inequality in the relationship above is satisfied for the first wall operation parameters and estimated momentum thickness of 3.9 $10^{-4}$ m. Therefore, Gortler vortices are expected to exist randomly in the turbulent boundary layer. The average height of the vortices for mildly curved back plate is expected to be approximately $50\upsilon/u_\tau$ [12] which corresponds 1.24 $10^{-3}$ m.

## CONCLUSIONS

This paper addressed several fundamental thermalhydraulics questions that must be answered before a realistic liquid wall design concept can be drawn. Over a travelling distance of 5 m ARIES-RS type geometric configuration, the hydraulics analyses showed that a 2 cm thick film can be maintained at a flibe velocity of 10 m/s. However a higher velocity of 20 m/s is required for lithium to overcome additional MHD forces. At the velocity of 20 m/s, the thermal analyses showed that the liquid surface evaporation rate can be maintained below $10^{20}$ #/m$^2$s for lithium flows under a 10 MW/m$^2$ neutron wall load and its corresponding 2 MW/m$^2$ surface heat load. However, a harder Bremsstrahlung radiation heating as opposed to the surface heating in conjunction with a turbulent heat transfer enhancement are the necessities for the Flibe first wall to satisfy the same criterion. If lithium is preferred due to its attainable lower surface temperature, MHD pressure drop appears too high for the liquid films, thus R&D on the electrical insulator coatings is unavoidable. For non-MHD gravity driven jet flows, the fluid tends to contract as flow proceeds downstream due to the gravitational acceleration. As a result, the liquid loses its potential with respect to the radiation protection. Ideas to combat the effect of thinning were proposed. Yet, the exact configuration of the thick liquid walls is still the subject of the detailed investigation in the near future.

The instability mechanisms investigated in the present study confirm the existence of heat transfer enhancement turbulent pockets, while the film surface is wavy yet stable under the specified operating conditions. Aside from the thermalhydraulics issues regarding heat transfer into turbulent jets, free turbulent jet flow characterizations, MHD developing flow and surface stability, there remains many concerns over plasma contamination by evaporated liquids, tritium flow, radiation damage, etc. Penetrations for pumping, fueling and beams will need to have a hydrodynamic design so as not to introduce excessive drag. Innovative engineering solutions endorsed by detailed analyses are needed to fully realize the profound advantages of the liquid wall approaches and proceed with a practically attractive design.

## NOMENCLATURE

$B_{T,R}$ ≡ Tordoidal and radial magnetic field components
Cp ≡heat capacity
D ≡ Characteristic length (First wall thickness) (m)
Fr ≡ Froude number
g ≡ acceleration of gravity
h ≡ film thickness
k ≡ thermal conductivity
p ≡ pressure
$q_o$ ≡ flowrate, $V_\theta \cdot h$
$q'''$ ≡ heat source
R ≡ arc radius
Re ≡ Reynolds number
U ≡ Average first wall velocity (m/s)
$u_\tau$ ≡ Friction velocity (m/s).
V ≡ velocity
$V_\infty$ ≡ Free stream velocity (m/s).
w ≡ width of the module segment
We ≡ Weber number

Greek
σ ≡ electrical conductivity
ν ≡ kinematics viscosity
ρ ≡ density
δ ≡ FW liquid film thickness

$\delta_m$ ≡ Momentum thickness (m)

Subscripts
$r,\theta$ ≡ cylindrical coordinates
x, y, z ≡ Cartesian coordinates

## ACKNOWLEDGEMENTS

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