APEX Task II – Summary of Progress this Year

Record of semi-annual APEX meeting – May, 2000

N. Morley, R. Kaita, S. Jardin, M. Youssef, S. Smolentsev, K. Gulec,
R. Moir, M. Kotschenreuther

The scope of the APEX Task II effort this year, in conjunction with cross-cutting Task B is to explore high payoff liquid wall concepts that increase the attractiveness of fusion energy, with emphasis on understanding the key scientific issues. Included in this scope are both liquid metals and Flibe, and thin and thick liquid walls that have the potential to improve the physics performance of plasma. Additionally, other new APEX concepts that are advanced this year will be treated under Task II. The Task II/Task B approach is centered around the development and application of much-needed, generic modeling tools for liquid walls and plasma interaction with liquid walls, and the initiation of experiments that address fundamental LW issues identified last year. These tools and experiments will be utilized to advance the conceptualization of various LW designs.

Lithium and LM-MHD Modeling and Experiments

New free surface MHD codes assuming 2D axisymmetry

Two new mathematical models and corresponding MHD codes have been worked out to analyze (1) arbitrary 1-component magnetic field variation, and (2) multi-component magnetic field problems with more limited field variations. These codes will be used to analyze the effects of field gradients on sensitive open channel flows, various active control and propulsion techniques with applied electric currents including the Magnetic Propulsion technique, and help design experiments for the toroidal MHD facility at UCLA and small scale magnetic field gradient experiments at UIUC. The details of the codes are discussed below along with some example calculations. More detailed analysis is planned for the upcoming months.

The arbitrary 1-component field code keeps all viscous and inertial terms in the 2D solution plane and uses a volume-of-fluid technique to track arbitrary free surface shapes. The power of this formulation is that very rapid field changes, geometry changes and free surface response can be modeled – for instance flow around a bluff body or flow in the 1/R toroidal field near the inboard. Also, 2d jet and droplet flows can also be modeled. The multi-component magnetic field MHD model includes all 3 components of the applied magnetic field, 3 velocity components as well as time and space (in the flow direction) variations of the applied field. The code can be applied to the analysis of MHD effects caused by the field gradients, transient effects and effects due to applied electric currents, such as active flow control. The code can be extended to different geometries including conventional Tokamak topology and NSTX central column. The present version of the code uses the cylindrical coordinates. The code is not applicable to flows with no axial symmetry, flows with Re_m>1, multi-surface flows (droplet formation, splashing) or reverse or stagnant flows.

Some test cases have been analyzed with both codes. Flow of an isolated droplet into a field gradient shows the droplet to be decelerated and deformed by the gradient MHD effect. Also, MHD flow in a gradient, linearly varying toroidal magnetic field was considered. It was shown that the flow becomes thicker as the gradient grows, but under NSTX conditions, the increase in the layer thickness is not large. Second, the effect of the normal field in the presence of the gradient toroidal field was analyzed. This effect results in a spiral-type motion and can lead to a centrifugal instability. It was demonstrated with the code that an applied longitudinal current could be used as a mean against the instability. Future plans include application of both codes to a variety of problems of interest to the APEX thin liquid wall flow, and the eventual merger of the different techniques into a unified code that takes advantage of the best features of both approaches.

Theory of Intense Lithium Streams in Tokamaks

The theory of high speed jets and thin lithium streams in a tokamak magnetic field has been presented, where the crucial role of the small (sub-centimeter) thickness of the fast lithium flow is seen in order to control the flow and to eliminate the drag forces due to inductively induced eddy currents in the flow. A stability criterion of the lithium streams inside the tokamak has been derived. It confirms the stability of intense lithium streams to electro-magnetic perturbations.

A lithium flow pattern, consistent with the basic theory, which includes: a) injection of the lithium in the form of jets into the tokamak magnetic field, b) injection of the high speed flow by external gas pressure into the vacuum chamber, c) magnetic propulsion of the lithium streams along the plasma boundary, d) ejection of the lithium in a form of jets from the vacuum chamber by electro-magnetic force, has been proposed for the power extraction from the tokamak plasma.

LM-MHD Experiments

The M-Tor magnetic torus facility is nearing completion at UCLA. The idea behind this experiment is to create a magnetic environment with geometric similarity to real tokamak. The M-Tor is being constructed with magnet coils from the MIT Tara magnetic mirror experiment, and a power supply on loan from PPPL. It will be integrated with the existing LM flowloop at UCLA to provide a flexible MHD testing environment for a variety of free surface flow experiments in a tokamak geometry. Initial experiments to investigate the effect of the 1/R field gradient on flow drag, and the possibility of using applied electric currents in the Magnetic Propulsion concept to offset the gradient drag and ensure adherence to the wall for inverted flows. Future plans include continual upgrade of the magnetic environment to simulate poloidal fields and upgrade of the flow capacity to allow completely axi-symmetric LM flow tests.

Additionally, some small-scale magnetic propulsion experiments are being carried out at UIUC in collaboration with PPPL. Using a gap magnet and a small volume of liquid gallium, these experiments have already demonstrated that the $J \times B$ force from an applied electric current will indeed interact with the gradient magnetic field to move liquid metal towards the low field region. This experiment, however, showed a significant amount of surface instabilities that could be very disruptive (or useful) to a magnetic fusion device. Work on these experiments is continuing.

Flibe Free Surface Flow Modeling and Experiments

Recent "k-epsilon" calculations

The current version of the "k-epsilon" code for MHD turbulent flows was used to analyze some fully developed and developing flows for CLiFF thin liquid wall concept with Flibe. The mathematical model incorporates the following features:

- turbulence suppression mechanism by a magnetic field through the Joule dissipation term, which is given more accurate formulation;
- well-tuned closure coefficients for all three orientations of a magnetic field;
- free surface boundary conditions with taking into account MHD effects;
- heat transfer degradation mechanism near the surface through the turbulent Prandtl number.

An important role of the Turbulent Prandtl number as a numerical parameter entering the "k-epsilon" model was demonstrated with a simple calculation. In this calculation, two different distributions for the turbulent Prandtl number were used. The first one is based on Ueda's experimental data for surfaces with no waviness. The second one corresponds to a wavy surface. It was shown that significant reduction of the surface temperature could be achieved with the surface waviness. It was emphasized that the experimental data will be needed for the turbulent Prandtl number depending on the level of the surface disturbances, especially if Fr>1 (supercritical flow regime).

Strategies to minimize evaporation

Enhancing convection near the surface of a liquid exposed to the plasma can carry the heat deposited near the surface to the interior and bring cool liquid to the surface. This will tend to minimize the surface temperature and hence the evaporation rate, especially important for flibe whose low thermal conductivity (high Prandlt number) results in high surface temperatures without convection. Droplets might be able to help in two ways, temperature dependent surface tension can lead to convection into the interior of the droplet (Marangoni effect), and droplets striking the liquid surface might be able to induce convection near the surface while causing no splash. These two effects can be quantified with 2-D computational fluid dynamic codes. While modifications to the back wall have a good chance of enhancing convection near the surface with thin flowing liquids (~20 mm thick) they will be less effective with thick flows (~0.5 m) which is the reason to consider the droplet injection approach.

FLI-HY experiment

The above described k-e code was also used to choose parameters for a test-section in the first phase of the FLI-HY experiment. This experimental apparatus is under design at UCLA and will utilize a large flowrate water/KOH loop to simulate hydrodynamics and surface heat transfer for Flibe (or other low conductivity, high Prandtl number liquid). Several experiments are planned to measure surface heat and mass transfer and to explore flow control in complex free surface shapes, like around penetrations. Facility construction is anticipated during the summer months and experiment with initial test section this fall.

The surface heat transfer test section is a straight rotatable (different slopes) chute. It was found that the experimental range for the slope should be from 5° to 60°. The test section length was chosen as 4 m, since smaller length do not provide conditions for establishing fully developed flows. It was concluded that the nozzle height affects the transition length much stronger than the initial velocity, so that a special attention should be paid to the nozzle construction. Also, the parameters of the surface heater were calculated. It was shown that reliable temperature measurements could be done if the heater power is 10 kW/m^2 or higher for smooth surfaces and it is higher than 20 kW/m^2 for wavy surfaces. The necessity of filtering the radiant heaters to pass only the wavelengths highly attenuated in water is evisioned, which will require a greater raw heating power than the estimates given above.

Plasma stability simulation with Liquid Walls

Stability work at IFS in collaboration with PPPL and GA

Substantial progress has been made at IFS in developing a code to investigate stabilization of resistive wall MHD modes. A procedure to interface with Princeton's MHD codes has been developed which requires almost no re-coding of PEST.

Initial results indicate that kink modes in highly elongated tokamaks (kappa=3) have a similar requirement for stabilizing shell as more conventional ARIES RS and ARIES AT cases (shell distance / minor radius ~.2 - .3) . Stabilization of the resistive wall kink mode will still be needed. Resistive wall kink stabilization by plasma rotation (as in ARIES) appears to require excessive power by a large margin (recirculating power fraction ~ 50%)

Liquid metal flow rates and thicknesses in the range considered by APEX for surface heat removal appear promising as a means to stabilize the kink modes, but the thickness / flow rate probably somewhat exceeds the requirement for heat removal. Code difficulties with these cases need to be fixed, however. Feedback stabilization of kink modes appears possible even with modestly conductive shells (e.g. 1-2 cm steel) without excessive power; however, the active feedback loops must be close to the shell. The voltages are quite low and it appears that these loops can be made of structural metals and ceramic insulators (V, FS, SiC) considered for fusion. Low impedance power supplies may be needed. In addition, with proper design these loops can be segmented and modularized within a blanket module with little additional power requirement.

Vertical instability feedback requirements for a 1 GW DT reactor with > 8 MW/m^2 wall loading are acceptable for a passive stabilized consisting of 2 cm of steel at the first wall. By modifying the shape of the active coils (but keeping them behind the shield) this thickness can be reduced by a factor of 2 or more. Active feedback consistent with vertical stabilization can reduce the radial magnetic field by over an order of magnitude; this reduces the flow damping rate for liquid metals by over two orders of magnitude, into a range which would probably be acceptable in a reactor. Use of flowing metals as sensors may make steady state operation with feedback possible.

The startup scenario needs more work to insure consistency with the conducting shell flux penetration time and the liquid metal flow rates

Use of TSC code at PPPL

New work is proposed by PPPL where the tokamak simulation code, a 2-D, time-dependent, free-boundary simulation code (see S. C. Jardin, N. Pomphrey, and J. L. DeLucia, J. Comput. Phys. **66**, 481 (1986)) to simulate “poloidally-local” regions that are occupied by lithium. TSC advances the MHD equations for the evolution of an axisymmetric magnetized toroidal plasma on the transport time scale. To date, TSC has been successfully used to compute the time evolution of a 1 MA NSTX discharge, including the effects of vacuum vessel currents. The near-term plan is to add a toroidal “pool” of liquid lithium to the bottom of the NSTX vacuum vessel. The resistivity, conductivity, and density of the lithium will be included. TSC already treats boundary between regions of different density and resistivity. The first step is to determine the effect of the time-evolving NSTX coil currents used in the 1 MA simulation on the liquid lithium in the absence of plasma. Simulations with plasmas will then be performed if the behavior of lithium appears to be reasonable.

Proposal on Lithium Wall Experiment (LWX) on PBX-M

Existing evidence from TFTR lithium pellet experiments, theoretical analysis of low recycling plasma edge as well as contemporary theory of the turbulent transport in the plasma core, all suggest that the plasma edge temperature pedestal is the most important factor in the tokamak overall performance. This gives a strong motivation for initiation of a special program for studying magnetic confinement with the lithium covered walls, which would utilize the unique lithium properties of absorbing hydrogen particles for creation the low recycling edge conditions and a new regime in tokamaks with the high plasma edge temperature pedestal comparable with the central plasma temperature.

The long term scientific goal of the proposal is to:

a) affect, suppress (or, probably, eliminate) the core turbulent thermal conduction as the dominant mechanism of the energy losses from the plasma,
b) achieve high beta (about 10 %) in the wall stabilized plasma,
c) check and calibrate the plasma core confinement theory by using edge temperature pedestal as the most significant experimental parameter,

d) develop and calibrate the edge model with the plasma facing lithium.

At the current initial stage, the proposal suggests performance of consistent technology and physics research (including experiments on existing tokamaks) which would focus on assessing possibility of achieving absorbing wall conditions with lithium plasma facing surface and on preparing the basis for designing Lithium Wall Experiment (LMX) facility. It was emphasized that existing in PPPL PBX-M tokamak (which is now under consideration to be destroyed as all other PPPL tokamaks) represents practically perfect facility for both short and long term lithium covered wall studies.

Nuclear analysis

Conducting shell effect on tritium breeding

The adverse effect on TBR due to the inclusion of a conducting shell (use for stabilizing the plasma) in front of the solid FW is highly system-dependent. Among the design features that quantify this effect are the type of breeder and structure, the degree of lithium-6 enrichment, the type of solid conducting shell (e.g. Cu, Al, FS, W, V alloy), and whether or not there is a front beryllium multiplying zone in the blanket. It is shown that removing the front Flibe convective layer itself (2m thick) can drop TBR by less than 1% (FS structure) and by ~4% (SiC structure) if no front beryllium multiplying zone is deployed. On the other hand, TBR increases (by ~3%) if a beryllium multiplying zone is implemented in the system (SiC structure with natural lithium). In this case, the presence of the convective layer degrades the multiplication effect of Be through Be(n,2n) reactions due to neutron moderation by the layer.

Placing tungsten as a conducting shell at the FW in a system that does not deploy beryllium as a multiplier will have lesser adverse impact on TBR (~-8-10%) if Flibe breeder uses natural lithium. However it improves TBR by ~+2-3% if 25%Li-6 enrichment is used. It is obvious that placing the conducting shell deeper in the blanket will have marginal adverse effect on TBR.

A front beryllium multiplying zone (60%Be, 30%Flibe, 10% SiC) of a thickness of 10 cm is most likely to be adopted for thin-liquid FW concept (optimized design is now in progress in APEX Task III). Natural lithium gives the largest local TBR in this case (TBR=1.5). Without the convective layer (TBR=1.54), using tungsten as the conducting shell gives the largest adverse impact on TBR (up to ~-30% for shell thickness d=2 cm) and the absolute value becomes TBR=1.08, which is not acceptable to meet tritium self-sufficiency condition. Copper is the next worse element with a TBR drop of ~ 20% at d=2cm. The corresponding drop with FS is ~ 15%. The least impact is with V and Al conductors (TBR drops by~-12% for 2 cm shell).

Damage and lifetime analysis of the structural lining of penetrations

It was shown that the 10-fold thickness (the thickness required to reduce a response by an order of magnitude) of Li, Flibe, and Sn-Li is ~58 cm, 26, and 36 cm, respectively, for

DPA in Ferritic steel back wall in liquid wall concept. The corresponding thickness for He-4 and H production is ~45, 22, and 22 cm, respectively. Thus, a 40 cm-thick flibe flowing layer can reduce the He-4 production rate by ~ 2 orders of magnitude. As we approach a penetration, however, the damage rates in the back wall start to peak due to the reduction in the effective thickness of the layer seen by the back wall. Also, neutrons steaming directly through penetrations increase the damage rate to the lining structural layer of the penetration.

A 2-D calculational model has been set to examine the peaking factors in the damage parameters in the back wall and lining as a function of the penetration size (both in the poloidal and toroidal direction.). The damage is intensified as the penetration size increase due to the increase in the uncollided neutron component reaching these locations. The analysis for these effects and the assessment of the component lifetime near penetrations in currently in progress and will be reported next electronic meeting (August 15-16, 2000).

Radwaste assessment in liquid first wall/blanket concepts

Waste volume and hazard per total blanket thermal output in the thick-liquid, thin-liquid, refractory first wall, and conventional SW blanket are currently under investigation and will be compared in a consistent manner. Shield thickness in these various concepts will be varied in each concept to reach same acceptable damage rates in the magnet. Component volume and associated radwaste will then be determined and compared. Clearance issues will be addressed. The preliminary results of this work will be discussed during the next electronic meeting.