FREE SURFACE HEAT TRANSFER AND INNOVATIVE DESIGNS FOR THIN AND THICK LIQUID WALLS

A. Y. Ying[1], N. Morley[1], S. Smolentsev[1], K. Gulec[1], P. Fogarty[2]
[1]Mechanical & Aerospace Engineering Department, UCLA, Los Angeles, CA 90095
Tel: (310) 206-8815, Fax: (310) 825-1715, ying@fusion.ucla.edu
[2]Oak Ridge National Lab, Oak Ridge, TN 37831-8218

ABSTRACT

Design windows on free surface flows in the APEX study are derived from the viewpoints of the free surface heat transfer, the adaptation of liquid flows to the topological constraints, and temperature requirements for plasma operation and power conversion efficiency. Within these constraints, the temperature of the free liquid surface facing the plasma is the most critical parameter governing the amount of liquid that evaporates into the plasma chamber. Present analyses show that a 2 cm or a 40 cm thick lithium layer can be established throughout the ARIES-RS reactor using a velocity of 10 m/s while operating under the plasma compatible surface temperature. However, like solid metallic walls, the liquid lithium walls require the use of electrical insulators to overcome the MHD drag. As for Flibe free surface flows, the MHD effect caused by interaction with the mean flow is negligible, while a fairly uniform flow of 2 or 45 cm thick can be maintained throughout the reactor based on 3-D hydrodynamics calculations. However, being a low thermally conducting medium, the Flibe surface temperature highly depends on the extent of the turbulent convection. The heat transfer analyses based on the κ–ε model of the turbulence, including MHD effects and various boundary conditions, predict a range of temperatures that may be beyond the plasma compatible temperatures. If indeed the Flibe surface temperature is high relative to the plasma operation limit, further design adjustments will be required to accommodate this deficiency.

I. **Introduction**

A liquid wall approach as pursued under the APEX (Advanced Power Extraction) study [1] can potentially increase power handling capability. It involves flowing liquids around the plasma to serve the functions of both first wall/blanket and divertor. The general liquid wall approach has some attractive features which include the reduction of radiation effects 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. However, in its application to a high fusion power density (for example a heat load of 2 MW/m^2 as specified in the APEX study [1]), the liquid wall design is constrained by the magnitude of the free surface temperature allowable such that it does not jeopardize the plasma operations. On the other hand, a high blanket coolant exit temperature is desired in order to achieve a high thermal efficiency.

There are three lithium-containing candidate liquids for the walls: 1) a good neutron absorber and inconspicuously electrical conducting medium of molten salt Flibe, 2) a low Z material and more likely compatible with plasma operation of lithium, and 3) an extreme low vapor pressure fluid of tin-lithium. Both lithium and tin-lithium are good electric conductors. Utilization of these two materials will have to deal with MHD effects, not just in the surface flows, but in supply lines and feed systems, and it requires electrical insulating coatings. In this paper, the free surface heat transfer phenomena and the resultant free surface temperature, its impact on design ideas and associated magnetic/hydrodynamics analyses for utilizing liquid metal lithium, and the molten salt Flibe applicable to the advanced tokamak confinement scheme are presented and discussed.

I-1 Design Description

Design ideas presently under investigation include both fast moving, thin liquid films flowing over the FW solid surface such as the "*CLiFF*" (Convective Liquid Flow First Wall) concept, and liquids of about a half meter thick flowing over a back plate acting as both FW and blanket flow (such as the "*GMD*" concept). Typically, the liquids adhere to the structural wall by the centrifugal force. In the *CLiFF* design configuration, in which the conventional solid first wall is replaced with a fast moving liquid layer, the liquid is injected into the vacuum chamber at a rate great enough to actively convect away surface heat. In this way, the *CLiFF* design reduces differential thermal stresses and the asociated failure modes in pressurized first wall structures. The liquid can then be used as a free surface divertor and recirculated as a coolant through the blanket to heat it to efficient power conversion temperatures as shown in Figure 1.

In contrast, the liquid in the gravity and momentum driven (*GMD*) thick liquid wall concept not only intercept the surface heat flux, but also neutron heating. Previous neutronics calculations show that, for about 45 cm of Flibe, the structural wall behind it becomes a life-time component [2]. Although thicker lithium of about 1 meter is needed to achieve the same goal, the *GMD* design adopts a uniform 45 cm thick liquid throughout the poloidal plane as a design goal in terms of the thickness and the associated hydrodynamics characteristics of the liquid. A *GMD* design, like *CLiFF*, involves an inlet nozzle assembly that discharges liquid into the plasma chamber while avoiding "drips", a free surface flow section, and an exit nozzle that accepts the flow and converts it from a free surface flow to a channel (pipe) flow. However, to minimize flow thinning caused by the gravitational acceleration and the toroidal flow area expansion, a high injection velocity and, therefore, huge liquid mass flowrate (~300 m^3/s for an ARIES-RS scale reactor) and inventory (~220 m^3) inside the chamber become unavoidable. An example 3-D hydrodynamics calculation (shown in Figure 2) indicates that about 30% of thinning can occur at the reactor mid-plane based on an initial velocity of 15 m/s along with an initial liquid thickness of 50 cm. On the other hand, to minimize fluid flow perturbation, the penetration port as required for heating or fueling in a *GMD* design is moved to the bottom of the reactor [3]. Typical design operating parameters for *CLiFF* and *GMD* are listed in Table 1

I-2 Influence of magnetic field on hydrodynamics and heat transfer for free surface flows

The influence of the magnetic field on liquid wall flow characteristics and heat transfer is crucial for both thick and thin liquid wall concepts. As two sorts of liquids are the candidates for the working fluid, the molten salt (Flibe) and the liquid metals (Li, Sn-Li), two separate treatments are needed. These two approaches should take into account differences in physical properties, mostly in the electrical and thermal conductivity and, as a consequence, different mechanisms of MHD interaction. Four independent parameters or their combinations specify the problem of MHD interaction for conducting fluids. They are the Reynolds number Re, Hartmann number Ha, the flow aspect ratio β number, and the orientation of the applied magnetic field relative to the flow field. Typically, the order of magnitude of the Hartmann number built through the flow half-width w (in the toroidal field direction) in the liquid wall concepts is 10^5 for liquid metals, while it is 10^2 for Flibe. This large difference between these two cases does not mean that the MHD effects are negligible for Flibe, but they differ strongly both qualitatively and quantitatively.

As for liquid metals, suppression of three-dimensional turbulence is expected. This phenomena of turbulence suppression by the magnetic field gives grounds to formulate high Hartmann flows in terms of laminar theory. Along with the effect of turbulence suppression, there are different MHD effects, owing to the interaction of the applied magnetic field with the induced electrical currents, which include the Hartmann effect, the M-type velocity profile formation, and the concomitant increase in the MHD drag force. These effects are described in details in a separate paper on MHD flows [4].

As for Flibe flows, the MHD effects caused by interaction with the mean flow are smaller, and in this analysis are neglected. On the other hand, the effects of MHD on Flibe turbulent flow characteristics can lead to turbulent eddies suppression as demonstrated by experimental observations for water electrolytes [5]. Data on closed channels heat transfer measurements can be found in the literature for both liquid metals and, to a lesser extent, strong electrolytes in a magnetic field. For Flibe, the most appropriate data will be those associated with the electrolyte since both have a high Prandtl number, and the heat transfer is dominated by turbulent convection. The following high Pr, MHD heat transfer correlation for closed channels in the region $Re > Re_c$ is given in Blums [5]:

$$Nu/Nu_o = (1 - 1.2\ N) \tag{1}$$

where N is the interaction parameter (based on the hydraulic diameter of the duct). This correlation predicts the approximate percentage decrease in the heat transfer at a Hartmann wall due to suppression of turbulent eddies by the magnetic field. It has been validated for the regime $Re > Re_{cr}$ and $N << 1$. Re_{cr} (again based on the hydraulic diameter) varies as $\{215 - 85 \exp(-0.35\beta)\}$ Ha; where both Re and Ha are based on the same length scale. A straightforward application of this equation to *CLiFF* type Flibe liquid walls gives about a 5% reduction in the heat transfer under a magnetic field of 10 T. However, a greater degradation in heat transfer (up to 50%) would be expected for the Flibe thick liquid concepts. The applicability of this relation to heat transfer along the side-wall (not Hartmann wall) and the free surface have not been validated.

II. MHD Analysis of Liquid Metal Walls

It is well known that the presence of electrically conducting walls can lead to larger electrical currents in the flow domain and, as a result, a significant increase in the MHD drag. In the case of free surface MHD flows, this effect manifests itself in the increase of the layer thickness with the accompanying reduction in the velocity. The effects of magnetic fields on the flow characteristics are analyzed for both toroidally segmented open insulated- and conducting channels.

To simplify the numerical solution, the three-dimensional set of the Navier-Stokes-Maxwell equations is first integrated analytically in the direction of the applied magnetic field. The drag Lorenz force and the viscous friction in the Hartmann layers at the side-walls are then accounted for in the resultant 2-D momentum equation. Furthermore, the shallow water approximation is implemented, where the flow is described using parabolic flow equations (Prandtl equations). From the computational viewpoint, this is much simpler than the original Navier-Stokes equations. Detailed descriptions of the mathematical formulations can be found in the APEX interim report [6].

As for boundary conditions, the no-slip condition at the solid wall and the zero tangential stress condition at the free surface are used. In addition, a kinematic free surface condition is used to calculate the film height:

$$\frac{\partial h}{\partial t} + U_s \frac{\partial h}{\partial x} = V_s$$

(2)

Here U_s and V_s are the components of the velocity vectors at the free surface.

II-1 MHD Results of *CLiFF* Thin Lithium Layer

In the case of insulated side-walls, the velocity profiles are characterized by a large gradient over a thin layer at the back wall proportional to $\beta Ha^{0.5}$ accompanied by a slug velocity profile in the core (Figure 3 a). The film thickness increases while the velocity decreases as the flow proceeds downstream due to the MHD drag. In the case of electrically conducting walls, the velocity has a classical "M shape" profile with two peaks: one located near the wall and the other near the free surface. However, as shown in Figure 4a, an increase of the fluid thickness of 3 times, and consequently a factor of 3 reduction in the fluid velocity, is observed due to the combined MHD effects of viscous friction in the Hartmann layers at the side walls and of Lorenz drag forces. These results show that in order to maintain a fairly fast velocity throughout the reactor, necessary for the surface heat flux removal while keeping the surface cold, an electrically insulated channel should be considered for the liquid metal free surface flow. Further analyses indicate that there is no conducting channel design possible to provide a fairly uniform film thickness with a reasonable side-wall separation width, requiring complete toroidal liquid flow with no breaks in axi-symmetry from side-wall, penetrations, *etc*. Detailed discussions on the numerical procedures are documented in APEX Interim report [6].

II-2 Results of Thick LM Insulated Walls

Numerical analyses are performed to define lithium initial velocity, in which a uniform thickness can be maintained throughout the plasma chamber in the presence of the toroidal magnetic field. In contrast to the non-MHD flow, the thinning effect due to gravitational acceleration can be minimized by the drag from the Hartmann velocity profiles. The calculations, as shown in Figure 5, indicate that a uniform 40 cm-thick lithium layer can be established along the poloidal path for an insulated open channel at a velocity of 10 m/s or higher. At this velocity, the total pressure (dynamic and static) exerted on the backplate is about 4800 N/m^2 (small). Furthermore, a fast surface layer will form naturally if the flow rate is increased slightly. The liquid near the surface, above the submerged insulated side-walls, will be unfettered by MHD drag except very near to penetrations, and a thin fast layer at the surface will result. More analysis is needed to further explore this idea [6].

II-3 MHD Results of a Conducting Back-Wall

The influence of the conducting backplate on the liquid metal flow characteristics is negligible in the presence of a purely toroidal magnetic field. But, the MHD drag can be significant if there is a radial magnetic field component – one normal to the free surface. Analyses indicate that in the presence of insulated side walls, a metallic backplate is acceptable if the radial magnetic field is no more than 0.1-0.15 T [6].

III. Heat Transfer at the Free Surface and Surface Temperature Estimation

Unlike solid metallic walls in which the heat transfer only depends on conduction, the heat transfer for liquid walls is governed by several physical mechanisms including laminar and turbulent convection and conduction, and it is intimately connected to the motion of the liquid through the convection terms. The temperature of the free liquid surface facing the plasma is the crucial parameter governing the amount of liquid that evaporates into the plasma chamber. However, it can only be determined accurately if the heat transfer at the free surface/vacuum boundary is well characterized.

Since a liquid metal wall will be highly laminarized and stabilized by the magnetic field, the heat transfer at the free surface wall is determined by the laminar convection and conduction. Furthermore, the lithium surface temperature is reduced because a portion of the surface heat load is really deposited into the bulk, owing to X-ray penetration into the low Z material. Previous calculations show that, under a surface heat flux of 2 MW/m^2, the lithium free surface temperature increase can be kept below than 140 ^oC at a velocity of 10 m/s throughout the reactor. This film temperature increase decreases to 80 ^oC if the lithium velocity increases to 20 m/s [7]. These results indicate the possibility of keeping the lithium free surface temperature below 400 ^oC – a temperature that may be acceptable to the plasma operation [8].

III-1 Flibe Surface Temperature Estimation based on κ–ε Model of Turbulence

As discussed in the introduction, Flibe is not fully laminarized by the presence of the magnetic field. The heat transfer at the Flibe free surface wall is dominated by the rapid surface renewal by the turbulent eddies generated either near the back wall or nozzle surfaces by frictional shear stress or near the free surface due to temperature driven viscosity variations. Accurate calculations of Flibe free surface temperature require the knowledge of the turbulent structures, eddy generation and dissipation, and the degree of damping by the magnetic field. In an attempt to calculate the free surface temperature, a κ–ε model of turbulence, including the effects of the magnetic fields on turbulent convection, was developed.

The transport equations for the turbulent kinetic energy, *k*, and the dissipation rate of the turbulent kinetic energy, ε, have been derived for Flibe flows including the additional MHD effects based on [9-10]:

$$\frac{\partial k}{\partial t} + U\frac{\partial k}{\partial x} + V\frac{\partial k}{\partial y} = \frac{1}{\mathrm{Re}}\frac{\partial}{\partial y}\left[\left(1+\frac{\nu_t}{\sigma_k}\right)\frac{\partial k}{\partial y}\right] + \frac{1}{\mathrm{Re}}\nu_t\left(\frac{\partial U}{\partial y}\right)^2 - \frac{\varepsilon}{\mathrm{Re}} - \frac{2}{\mathrm{Re}}\left(\frac{\partial \sqrt{k}}{\partial y}\right)^2 - C_3\beta^2 Nk\ ; \qquad (3)$$

$$\frac{\partial \varepsilon}{\partial t} + U\frac{\partial \varepsilon}{\partial x} + V\frac{\partial \varepsilon}{\partial y} = \frac{1}{\mathrm{Re}}\frac{\partial}{\partial y}[(1 + \frac{\nu_t}{\sigma_\varepsilon})\frac{\partial \varepsilon}{\partial y}] + \frac{f_1}{\mathrm{Re}}C_1\nu_t\frac{\varepsilon}{k}(\frac{\partial U}{\partial y})^2$$

$$- \frac{f_2}{\mathrm{Re}}C_2\frac{\varepsilon^2}{k} + \frac{2}{\mathrm{Re}}\nu_t(\frac{\partial^2 U}{\partial y^2})^2 - C_4\beta^2 N\varepsilon \qquad (4)$$

where C are constants [11] and the functions "f" are chosen in accordance with [9] as follows:

(1) at the wall: $f_1=1$; $f_2=1-0.3\exp(-R_t^2)$; $f_D=\exp[2.5/(1.+0.02R_t)]$; $R_t=\mathrm{Re}^2k^2/\varepsilon$

(2) at the free surface: $f_1=1.0$; $f_2=1.0$; $f_D=1.0$.

Additional details of the method are described in [6].

The no-slip conditions for the velocity together with zero conditions for κ and ε were used on the solid wall. As for the boundary conditions at the free surface, two variants were considered. In the first variant, Naot's boundary conditions [12] were used as follows:

$$\frac{\partial k}{\partial y} = 0, \quad \varepsilon = \frac{C_D^{3/2}\,\mathrm{Re}\,k^{3/2}}{\kappa 0.07h} \qquad (5)$$

The first condition in Eq. 5 is the symmetry condition, while the second one stands for the experimentally established fact that the dissipation length scale at the free surface is equal to the distance from a virtual origin located at a distance of 0.07h above the real open surface [12]. In the second variant, the turbulent kinetic energy is zero, but the symmetry boundary condition is used for the dissipation rate.

$$k = 0\,, \quad \frac{\partial \varepsilon}{\partial y} = 0 \tag{6}$$

The turbulent viscosity in the low-Reynolds number k-ε model is defined by means of the Kolmogorov-Prandtl equation as follows [9]:

$$\nu_t = C_D f_D \mathrm{Re}^2 \frac{k^2}{\varepsilon} \tag{7}$$

By the introduction of turbulent viscosity for heat, the energy equation is written as:

$$\frac{\partial T}{\partial t} + U\frac{\partial T}{\partial x} + V\frac{\partial T}{\partial y} = \frac{1}{Pe}\frac{\partial}{\partial y}[(1+\frac{\nu_t}{\sigma_t}\mathrm{Pr})\frac{\partial T}{\partial y}] + q_v \tag{8}$$

where the symbol σ_t stands for the turbulent Prandtl number (In our calculations, σ_t=1 based on Reynolds analogy [11]).

III-2 Flibe surface temperature predictions from the κ–ε model

The calculated surface temperature increase (the surface temperature minus the initial temperature) for different boundary conditions are shown in Figure 6 using the CLiFF design parameters. In particular, curve 1 was calculated assuming zero turbulence and shows that if the Flibe flow is laminarized, the Flibe free surface will be over-heated. The film temperature increase can reach 700 ^{o}C at the bottom of ARIES-RS under APEX 2 MW/m^2 surface heat load. Turbulent heat transfer can considerably reduce Flibe free surface temperature, as the film temperature increase is about 160 ^{o}C as indicated in curve 2 assuming zero surface turbulence as a boundary condition. Furthermore, heat transfer at the free surface interface can be significantly enhanced by the existence of finite surface turbulence as the results show in curve 4. In that case, the film temperature increase is only about 40 ^{o}C.

The effect of MHD on Flibe heat transfer at the free surface is analyzed and shown in Figure 7. All curves were computed with Naot's boundary conditions for surface heating that correspond to the most optimistic level in our estimations of the temperature rise. The curves 1 (Ha=0) and 2 (Ha=560) are very close. The results indicate that the turbulence suppression due to MHD can be neglected within current *CLiFF* design parameters. Yet, the surface temperature increases significantly at higher Hartmann numbers as a result of the turbulence reduction.

Numerical results of the κ–ε model, for a 45 cm thick Flibe layer flowing at a velocity of 15 m/s without the MHD effect, show an overall increase of 20-110 ^{o}C at the bottom of the ARIES-RS reactor. The results are based on different boundary condition assumptions while taking into account of x-ray penetration. The MHD effect on heat transfer may not be neglected as shown previously and can be as much as 50% in accordance with Blum's prediction [5]. The surface temperature increase must be more fully quantified before conclusion can be drawn on the viability of the thick liquid wall concepts.

IV. Summary and Further Design Implication

In this paper, the free surface heat transfer and MHD phenomena, and their impact on design ideas of liquid metal lithium and the molten salt Flibe liquid walls for an APEX advanced tokamak reactor are presented and discussed. The *CLiFF* concept utilizes a convective layer facing the plasma, which removes first wall surface heat and eliminates differential thermal stress and the associated failure modes. The *GMD* concept involves a liquid wall followed by a flowing neutronically-thick liquid blanket and has the highest attractiveness potential for a fusion energy system. Both 2-D MHD and 3-D hydrodynamics calculations show that fairly uniform thick liquid layers (Flibe and lithium) can be formed in the ARIES-RS type configuration as long as the injected fluid carries adequate inertial momentum (e.g., in correspondence to liquid velocity of 10 m/s or higher). However, like solid metallic walls, the free liquid metal walls require insulators to minimize MHD drag and to help achieve a uniform liquid thickness. Other MHD issues such as flow across field gradients (1/R dependence of the toroidal field for example), spatial variations, and temporal fluctuations during start-up and plasma control, have yet to be addressed.

The temperature of the free liquid surface facing the plasma is the critical parameter governing the amount of liquid that evaporates into the plasma chamber. Analyses show that the best estimate of plasma compatibility temperature limit can be satisfied by flowing lithium faster than 10 m/s. Although, there still remains uncertainty in the calculation of Flibe free surface temperatures, it is conceivable to keep this temperature below the maximum temperature limit, albeit at the expense of high pumping power needed to produce high velocity and volumetric flowrate. The effects of MHD on Flibe free surface heat transfer can be neglected for the *CLiFF* design parameters. However, it may cause up to 50% heat transfer reduction at the free surface in the thick Flibe first wall/blanket concepts. Thus, some sort of heat transfer enhancement techniques and /or design innovation might be required to allow the Flibe free surface temperature to be acceptable.

The challenges of the liquid wall designs go beyond achieving a low surface temperature in order to be compatible with the plasma operations, but also to maintain a mean bulk temperature of greater than 600 ^{o}C to achieve a high thermal efficiency. This temperature can be higher than the maximum allowable free surface temperature. Thus, a *GMD* design might require two different coolant streams: one for surface heat removal and the other for neutronics heat deposition in order to simultaneously achieve these two temperature requirements. Further explorations of liquid-wall designs shall involve hydrodynamics analyses concerning flow around penetrations and MHD effects at the existence of the port structures.

NOMENCLATURE

$B_{T,R}$ ≡ Tordoidal, radial magnetic field components
C_d ≡ Constant = 0.09
Cp ≡ heat capacity
C_{1-4} ≡ Constant = 1.55, 2.0, 2/3, 1.0
D ≡ Characteristic length (FW thickness) (m)
Fr ≡ Froude number, U_0^2/gh_0
g ≡ acceleration of gravity
h ≡ film thickness
Ha ≡ Hartmann Number, $B \cdot b(\sigma/\rho\nu)^{1/2}$
k ≡ thermal conductivity
N ≡ Interaction Number = Ha^2/Re
Nu ≡ Nusselt number = hD/k
Pe ≡ Peclet number = Re·Pr
Pr ≡ Prandtl number
q_v ≡ volumetric heat source
R ≡ arc radius
Re ≡ Reynolds number $=U_0h_0/\nu$
Re_{cr} ≡ ritical Reynolds number
t ≡ fluid residence time in plasma chamber
T ≡ Temperature (C)
U ≡ Main velocity (m/s)
u_τ ≡ Friction velocity (m/s).
V ≡ Velocity (m/s)
w ≡ half width of the module segment
X^* ≡ dimensionless coordinate (x/h_o)

Greek
β ≡ aspect ratio = h/w
ε ≡ dissipation rate of turbulent kinetic energy
κ ≡ turbulent kinetic energy
σ ≡ electrical conductivity
σ_κ ≡ turbulent coefficient in κ–ε model =1.0
σ_ε ≡ turbulent coefficient in κ–ε model = 1.3
σ_t ≡ turbulent Prandtl number = 1.0
ν ≡ kinematics viscosity
ρ ≡ density
δ ≡ FW liquid film thickness
δ_m ≡ Momentum thickness (m)

Subscripts
0 ≡ initial condition

o ≡ without MHD effect
r,θ ≡ cylindrical coordinates
s ≡ free surface
t ≡ turbulent
x, y, z ≡ Cartesian coordinates

ACKNOWLEDGEMENT

This work was performed under U.S. Department of Energy Contract DE-FG03-88ER52150 A008.

REFERENCES

1. M. Abdou, The APEX Team, "Exploring novel high power density concepts for attractive fusion systems", Fusion Engineering and Design 45 (1999) 145-167

2. M. Youssef and M. Abdou, Heat Deposition, Damage, and Tritium Breeding Characteristics in the Thick Liquid Wall Blanket Concepts, This conference

3. B. Nelson and P. Fogarty, APEX Presentation, PPPL, May 6-8, 1999.

4. N. Morley, L. Barleon, I. R. Kirillov, M. Takahashi, Liquid Phase Magnetohydro-dynamics: Recent progress and future directions for fusion, This conference

5. Blums E., Mikhailov Yu.A., Ozols R. Heat and Mass Transfer in MHD Flows. Series in Theoretical and applied Mechanics, Vol. 3 (1987).

6. APEX Interim Report, UCLA-FNT-, In progress, August, 1999

7. Ying A., Morley N., Gulec K., Nelson B., Youssef M. and Abdou M. Concept Description and Thermalhydraulics of Liquid Surface FW/Blankets for High Power Density Reactors, Fusion Technology, 34, 3, Pt. 2, 855 (1998).

8. Rognlien T., APEX presentations, PPPL, May 6-8, 1999.

9. Jones W.P., Launder B.E., The Prediction of Laminarization with a Two-Equation Model of Turbulence, Int. J. Heat and Mass Transfer, 15, 301 (1972).

10. Kitamura K., Hirata M. Turbulent Heat and Momentum Transfer for Electrically Conducting Fluid Flowing in Two-Dimensional Channel under Transverse Magnetic Field, 6th Int. Heat Transfer Conf., 3, 159 (1978).

11. Takahashi M., Inoue A., Aritomi M., Matsuzaki M. Numerical Analysis for Laminar and Turbulent Liquid-Metal Flow in a Transverse Magnetic Field, Fusion Engineering and Design, 8, 249 (1989).

12. Naot D., Rodi W. Calculation of Secondary currents in Channel Flow, Proc. ASCE, 108, No.Y8, 948 (1982).

Table 1 Characteristics Hydrodynamics Parameters of CLiFF and GMD Liquid Walls

Parameters	**CLiFF**		**GMD**	
Fluid	Li	Flibe	Li	Flibe
Operating Temperature	400 ^oC	500 ^oC	500 ^oC	550 ^oC
Film Depth , h (cm)	2	2	40	45
Film Velocity, U (m/s)	10	10	10	8.1
Channel 1/2 Width, w (m)	1	1	0.57	0.68
Flow Length, (m)	8	8	8	8
Toroidal Field, B_T (T)	8	8	8	8
Radial Field, B_R (T)	0.2	0.2	0.2	0.2
Radius of Curvature, R (m)	3	3	6.7	6.7
Prandtl no., Pr	0.034	33	0.0269	25.56
Reynolds No., Re	$2.44x10^5$	$2.71x10^4$	$6.187x10^6$	$6.32x10^5$
Hartmann no., Ha	$7.13x10^5$	$8.13x10^2$	$4.288x10^5$	685.14
Interaction no., N	831	0.01	$1.46x10^4$	0.325

Figure Caption

Figure 1: Conceptual Design of CLiFF in ARIES-RS scale reactor

Figure 2: 3D Calculation of Thick Flibe GMD Concept with initial injection velocity of 15 m/s and thickness of 50 cm (ARIES-RS Geometric Configuration-Major radius 5.52 m)

Figure 3: (a) Dimensionless cross-sectional velocity profile at the bottom of reactor and (b) dimensionless film thickness evolution as flow proceeds downstream (for insulated open channels)

Figure 4: (a) Dimensionless cross-sectional velocity profile at the bottom of reactor and (b) dimensionless film thickness evolution as flow proceeds downstream (for conducting open channels)

Figure 5: Film thickens evolution as a function of dimensionless coordinate X^* for a lithium thick liquid wall concept (Curves 1-6 correspond to U_0=5-10 m/s)

Figure 6: Calculated free surface film temperature drop as a function of distance away from the inlet based different model assumptions

Figure 7: The effect of the magnetic field on Flibe free surface heat transfer degradation. Surface temperature rises as a function of distance away from the inlet (1 - Ha=0; 2 - Ha=560; 3 - Ha=2000; 4 - Ha=3000)

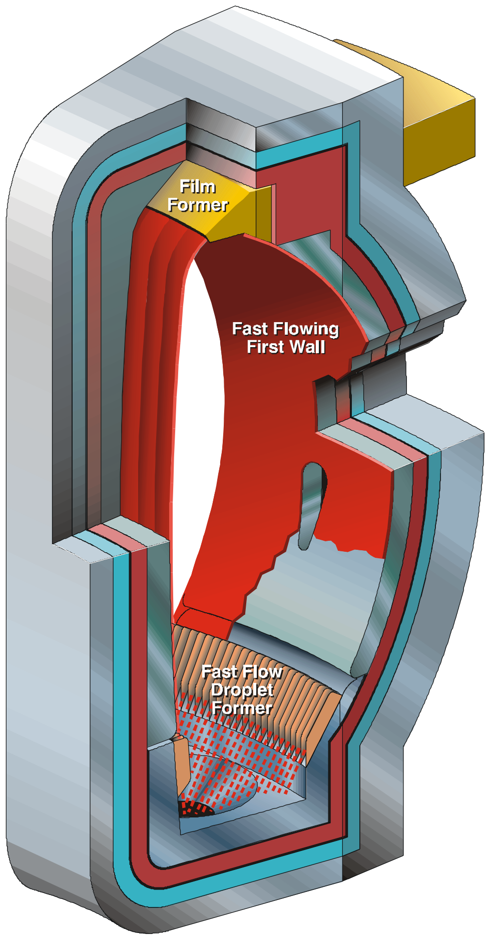

Figure 1: Conceptual Design of CLiFF in ARIES-RS scale reactor

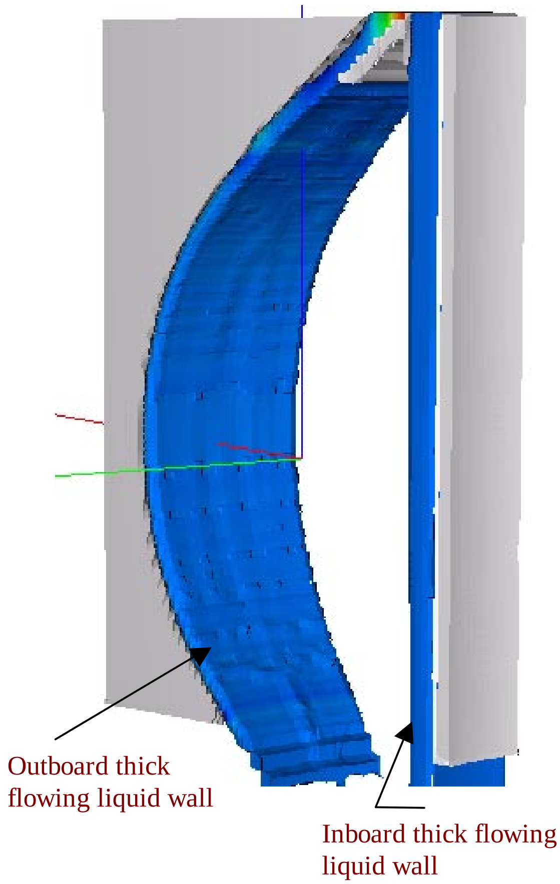

Figure 2: 3D Calculation of Thick Flibe GMD Concept with initial injection velocity of 15 m/s and thickness of 50 cm (ARIES-RS Geometric Configuration-Major radius 5.52 m)

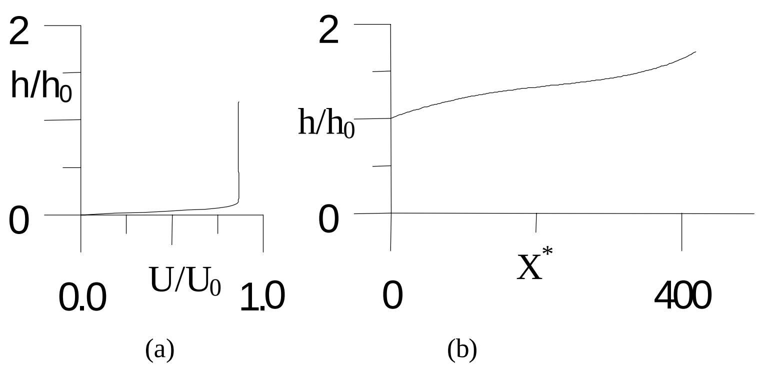

Figure 3: (a) Dimensionless cross-sectional velocity profile at the bottom of reactor and (b) dimensionless film thickness evolution as flow proceeds downstream (for insulated open channels)

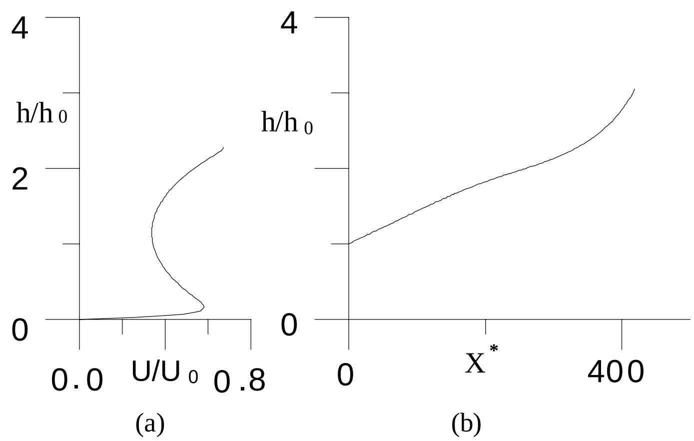

Figure 4: (a) Dimensionless cross-sectional velocity profile at the bottom of reactor and (b) dimensionless film thickness evolution as flow proceeds downstream (for conducting open channels)

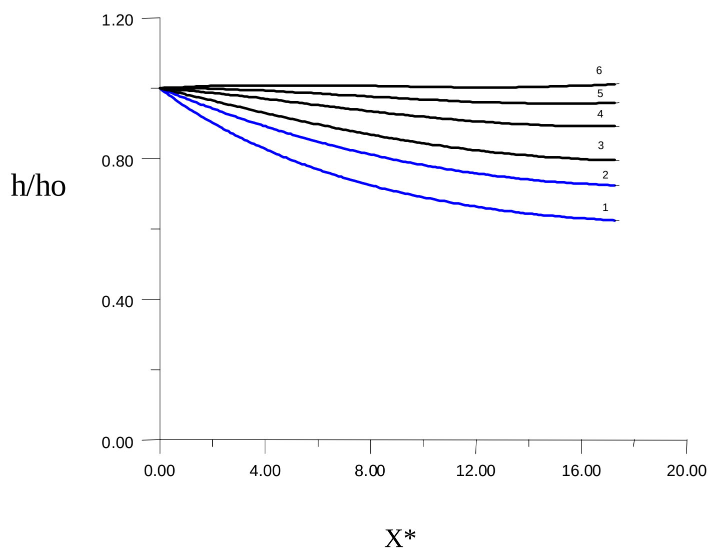

Figure 5: Film thickens evolution as a function of dimensionless coordinate X^* for a lithium thick liquid wall concept (Curves 1-6 correspond to U_0=5-10 m/s)

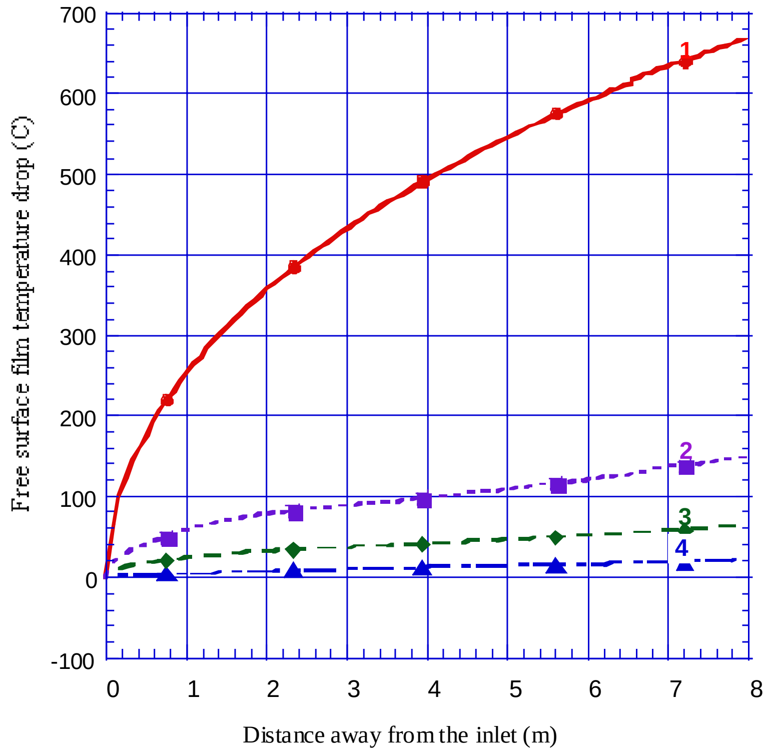

Figure 6: Calculated free surface film temperature drop as a function of distance away from the inlet based different model assumptions (1. Laminar flow (without accounting x-ray penetration); 2. Turbulent film (without accounting x-ray penetration); 3. Accounting x-ray penetration for turbulent film; 4. Accounting MHD effect yet including surface turbulence for turbulent film.

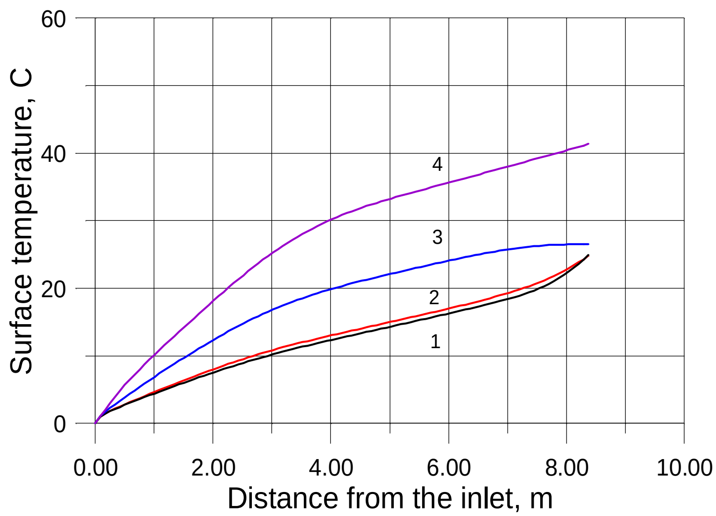

Figure 7: The effect of the magnetic field on Flibe free surface heat transfer degradation. Surface temperature rises as a function of distance away from the inlet (1 - Ha=0; 2 - Ha=560; 3 - Ha=2000; 4 - Ha=3000)