On the exploration of innovative concepts for fusion chamber technology


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Received 10 March 2000; accepted 7 June 2000

Abstract

This study, called APEX, is exploring novel concepts for fusion chamber technology that can substantially improve the attractiveness of fusion energy systems. The emphasis of the study is on fundamental understanding and advancing the underlying engineering sciences, integration of the physics and engineering requirements, and enhancing innovation for the chamber technology components surrounding the plasma. The chamber technology goals in APEX include: (1) high power density capability with neutron wall load $> 10 \text{ MW}/\text{m}^2$ and surface heat flux $> 2 \text{ MW/m}^2$, (2) high power conversion efficiency ($> 40\%$), (3) high availability, and (4) simple technological and material constraints. Two classes of innovative concepts have emerged that offer great promise and deserve further...
research and development. The first class seeks to eliminate the solid ‘bare’ first wall by flowing liquids facing the plasma. This liquid wall idea evolved during the APEX study into a number of concepts based on: (a) using liquid metals (Li or Sn–Li) or a molten salt (Flibe) as the working liquid, (b) utilizing electromagnetic, inertial and/or other types of forces to restrain the liquid against a backing wall and control the hydrodynamic flow configurations, and (c) employing a thin (~ 2 cm) or thick (~ 40 cm) liquid layer to remove the surface heat flux and attenuate the neutrons. These liquid wall concepts have some common features but also have widely different issues and merits. Some of the attractive features of liquid walls include the potential for: (1) high power density capability; (2) higher plasma β and stable physics regimes if liquid metals are used; (3) increased disruption survivability; (4) reduced volume of radioactive waste; (5) reduced radiation damage in structural materials; and (6) higher availability. Analyses show that not all of these potential advantages may 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. Of the many scientific and engineering issues for liquid walls, the most important are: (1) plasma–liquid interactions including both plasma–liquid surface and liquid wall–bulk plasma interactions; (2) hydrodynamic flow configuration control in complex geometries including penetrations; and (3) heat transfer at free surface and temperature control. The second class of concepts focuses on ideas for extending the capabilities, particularly the power density and operating temperature limits, of solid first walls. The most promising idea, called EVOLVE, is based on the use of a high-temperature refractory alloy (e.g. W–5% Re) with an innovative cooling scheme based on the use of the heat of vaporization of lithium. Calculations show that an evaporative system with Li at ~ 1200°C can remove the goal heat loads and result in a high power conversion efficiency. The vapor operating pressure is low, resulting in a very low operating stress in the structure. In addition, the lithium flow rate is about a factor of ten lower than that required for traditional self-cooled first wall/blanket concepts. Therefore, insulator coatings are not required. Key issues for EVOLVE include: (1) two-phase heat transfer and transport including MHD effects; (2) feasibility of fabricating entire blanket segments of W alloys; and (3) the effect of neutron irradiation on W. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: Chamber technology; First wall; Blanket; Liquid walls; Free surface; Refractory alloys; Two-phase flow; Plasma–material interaction; MHD effects

1. Introduction

A study, called APEX, was initiated in early 1998 as part of the US Fusion Energy Sciences Program initiative to encourage innovation and scientific understanding. The primary objective of APEX is to identify and explore novel, possibly revolutionary, concepts for the chamber technology that can substantially improve the attractiveness of fusion energy systems. The chamber technology includes the components in the immediate exterior of the plasma (i.e. first wall, blanket, divertor, and vacuum vessel) and has a tremendous impact on the economic, safety and environmental attractiveness of fusion energy systems.

The APEX study is being carried out by a multi-disciplinary, multi-institution integrated team. The emphasis of the study has been on fundamental understanding and advancing the underlying engineering sciences, integration of the physics and engineering requirements, and enhancing innovation for the chamber technology.

This paper presents a summary of the technical results from the first phase of the APEX study. A number of promising ideas for new innovative concepts have already emerged from this first phase. While these ideas need extensive research before they can be formulated into mature design concepts, some of them offer great promise for fundamental improvements in the vision for an attractive fusion energy system.

These ideas fall into two categories. The first category seeks to totally eliminate the solid ‘bare’ first wall. The most promising idea in this category is a flowing liquid wall. The liquid wall idea is ‘concept rich’. These concepts vary from ‘liquid first walls’, where a thin layer of liquid (< 2 cm)
flows on the plasma-side of the first wall, to ‘thick liquid walls’, where an all-flowing thick liquid (> 40 cm) serves as the liquid wall/liquid blanket. Other variations in the liquid wall concepts include the type of ‘restraining force’ utilized to ‘control’ the movement and geometry of the liquid. Candidate liquids range from high conductivity, low Prandtl number liquid metals to low conductivity, high Prandtl number liquids such as the molten salt Flibe. While all concepts in the liquid wall category share some common advantages and issues, each concept has its own unique set of incentives and issues.

The second category of ideas focuses on extending the capabilities, particularly the power density and temperature limits, of solid first walls. A promising example is the use of high temperature refractory alloys (e.g. tungsten) in the first wall together with an innovative heat transfer and heat transport scheme based on vaporization of lithium.

This paper is organized as follows. Section 2 summarizes the study approach. Section 3 provides an introduction to the basic scientific principles of liquid walls. Sections 4 and 5 present the analysis of free-surface hydrodynamics, heat transfer, and MHD effects, as well as tritium breeding, activation, and other considerations for thick and thin liquid walls, respectively. A liquid wall concept based on the utilization of electromagnetic forces to restrain the liquid flow movement and geometry is introduced in Section 6. Plasma–liquid interactions are addressed in Sections 7 and 8. Concepts based on using high-temperature refractory solid first walls are analyzed in Section 9 for evaporative lithium cooling and in Section 10 for helium cooling. Section 11 highlights a concept for flowing Li2O particulates. Structural material and safety considerations for all concepts are investigated in Sections 12 and 13, respectively. A summary of the study is provided in Section 14. It should be noted that because of the depth and breadth of the study, the scope of the presentation in this paper has been limited to the key technical points. Considerable additional details are provided in the study ‘report’ of ref. [1].

Table 1

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<th>Highlights of the APEX study approach</th>
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<td>(1) Emphasize innovation</td>
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<td>(2) Understand and advance the underlying engineering sciences</td>
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<td>(3) Utilize a multidisciplinary, multi-institution integrated TEAM</td>
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<td>(4) Provide for open competitive solicitations</td>
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<td>(5) Close coupling to the plasma community</td>
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<td>(6) Direct participation of material scientists and system design groups</td>
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<td>(7) Direct coupling to IFE Chamber Technology community</td>
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<td>(8) Encourage international collaboration</td>
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2. Study approach

The APEX objective, ‘to identify and explore novel, possibly revolutionary, concepts for the Chamber Technology that can substantially improve the attractiveness of future fusion energy systems’, represents a challenge that was clearly recognized from the onset of the study. Therefore, careful attention was paid to the study approach. Some of the key elements of the APEX approach are highlighted in Table 1.

Chamber Technology includes the components in the immediate exterior of the plasma (e.g. first wall, blanket, divertor, and vacuum vessel). Concepts for Chamber Technology must satisfy the basic functional requirements shown in Table 2, which include providing a vacuum environment, plasma exhaust, heat removal, and tritium breeding.

A set of primary goals for Chamber Technology was adopted to guide the APEX study. These

Table 2

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<th>Functional requirements of chamber technology</th>
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<td>Provision of vacuum environment</td>
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<td>Exhaust of plasma burn products</td>
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<tr>
<td>Heat removal and power extraction of surface heat loads (from plasma particles and radiation)</td>
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<td>Heat removal and power extraction of bulk heating (from energy deposition of neutrons and secondary gamma rays)</td>
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<td>Tritium breeding at the rate required to satisfy self-sufficiency</td>
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<td>Radiation protection</td>
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goals, shown in Table 3, have been used as guidelines to calibrate the potential attractiveness of new ideas and to measure progress. These goals provide quantitative targets for key parameters and features related to Chamber Technology that have the highest impact on the attractiveness of fusion energy systems. The rationale for these goals is provided in Ref. [2].

In the early stage of the APEX study, an assessment was conducted to understand the limitations and constraints of traditional concepts (i.e. concepts that were developed over the past 20 years). The results of this assessment [2] are not repeated here. By understanding the limitations and constraints of the traditional concepts, this assessment partially illuminated the path toward extending limits, overcoming constraints, and helped stimulate ideas for potentially more attractive novel concepts.

A diagram illustrating the APEX process for screening and evaluating the scientific bases of new ideas is given in Fig. 1. These ideas went through a ‘screening process’ which relied on ‘expert judgement’ by the APEX team. The team tolerated ‘high-risk’ ideas whenever there was a clear potential for high-payoff. The ideas that passed the screening test proceeded to the stage of ‘design idea formulation and analysis using existing tools’. The technical work on those ideas is reported in ref. [1]. However, it should be noted that in the course of this work it became evident that existing models and data were not sufficient. Therefore, substantial effort was devoted to developing new models and exploring new phenomena for the more promising concepts such as liquid walls and high-temperature refractory alloys.

During the work on exploring novel ideas, the team adopted a set of scientific evaluation criteria which are discussed in ref. [1]. These criteria included:

1. Satisfying functional requirements (see Table 2).
2. Demonstrating potential for improved attractiveness, based on: (a) high power density capability; (b) high conversion efficiency; (c) high availability; (d) attractive safety and environmental attributes; (e) simple technological and material constraints, and (f) low cost.

It is important to note that the process flow diagram in Fig. 1 was not intended as a ‘rigid’ sequence of events. Rather, it was only a ‘guide’ to measure progress and a tool to focus resources on ideas with better potential. Strong technical judgement by the scientists was the best guidance whenever new, and often surprising, technical results were obtained. Innovation was needed, and has taken place as an ongoing process. For example, when technical results indicated that the temperature of a free-surface liquid wall may be limited by plasma impurity considerations, the following innovative ideas were proposed by team scientists:

1. The use of Sn–Li because it has low vapor pressure at elevated temperatures.
2. Effective schemes to promote controlled surface mixing and wave formation to eliminate the surface thermal boundary layer.
3. Novel ideas for two-stream flows that keep the free-surface temperature low enough for compatibility with plasma operation while the bulk liquid temperature is sufficiently high for attractive energy conversion.

3. Introduction to liquid walls

The idea of flowing liquid walls has emerged as one of the most promising concepts explored so far in APEX. The area of liquid walls appears to be ‘concept rich’ with many ideas emerging in the past 2 years that have widely different characteristics. Therefore, an introduction to liquid walls is necessary before presenting the technical results of the next five sections.
Fig. 1. Flow diagram illustrating steps in the APEX process.
It must be clearly noted here that the concept of liquid walls is an idea that, prior to APEX, has not been subjected to extensive analysis and evaluation. A brief history is in order. The idea of using a liquid blanket in a fusion device was first suggested by Christofilos in 1970 [3] for a field reversed concept (FRC). In this design, the plasma volume was surrounded by a 75 cm thick, free surface lithium blanket flowing at 30 m/s\(^{-1}\). Subsequent uses of the liquid walls for magnetic fusion devices have been documented [4–7].

With regards to inertial fusion reactors, the first published reactor design concept was a liquid wall concept proposed by Fraas of ORNL [8]. This design, called BLASCON, features a cavity formed by a vortex in a rotating liquid-lithium pool. Subsequent liquid wall design concepts include a liquid-lithium waterfall [9], HYLIFE [10], HYLIFE-I [11], and HYLIFE-II [12].

3.1. Liquid wall options

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 (as shown in Table 4) according to: (a) thickness of the liquid; (b) type of liquid used; and (c) the type of restraining force used to control the liquid flow (i.e. adhere to a backing wall).

The working liquid must be a lithium-containing medium in order to provide adequate tritium. The only such practical candidates are the liquid metals lithium and Sn–Li, and the molten salt Flibe. Lead–lithium was eliminated as a candidate early in the study [1,2]. Lithium and Flibe were considered for traditional concepts for many years. Sn–Li was introduced into APEX because it has very low vapor pressure at elevated temperature, which is an important advantage in a plasma-facing flowing liquid. The hydrodynamics and heat transfer related characteristics and issues of high-conductivity, low Prandtl Number liquid metal flows are considerably different from those of the low-conductivity, high Prandtl Number Flibe flows. Flowing liquid metals may require the use of electrical insulators to overcome the MHD drag, while for Flibe free surface flows, MHD effects caused by the interaction with the mean flow are less significant. The effects on plasma stability and confinement also differ based on the electrical conductivity of the working liquid.

The thickness selected 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. As seen later, the ‘thin’ liquid wall concept is easier to attain, but ‘thick’ liquid wall concepts greatly reduce radiation damage and activation of the structure behind the liquid.

Widely different liquid wall concepts are obtained by applying various forces to drive the liquid flow and restrain it against a backing solid wall. As shown in Table 4, at least four concepts can be considered based on the driving/restraining force scheme. The first is called gravity–momentum driven (GMD). In the

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<td><strong>Working liquid</strong></td>
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<td><strong>Liquid structure</strong></td>
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GMD concept, illustrated in Fig. 2, the liquid is injected at the top of the chamber with 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 the gravitational force.

A GMD with the swirl flow concept is obtained by giving the fluid an azimuthal velocity to produce rotation. The ‘swirl flow’ results in a substantial increase in the centrifugal acceleration towards the back wall and better adherence to the wall, when the backing wall curvature in the poloidal direction is large and the toroidal curvature is comparable to poloidal curvature. While swirl flow may not be needed for moderate aspect ratio tokamaks, it appears to be necessary in the highly elongated, very low aspect ratio spherical torus (ST).

In APEX, the GMD has been explored for tokamaks. The GMD with the swirl flow concept has been investigated for both the ST and FRC tokamaks. Other plasma confinement schemes will be investigated in the future. The analysis of the GMD and GMD with swirl flow concepts are described in more detail in Sections 4 and 5.

The electromagnetically restrained (EMR) concept, illustrated schematically in Fig. 3, is applicable only to liquid metals. The EMR concept has been explored only for lithium in tokamak configurations. In the EMR, a force field pushing the liquid against the backing wall is generated by injecting current to flow through the liquid lithium in the poloidal direction. The injected poloidal current interacts with the toroidal magnetic field to generate an internal ‘\( J \times B \)’ body force causing the liquid layer to adhere to the back wall. The EMR concept is explored in Section 6.

Another liquid wall concept not yet explored in APEX is the magnetic propulsion idea proposed by Zakharov [13] and illustrated in Fig. 4. The idea is to create a pressure driving force through the interaction of the toroidal magnetic field with an externally applied longitudinal electrical current in the liquid metal layer. The non-uniformity of the toroidal magnetic field thus generates a non-uniform Lorentz force. The resultant pressure gradient or propulsion effect causes the flow to accelerate from the inboard, where the magnetic field is stronger, to the outboard region. In addition, the Lorentz force provides an active feedback mechanism for stabilizing the flow while its normal component keeps the layer adhered to the structural wall.

3.2. Motivation for liquid wall research

Liquid walls offer many potential advantages that represent an excellent opportunity to substantially enhance the attractiveness of fusion energy systems. Examples of advantages that may be realized if we can develop good liquid wall designs are listed in Table 5. The potential improvements in plasma stability and confinement are analyzed in Section 8. The other potential advantages are discussed in Sections 4–6.

As explained earlier, there are many options for liquid wall concepts. 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 the attractiveness of fusion energy systems.

3.3. Key issues for liquid walls

The scientific and engineering issues for liquid walls are addressed in Sections 4–8. Of all these issues, a number of scientific issues stand out as the highest priority for near-term liquid wall research, which are summarized in Table 6. These include:

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.
- Liquid adherence to back wall by centrifugal force.
- Applicable to liquid metals or molten salts.

Fig. 2

Fig. 3

Externally driven current ($\vec{J}$) through the liquid stream.

Liquid adheres to the wall by EM force $\vec{F} = \vec{J} \times \vec{B}$

Fig. 4

$\vec{V}$ is driven by $\Delta P$

- Adheres to the wall by $\vec{F} = \vec{J} \times \vec{B}$
- Utilizes $1/R$ variation in $\vec{F} = \vec{J} \times \vec{B}$ to drive the liquid metal from inboard to the outboard.
Table 5
Motivation for liquid wall research

What may be realized if we can develop good liquid wall designs:

- Improvements in plasma stability and confinement
  - Enable high $\beta$, stable physics regimes if liquid metals are used
- High power density capability
  - Eliminate thermal stress and wall erosion as limiting factors
  - Smaller and lower cost components (chambers, shield, vacuum vessel, magnets)
- 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
  - Increased lifetime and reduced failure rates
  - Faster maintenance (design-dependent)

2. Hydrodynamics flow feasibility in the complex geometry including penetrations needed for plasma maintenance. The issue of establishing a viable hydrodynamic configuration threatens feasibility, while 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 interaction. 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 issue concerns 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 is a critical, tightly coupled problem between plasma edge and liquid free surface conditions including radiation spectrum, surface deformation, velocity and turbulent characteristics. Being a low thermally conducting medium, the Flibe surface temperature highly depends on the extent of the turbulent convection. However, the normal velocity at the free surface as well as the turbulent eddy near the surface can be greatly suppressed. A greater degradation in heat transfer (up to 50%) would be expected for the Flibe thick liquid concepts. The heat transfer at free surface issue is an even more serious concern, as the current limit on surface temperature for Flibe, as estimated by the plasma interface group, is significantly low. The effects of liquid walls on the plasma core as well as edge plasma–liquid surface interactions require modeling and experiments in plasma devices. Free-surface fluid flow and heat transfer, with and without magnetic field and hydrodynamic control of free-surface flow in complex geometries require modeling and laboratory experiments. It is worth noting that a number of such important modeling and experimental R&D activities have already started as part of APEX and as part of the US Liquid Wall Research Program.

Table 6
Key scientific issues for liquid walls

- Effects of liquid walls on core plasma including:
  - Discharge evolution (start-up, fueling, transport, beneficial effects of low recycling)
  - Plasma stability including beneficial effects of conducting shell and flow
- Edge Plasma–liquid surface interactions
- Free-surface heat transfer and turbulence modifications at and near free-surfaces
- MHD effects on free-surface flow for low- and high-conductivity fluids
- Hydrodynamic control of free-surface flow in complex geometries, including penetrations, submerged walls, inverted surfaces, etc.

4. Thick liquid wall concepts

4.1. Introduction

The replacement of the first wall with a flowing thick liquid offers the potential advantages of high power density, high reliability and availability (due
to simplicity and low failure rates), reduced volumes of radioactive waste, and increased structure lifetime. All these advantages make the thick liquid wall approach a strong candidate in the APEX study. Specifically, neutronics analyses showed that with ~ 42 cm layer thickness, about two orders of magnitude reduction in helium and hydrogen production is achieved with either Flibe or Sn–Li. With this thickness, and a 200 DPA damage limit for structure replacement, the use of Flibe or Sn–Li can make the structure behind it a lifetime component. Furthermore, the volumes of radioactive waste from the FW/blanket system, as well as from the entire system, are substantially reduced. The emphases of the Phase I study included the exploration of design ideas, quantification of their high power density capabilities, and identification and analyses of the key feasibility issues of thick liquid wall configurations for various confinement schemes. The initial goal is to establish a viable free surface flow configuration. This involves: (1) an inlet nozzle and penetrations that pass flow without dripping or splashing; (2) a free surface flow section that allows liquid to cross temporally and spatially variable magnetic fields and provides full wall coverage; and (3) a head recovery nozzle system that accepts the flow and converts it from a free surface flow to a channel (pipe) flow without complete loss of kinetic energy.

There are three lithium-containing candidate liquids for the walls: (1) Flibe — a good neutron absorber and low electrically conducting medium of molten salt; (2) lithium — a low Z material that is more likely compatible with the plasma operation; and (3) tin–lithium — an extremely low vapor pressure fluid at elevated temperatures. Both lithium and tin–lithium are good electric conductors. Utilization of these two liquid metals will require an understanding of MHD effects, not just in the surface flows, but in supply lines and feed systems, and it also would likely require electrically insulating coatings.

4.2. Design options

Design ideas for establishing thick liquid walls were addressed for the tokamak (such as ARIES-RS) [14], spherical torus (ST), and field reverse configuration (FRC). The fact that topologies are different in different confinement schemes requires different liquid wall design approaches. For example, as compared to the ARIES-RS, the ST confinement scheme tends to be highly elongated (larger back wall radius of curvature). The centrifugal force acting on the liquid layer due to its poloidal motion is less than in the ARIES-RS. However, it uses a smaller toroidal radius as illustrated in Fig. 5. The centrifugal force acting on the flowing liquid layer in the ST configuration can be increased by utilizing swirl motion in the azimuthal (toroidal) direction. Thus, one may expect a more stable hydrodynamics condition in the ST liquid blanket. However, being highly elongated, the fluid takes more time to travel through the reactor if only one coolant stream is used. This implies that the free surface side may be overheated from a long plasma exposure time. A typical FRC reactor can be viewed as a long cylinder in which a football shaped volume of plasma lies at the center of the reactor chamber (see Fig. 6). The FRC confinement scheme appears more amenable to thick liquid walls due to its geometrical simplicity and lower strength magnetic fields.

4.3. Hydrodynamics and MHD effects

One of the most fundamental issues for the thick liquid blanket is how to form, establish, and maintain a thick liquid flow in a fusion reactor such as the ARIES-RS (as shown in Fig. 5). The simplest approach that can be conceived for a thick liquid blanket is free-flowing liquid under the effect of gravitational and inertial forces. As illustrated in Fig. 7, the thick liquid layer is injected at the top of the reactor chamber with an angle tangential to the backing structural wall. As it flows along the curved wall the fluid adheres to the structural wall by means of centrifugal and inertial forces. It then is collected and drained at the bottom of the reactor.

This Flibe approach has been modeled with a three-dimensional, time-dependent Navier–Stokes Solver that uses Reynolds Averaged Navier Stokes (RANS) equations for turbulence modeling and the volume of fluid (VOF) free surface tracking algorithm for free surface incompressible fluid flows.
Fig. 5. Hydrodynamic configurations of thick liquid walls may be very different for ARIES-RS and ARIES-ST. Both configurations are converted to single null at the bottom of the plasma, in order to be compatible with the liquid wall configuration.