ROTATING LIQUID BLANKET WITH NO FIRST WALL FOR FUSION REACTORS*

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ABSTRACT

A toroidal vortex of liquid FLiBe ($\text{LiF} + \text{BeF}_2$) is suggested for the blanket of a fusion reactor. Because this reactor chamber has no solid first wall, it might avoid many of the problems that accompany conventional blanket design. The liquid blanket is sustained by nozzles that inject a continuous layer of cool liquid on the inner surface. A second set of nozzles sends a stream of droplets across the diverted scrape-off layer or edge plasma to carry its heat away. The feasibility issues of most importance are judged to be avoiding turbulent breakup of the vortex and preventing too much contamination of the plasma by the evaporating FLiBe.

INTRODUCTION

Eliminating most if not all the solid material from a fusion reactor's first wall and support structure would have enormous implications for fusion reactor development. This paper considers replacing the first wall with a liquid blanket formed by rotating the liquid fast enough to overcome gravity. Plausible explanations for how such a scheme might work in a toroidal geometry are given in Ref. 1, which also cites prior work on other geometries. A possible working fluid might be the well-known molten salt, $\text{LiF} + \text{BeF}_2$. The rotation is maintained by nozzles that penetrate the moving layer of liquid. These nozzles are the only solid materials in the blanket. Since the nozzles would be replaceable, and the liquid acts as a shield, this blanket concept virtually eliminates the need to develop long-lived materials for the fusion environment.

In linear or open-ended geometry, the two problems of gas and heat removal from the leaking plasma have been worked out satisfactorily. However, in toroidal geometry, these two problems remain paramount, as even a slight failure to remove heat and gas sufficiently can lead to excessive plasma contamination. This paper addresses these problems. Related work that uses droplet jets or solid spheres to remove heat from the edge of fusion reactors is described in Refs. 2 and 3.

The concept of a rotating liquid blanket is shown in Fig. 1. One set of nozzles produces a droplet stream that exposes a large surface area to the leaking plasma. This stream minimizes the temperature rise for a given heat flux, thus minimizing evaporation. A second set of nozzles lays a fresh, cool layer of salt over the hot layer of droplets. The nozzles are closely spaced all the way around the torus in the toroidal direction. They are hydrodynamically shaped to minimize flow disturbances. Vanes are used to reduce turbulence that could bring hot fluid up to the front surface and cause excessive evaporation. The nozzles could be made of graphite, beryllium, tungsten or certain other materials, possibly even steel.

Start-up of Vortex or Rotation

The vortex shown in Fig. 1 can be thought of as a portion of a Hill's vortex and can have an elliptical cross section if desired. To start the vortex flow, we close off the beam and pellet tube and fill the chamber with FLiBe, which is pumped to the inlet nozzles and removed from the outlet nozzles. These nozzles establish the vortex motion and sustain it against viscous drag on the penetrations and back wall. With the removal of a portion of the FLiBe, the vortex opens a void in the center at the desired location. The access tubes and two sets of inlet nozzles then penetrate into this void, as shown in Fig. 1, and the access tubes can be drained. The plasma discharge can now be produced repetitively or continuously, independent of the vortex motion.

The above description may be flawed. For example, it is by no means clear that the vortex will present a smooth inner surface facing the plasma and not be violently turbulent, resulting in hopelessly contaminating the plasma with evaporated FLiBe. There is hope, however, that the optimistic picture may be completely realizable, and it is worth serious examination as a means of overcoming the many uncertainties and problems of more conventional blanket designs.

Droplet Heat-Removal Capability

We introduce some of the issues by presenting a calculation of heat removal by droplets. Many simplifying assumptions are included. We assume that the nozzles produce

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Fig. 1. Schematic of rotating liquid blanket with no solid first wall.

droplets of radius r_0 and speed v_0 injected across an edge plasma of path length l_0 . For simplicity, we assume that the plasma deposits heat uniformly over the entire droplet surface. This heat load is denoted as q_0 . The droplet surface temperature is given by the solution to the well-known heat conduction equation (see, for example, Ref. 4).

The thermal diffusivity is $k/\rho c$, which for FLiBe is $1.7 \times 10^{-7} \text{ m}^2/\text{s}$, where k is 6.8 W/m K , ρ is 2050 kg/m^3 , and c is 2350 J/kg K . The thermal diffusivity time is

$$\tau = r_0^2 \rho c / k.$$

The surface temperature T equals the temperature at the droplet center T_0 at zero time and increases with time. The quantity $(T - T_0)k / q_0 r_0$ is given in Ref. 4 as a function of the dimensionless time

$$F_0 = t / \tau = 0.1245 \times (50 \text{ ms}^{-1} / v_0)(0.2 \text{ mm} / r_0)^2$$

Figure 2 shows the heat absorption for several droplet speeds vs droplet size, where the temperature rise is 300 K and path length is 1.5 m . As an example, for 50 m/s and a diameter of 0.6 mm , q_0 is 2.5 MW/m^2 .

The area of a cut across the edge plasma in relation to the sheet of droplets is $2\pi \times 6 \times 1.5 = 56.5 \text{ m}^2$. If the fusion power is 3000 MW , 20% is non-neutron power. We assume

that half of this 20% is converted to 300 MW of penetrating radiation (bremsstrahlung, x-rays, synchrotron,¹ and optical), leaving 10% (300 MW) as nonpenetrating heat on the inside surface. Of this we assume that 240 MW goes to the flowing edge plasma and 60 MW is distributed over the liquid first wall, giving 0.1 MW/m^2 over the 474 m^2 of liquid first wall. The surface temperature increase is calculated from the equation, $\Delta T = 2q_0(t/\pi k \rho c)^{1/2}$. At a surface liquid speed of 25 m/s , the FLiBe will increase in temperature by 20°C in one revolution, i.e., by the time the fresh cool liquid covers the heated-up surface. The 240 MW is spread over 56.5 m^2 , giving an average power loading of 2.2 MW/m^2 on the droplet sheet.

Internal circulation increases the effective conductivity of the droplet.⁵ This might give three times the heat-load capability. Oscillations of the droplet are predicted to further increase conductivity by a similar factor.⁶ Also, the rotation of droplets and charge exchange of plasma particles, giving a neutral particle heat load, will tend to distribute the heat load over the total droplet surface, that is, the total droplet area is four times its frontal area, and all the area

¹Because the salt is practically nonconducting electrically, microwave radiation is absorbed, not reflected back into the plasma as is usually the case. This will affect the ignition condition and tend to put more of the charged power into the first millimeter of the liquid first wall.

Fig. 2. Uniform heat load on a droplet vs droplet speed. This heat load is indicative of the heat-removal capability of a thick droplet stream or sheet.

is heated. These two effects might increase the heat-load capability by well over a factor of 10. Our example of q_0 of 2.5 MW/m² translates into an average heat flux on the droplets' exposed surface of about 90 MW/m².

The plasma particles v -like the droplet sheet at an acute angle because they follow the magnetic field lines, which are mostly into the paper (toroidal direction) and only slightly in the plane of the figure (poloidal direction). (The droplet sheet can be seen in Fig. 1, as dashed lines.) The power density would be enhanced by the inverse sine of this acute angle in relation to individual droplets over the average power density on the sheet. This might enhance the heat load on the droplets by an order of magnitude. That is, the 4.2 MW/m² might be enhanced to about 42 MW/m², thus just matching the heat-removal capability. The heat-removal capability of droplets must be calculated more carefully in future work with an emphasis on minimizing evaporation, which means keeping the temperature rise at the droplet surface low.

For droplet heat removal to be efficient, the kinetic power carried by all the droplets (a large part of the pumping power) must be a small fraction of the thermal power picked up [2]. This ratio is proportional to $r_0 v_0^3 / q_0$, which requires that the 100 m/s droplets should be kept under 1 mm in diameter. For speeds less than 100 m/s, the droplets can be much larger ($r_0 \propto q_0 / v_0^3$).

Incidentally, the plasma will charge the droplets negatively to a few times the electron temperature. The effects of this electrical charge are unknown.

Evaporation of FLiBe

The evaporation of the liquid produces a vapor of LiF and BeF₂ (plus some Li₂F₂) that will strike the edge plasma, where it will be ionized. Most of the Li, Be, and F ions will be returned to the liquid, but some will enter the hot plasma region and there dilute the fusion fuel and produce radiation. One can make reasonably accurate estimates of the evaporation rate and therefore of the rate of arrival of this vapor at the edge plasma. One can also estimate the tolerable level of Li, Be, and F ions in the hot plasma. It is

much more difficult to predict the fraction of incident ions on the edge plasma that penetrates into the hot plasma and the lifetime of these ions in the hot plasma. These difficult calculations are suggested for future work.

The vapor pressure of FLiBe for the 47% LiF - 53% BeF₂ mixture is given by [1]

$$\log_{10} P \text{ (Torr)} = 9.407 - 10,054/T \text{ (K)}$$

Using an average molecular weight of 37, the evaporation rate $J = \bar{n}i/4$, and the evaporative cooling rate Q (where the heat of vaporization of 49,000 cal/g mole is used), we get the values shown in Table 1.

To illustrate the evaporation problem, we consider a case at 450°C; however, other temperatures coming out of a transient heat-transfer analysis should be carried out. At 450°C, $J = 7.7 \times 10^{15} \text{ cm}^{-2} \text{ s}^{-1}$. The surface area of the first wall is $2\pi \times 6 \times 2\pi = 473.7 \text{ m}^2$, giving 3.65×10^{22} FLiBe molecules evaporated per second. This evaporation rate can be compared to the helium production rate of 10^{21} s^{-1} for 5000 MW of fusion power. The plasma volume is $2\pi \times 6 \times 2\pi = 473.7 \text{ m}^3$.

Assuming that the impurity lifetime is 1 s and that a fraction f of the evaporating molecules penetrates into the hot plasma ($1 - f$ is the fraction swept out of the edge plasma), then the impurity density is

$$n_{\text{FLiBe}} = 3.65 \times 10^{22} / 474 = 7.7 \times 10^{19} \text{ f (m}^{-3}\text{)}.$$

The ratio of impurity to fuel ions is

$$n_{\text{FLiBe}}/n_{\text{DT}} = 7.7 \times 10^{19} / 2 \times 10^{20} = 0.38 f.$$

If the impurity concentration can be 10^{-3} , then f must be < 0.0026 . It seems at least possible that the edge plasma can expel or sweep out the ionized, evaporating FLiBe this thoroughly and that the plasma may not be swamped with impurities. There are lower-viscosity (less BeF₂) salt mixtures that have much lower vapor pressure than the mixture used here, but those mixtures also must operate at higher temperatures. The evaporation from the droplet stream must be added to the above rate, and sputtering must also be included. The impurity lifetime and the ability of the edge plasma to sweep out ionized impurities are especially in need of more analysis, while the simple calculations above should also be done much more thoroughly.

We have discussed the evaporation of molten salt, but the removal of tritium, deuterium and helium is also necessary and will be left for future work.

T (°C)	T (K)	P (Torr)	$\bar{n}$ (cm ⁻³)	J (cm ⁻² s ⁻¹)	Q (W cm ⁻²)
400	673	2.9×10^{-6}	4.2×10^{10}	7.4×10^{14}	2.5×10^{-4}
450	723	3.2×10^{-6}	4.2×10^{11}	7.7×10^{16}	2.6×10^{-3}
500	773	2.5×10^{-6}	3.1×10^{12}	5.9×10^{16}	2.0×10^{-2}
550	823	1.6×10^{-5}	1.8×10^{13}	3.5×10^{17}	0.12
600	873	7.8×10^{-5}	8.6×10^{13}	1.7×10^{18}	0.58

Fig. 3. Cross section of a fluid element as the element is followed around the minor radius. The acceleration g is shown for various positions as the fluid element rotates around the circumference of the torus.

Hydrodynamics of Rotating Layer

Turbulence. Turbulence could break up the vortex. By break up we mean that eddy motion could bring hot FLiBe to the surface that is exposed to the plasma and contaminate the plasma by its evaporation, whereas the evaporation rate of the cool FLiBe might be tolerable. There are two main driving forces for the turbulence. First, the drag on the back wall and nozzles results in a shear in the flow. Second, the cross section of the flow varies as it rotates, as shown in Fig. 3. The layer on the outside is typically about half as thick (0.38 m) as the layer on the inside (0.84 m).

For example the rotating speed could vary from 10 to 50 m/s. The acceleration is v^2/r , so for a first-wall radius of 2 m, the acceleration is 25 to 1250 m/s^2 , or 2.55 to 127 times the acceleration due to gravity. (The acceleration due to gravity is 9.8 m/s^2 and is called 1 g.) The Reynold's number is given below:

$$N_{Re} = d v_m \rho / \mu$$

At 400°C, corresponding to the inlet temperature, the viscosity μ is 0.65 Pa s; at 600°C it is 0.05 Pa s. (For 45% LiF + 55% BeF₂, other mixtures with less BeF₂ have much lower viscosities and lower vapor pressures.) The mean speed v_m is taken to be approximately 15 m/s (11 g), and the density is 2050 kg/m^3 . The Reynold's number varies from 28,000 to 370,000. These values are more than an order of magnitude larger than the usual transition Reynold's number of a few thousand. Perhaps the hydraulic diameter should be less than the full thickness assumed above. The large g force might allow a larger Reynold's number for a given amount of turbulence. The magnetic field might also help in suppressing

the turbulence. Using flow vanes or artificially producing a flow on the back wall with jets or moving surfaces might also help prevent turbulence or minimize the effect of bringing hot liquid to the free surface.

Splash Suppression. Each tube penetrating through the moving layer must be designed to minimize splashing. The flow of liquid past the tube is analogous to the movement through water of the outboard motor shaft on a speed boat. Because the speeds for the moving liquid and for speed boats are similar, the design of the tubes and shaft could be similar. The leading and trailing edges of the tube would be made sharp, like those of the housing on an outboard motor shaft, as shown in Fig. 4. Splash plates as shown in Fig. 1 would also be used. A calculation of the drag of the liquid on the penetrating tubes and on the back wall should be made.

Fig. 4. Cross section of a hydrodynamically designed tube that penetrates the moving liquid. Ducts in the tube can carry coolant and pump gas

POSSIBLE SOLUTION TO CONTAMINATION PROBLEM

A potential solution to the problem of plasma contamination by evaporating FLiBe has been suggested [7]. It may be possible and practical to replace the droplet nozzles on the end of the tubes that penetrate the flowing liquid with limiter or divertor plates. Such an alternative configuration is shown schematically in Fig. 5. Almost all of the plasma power will hit the limiter plates and little will hit the liquid, thus greatly reducing the heat-removal requirements on the liquid and the evaporation problem. In addition, the tubes themselves can carry coolant to and from the structure and accommodate ducts to pump gas as well (see Fig. 4).

ELECTRICAL RESISTANCE IN TOROIDAL DIRECTION

For a 6-m major radius, a 2-m first-wall minor radius and a 1-m-thick rotating layer, we get the following resistance:

$$R = \rho \times l / A = 0.038 \Omega,$$

where

$$A = \text{area} = 1 \times 2 \times \pi \times 2.5 = 15 \text{ m}^2,$$

$$l = 2 \times \pi \times 6 = 36 \text{ m, and}$$

$$\rho = 0.016 \text{ } \Omega\text{-m.}$$

This high resistance will result in negligible short circuiting of the induced toroidal current. Other liquids that have much lower resistance and higher induced currents, such as lithium, could have important harmful effects.

CONCLUSION

The idea of eliminating the solid first wall of a fusion reactor and replacing it with a flowing or rotating liquid blanket is attractive because it promises to eliminate many problems faced by fusion reactor designers. This paper discusses the two most important feasibility issues: avoiding turbulent breakup of the vortex and preventing too much contamination of the plasma by the evaporating FLiBe. Both issues are judged to be serious but possibly surmountable problems.

Fig. 5. As an alternative configuration, limiter or divertor plates are mounted on the hydrodynamically shaped tubes penetrating the rotating liquid. Gas-pumping ducts are incorporated into these tubes. The limiter plates replace the droplet-sheet heat-removal system of Fig. 1.

Other issues are the lifetime of impurities, the allowed impurity concentration, the fraction of evaporated FLiBe that penetrates into the hot plasma, the heat-removal capability of the droplets, and the effect of electrical charge on the droplets. Eliminating the first wall would be extremely beneficial; therefore, we welcome and encourage further work to address the issues discussed in this paper.

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