

## Research on Liquid Walls for Fusion Systems

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**Abstract.** Liquid Walls appear promising in improving the attractiveness of fusion energy systems and improving the performance of present plasma devices. Research on free-surface, turbulent MHD is extending the frontiers of Science.

### 1. Introduction

The APEX study is exploring novel concepts for fusion chamber technology that can, in the near term, improve the capabilities of plasma devices, and, in the long term, substantially improve the vision for attractive fusion systems.

Among the most promising concepts is the idea of flowing liquid walls around the plasma so that all surfaces exposed to the plasma are liquids.

There are many attractive features of liquid walls that have motivated this research:

- High Power Density Capability
  - Eliminate thermal stress and wall erosion as limiting factors
  - Smaller and lower cost components (chambers, shield, vacuum vessel, magnets)
- Improvements in Plasma Stability and Confinement
  - Enable high  $\beta$ , stable physics regimes if liquid metals are used
- Increased Potential for Disruption Survivability
- Reduced Volume of Radioactive Waste
- Reduced Radiation Damage in Structural Materials
  - Makes difficult structural material problems more tractable
- Potential for Higher Availability

It is not clear yet that all these advantages can be realized simultaneously in a single concept. However, the realization of only a subset of these advantages will result in remarkable progress toward attractive fusion energy systems.

### 2. Liquid Wall Designs

The liquid wall idea evolved during the APEX study into a number of concepts that have some common features but also have widely different issues and merits. These concepts can be classified according to: (a) the type of working liquid, (b) the thickness of the liquid flow, and (c) the type of restraining force used to control the liquid flow.

The practical candidates for the working liquid are the liquid metals lithium and Sn-Li (Sn-Li was introduced into APEX because it has very low vapor pressure), and the molten salt Flibe. Many different considerations must be taken into account when assessing the performance of various liquid wall ideas. The hydrodynamics and heat transfer characteristics of high conductivity, low Prandtl Number liquid metal flows will depend heavily on the interactions with the magnetic field. In contrast, low-conductivity, high Prandtl Number Flibe flows will be dominated by turbulence considerations. The Z number and ionization potential of any vapor generated from the liquid surface will affect significantly the plasma contamination levels. The relative hydrogen solubility in the working liquid will play a significant role in the structure of the edge and the stability of the plasma discharge.

In addition, high conductivity liquid metal (LM) flows have the potential to affect the local magnetic fields and the plasma stability in a potentially positive manner. LM walls appear 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 improvement in stable (from 5-7% to 20-22%) at aspect ratio 4 and 3, respectively. Flowing liquid metals can potentially stabilize resistive wall modes as well allowing higher steady state equilibria with very hollow current profiles. Steady state operation with such profiles enables high bootstrap fractions and thus low recirculating power. Also, hollow current profiles are theoretically predicted to give  $\mathbf{E} \times \mathbf{B}$  shearing rates larger than instability growth rates for conventional drift instabilities, leading to transport barriers and high confinement.

The selection of the thickness for the liquid wall layer flow (directly facing the plasma and in front of a solid "backing wall") leads to different concepts that have some common issues but many unique advantages and challenges. Both thin and thick liquid walls can adequately remove high surface heat flux. A primary difference between thin and thick liquid walls is the magnitude of attenuation of neutrons in the liquid before they reach the backing wall. The "thin" liquid wall concept is easier to attain, but "thick" liquid wall concepts greatly reduce radiation damage and activation of the structure. Assuming a 200 DPA damage limit for structure replacement, the use of about 40 cm of Flibe or Sn-Li can make the structure behind it a lifetime component. Furthermore, the volume of the radioactive waste from the FW/blanket system is greatly reduced.

Widely different liquid wall concepts are also obtained by applying various forces to drive the liquid flow and restrain it against a backing wall. An example is the Gravity-Momentum Driven (GMD) concept, where the liquid is injected at the top of the chamber at an angle tangential to the curved backing wall. The fluid adheres to the backing wall by means of centrifugal force and is collected and drained at the bottom of the chamber. The criterion for the continuous attachment of the liquid layer is simply that the centrifugal force pushing the liquid layer towards the wall is greater than any destabilizing gravitational force.

Serious effort is now being devoted to the exploration and analysis of various liquid wall concepts. The analysis includes: a) effects of flowing liquid metals on plasma stability and confinement, b) plasma-liquid surface interactions, c) fluid dynamics for free-surface, turbulent, MHD flows, d) interfacial transport, and e) engineering analysis. Many interesting new scientific phenomena are observed.

### 3. Liquid Wall Issues

The scientific and engineering issues for liquid walls being analyzed are many. Of all the potential issues, a number of them stand out as the highest priority for near-term liquid wall research.

**1. Plasma-liquid interactions including both plasma-liquid surface and liquid wall-bulk plasma interactions:** plasma stability and transport may be seriously affected and potentially improved through various mechanisms including control field penetration, H/He pumping, passive stabilization, etc. More careful estimates for the allowable amount of liquid evaporation and sputtering need to be obtained and benchmarked.

**2. Hydrodynamics flow feasibility in complex geometries including penetrations:** the issue of establishing a viable hydrodynamic configuration threatens feasibility for all concepts, but it differs significantly for thick versus thin and for molten salts versus liquid metals. The main issue facing liquid metals is of course that of MHD interactions. Without toroidal axi-symmetry of the flow and field, reliable insulator coatings will 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 complete axi-symmetry is assumed in the toroidal direction. Additionally, gradients in toroidal field can exert a significant drag on the free surface flow. For thick liquid walls, the main issues concern the formation and removal of the liquid flow in the plasma chamber, and the accommodation of penetrations.

**3. Heat transfer at free surface and temperature control:** liquid surface temperature and vaporization are tightly coupled plasma edge and free surface hydrodynamic problems that require knowledge of the radiation spectrum, surface deformation, velocity and turbulence characteristics. Being a poor thermally conducting medium, the Flibe surface temperature highly depends on the turbulent convection. However, the normal velocity at the free surface as well as the turbulent eddies near the surface can be greatly suppressed. The issue of heat transfer at free surfaces is a serious concern, especially considering that the preliminary plasma-edge modelling predicts a relatively low limit on the surface temperature for Flibe.

### 4. Conclusions

Liquid walls appear to be a very promising way to improve the attractiveness of fusion energy systems and to extend the capabilities of plasma devices. Liquid wall issues are being addressed in the APEX study.

### References

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