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THERMAL AND MECHANICAL DESIGN CONSIDERATIONS FOR LITHIUM-COOLED TOKAMAK REACTOR BLANKETS

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Summary

A strategy is described for the design of lithium-cooled Tokomak reactor blankets. A design is proposed for a 5000 MW(th) D-T Tokamak reactor with a thermal wall loading of 1.77 MW/m^2 and a toroidal field on axis of 38.6 kG. Stainless steel is used for the structure and moderator-reflector material; lithium is used as the coolant. A maximum coolant temperature of 500°C is imposed to limit the rate of corrosion of the stainless steel by the lithium. The coolant is supplied to the reactor at 283°C. The maximum coolant pressure at the first wall is 300 psia.

The present design achieves a lower pressure drop than the design of Reference 4, despite a higher magnetic field, reduced blanket thickness and double wall loading. The improvement is due to changes in manifolding and in the moderator-reflector design.

Introduction

The Wisconsin fusion feasibility study group is currently working on D-T fueled toroidal reactors. A conceptual design is given in References 1-4 and is shown schematically in Figure 1; the system parameters are given in Table 1. The present paper gives an improved blanket design for this reactor, and indicates some important problems for further study.

The blanket of a D-T reactor has three main tasks: removing heat, breeding tritium, and moderating neutrons. These tasks have to be performed in the presence of intense radiation, high temperatures and strong magnetic fields. Magnetohydrodynamic effects are important unless very low velocities are used for circulation of the breeding material (lithium or flibe*). Thus, the design of a blanket is a complicated problem, requiring input from many disciplines. The design given here represents the latest iteration in a cooperative study of the whole reactor system[1], in which detailed consideration is being given to plasma physics, neutronics, magnets, divertors, materials, fueling, reactor safety, ecology and economics.

In this study, lithium is used both as the coolant and the breeding material; a stainless steel layer is used for neutron moderation. The use of lithium as a coolant requires careful attention to magnetohydrodynamic effects on the flow distribution, heat transfer and pressure drops. Early workers[5,6] reported unacceptably large pressure drops, but this difficulty has recently been reduced by more efficient coolant flow designs[4,7,8]. The present design represents a further improvement, such that lithium cooling appears very attractive for D-T reactor systems.

The combination of high magnetic field and electrically conducting coolant produces laminar flow throughout the blanket for all feasible coolant velocities. Thus the temperature profiles are predictable once the flow conditions are determined. The main problem in the blanket design is the selection of appropriate means to distribute the coolant flow, and to achieve good heat transfer effectiveness in a limited space without excessive power consumption or pressure drop.

Design Strategy

The design given here is based on several simple rules obtained from Figure 1 and physical considerations:

a. Coolant must enter and leave the torus through the gaps between the D-shaped magnets.

b. The main headers inside the magnets should follow the toroidal magnetic field lines to minimize pressure drops and utilize available space.

c. Large cross sections should be provided for coolant distribution in the poloidal direction, to minimize the pressure drops in these long flow paths perpendicular to the toroidal field.

d. The coolant for the inner zone of the blanket should be routed to the first wall in large radial ducts. The radial velocities should be small to minimize magnetohydrodynamic pressure drops, but large enough to avoid undesired heat exchange between adjacent radial streams.

e. The stainless steel moderator-reflector in the outer zone of the blanket should have a separate coolant loop, to accomodate its different heat load and flow resistance.

System Description

A design consistent with these ideas is shown in Figures 2 and 3. The blanket structure is 316 stainless steel, and is designed with a maximum temperature of 500°C on the coolant walls to limit corrosion by the lithium. A corrosion allowance of 0.6 mil/year (0.00152 cm/year) is included in the initial wall thickness. The first 20 cm of the blanket is designed for 2 years life, while the rest for 40 years.

The reactor has 12 independent modules, one for each magnet. Each module has four blanket units: one between the upper and lower divertors and three for the rest of the wall (see Figure 2). The coolant is supplied and removed through bundles of four pipes, rather than single large pipes, in order to reduce magnetohydrodynamic losses as discussed below. Each pipe is connected to a toroidal header for the inner or outer zone of the blanket.

The coolant for the inner zone flows from the inner toroidal headers into poloidal headers, and then to the radial flow cells as shown in Figure 3. Each radial flow cell consists of four U-bends connected in series along the first wall. Series connection is used to decrease the residence time in each bend, and thus reduce undesired conduction of heat between adjacent radial streams.[4] To further reduce this exchange, the

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*Li_2BeF_4

outlets of adjacent cells are juxtaposed; this requires provision of a different flow resistance in each cell to distribute the coolant properly. The U-bends are reinforced by poloidal tie-rods to maintain their alignment and contain the coolant pressure.

The alternating inward and outward radial flows in the U-bends produce corresponding alternations in the induced electric field [$\underline{v} \times \underline{B}$]. It is desirable to place the walls normal to this electric field to avoid short circuits between the adjoining radial streams. The arrangement in Figure 3 is consistent with this except for the small poloidal component of the magnetic field.

The stainless steel moderator-reflector in the outer zone of the blanket generates 35% of the 5000 MW thermal output. To avoid overheating, the steel is divided into two layers, each cooled by lithium on both sides. The maximum allowed temperature on the interface of the coolant and stainless steel is 500°C. The calculated maximum temperature in the steel is 670°C.

Pressure Drops

The coolant pressure drop inside the reactor is almost entirely due to magnetohydrodynamic effects. It is calculated here by summing the following contributions as described by Hoffman and Carlson[9].

$$-\Delta p = K_{p1E}\, b\sigma\, \Delta(vB_\perp^2) \qquad \text{Entrance or Exit} \qquad (1)^*$$

$$-\frac{dp}{dx} = \frac{vB_\perp^2\, \sigma_w t_w}{a(1 + C)} \qquad \text{Steady flow in large uniform ducts} \qquad (2)$$

Equation 1 is applied here to changes in velocity, transverse magnetic field, or both. The coefficient K_{p1E} is obtained from Figure 14 of Reference 9 by using $\Delta(vB_\perp^2)$ in place of $v\Delta(B_\perp^2)$. Equation 2 is an asymptotic result for $H_\perp \gg 1 + C^{-1}$, where $H_\perp$ is the transverse Hartmann number; this condition of validity is well satisfied here since $H_\perp \sim 10^5$ and $C \sim 0.1$.

The calculated pressure drops are summarized in Tables 2 and 3 for each blanket unit. The calculations are based on local magnetic fluxes $\underline{B}$, including the poloidal and toroidal components. The resulting pressures are shown in Figure 4 for the unit between the divertors. The pressures are much lower than in the design of Reference 4; this is mainly due to changes in the feed and discharge tubes and in the structure of the poloidal headers. The maximum coolant pressure on the first wall is 300 psia. The pumping power required is 22 MW, which amounts to 0.44% of the reactor's thermal output.

Equation 1 indicates that a bundle of feed or discharge pipes gives less entrance pressure drop than a single pipe of the same total cross section, since both b and K_{p1E} of Reference 9 increase with the pipe diameter. The pressure gradient of Equation 2, however, increases with decreasing pipe size when a corrosion allowance is included in t_w. The pressure gradient is reduced in this design by using laminated pipes with an electrical insulating layer protected by a thin inner wall of stainless steel. An inner wall thickness t_w of 2 mm is used to withstand corrosion by the lithium; a heavier outer wall carries the hoop stress.

The poloidal headers constitute the main flow resistance in the coolant system. These channels are tapered to equalize the velocities in adjoining headers, and thus minimize electromagnetic interactions. Heat exchange between the adjoining header streams is a minor factor because of the substantial width of the channels and the insulating effect of the stainless steel header walls. Electrically insulated liners were considered for reducing the pressure drop, but they are not used in this region, in view of uncertainties about radiation damage.

Rectangular orifices are used to connect the poloidal headers to the radial flow cells. The pressure drop, according to Equation 1, is nearly proportional to vb = V/4a, where V is the volumetric flow and a is the orifice half-width in the poloidal direction. This gives the surprising result that the pressure drop is independent of the orifice length b in the toroidal direction. The length b is taken here as half of the full poloidal header width, to aid in distributing the coolant along the radial flow cells.

The pressure gradient in the radial flow cells is due mainly to eddy currents, which flow through the fluid in the direction of $\underline{v} \times \underline{B}$ and return through the poloidal tie-rods. Radial flow is thus resisted by the toroidal magnetic field, but toroidal flow is not; this causes the flow to distribute readily over the toroidal length of each heat removal cell. For these cells, t_w/a of Equation 2 is taken as the ratio of the conducting cross sections of the tie-rods and fluid.

Wall Stresses

The maximum pressure at the first wall of the blanket is 300 psia. To contain this pressure and impart rigidity to the blanket, we use a wall of toroidal half-tubes as shown in Figure 2. A tube size of 7.5 cm is used; larger sizes give larger total stresses in the first wall.

The local stress in the wall is the resultant of the thermal and hoop stresses. The maximum stress occurs on the coolant side of the wall where both stresses are tensile. Figure 5 shows these stresses and their sum as functions of the wall thickness. We pick 2.5 mm as the initial thickness of the first wall.

Temperature Distribution

Steady state temperature profiles have been calculated for a radial flow cell on the assumption of negligible temperature changes in the headers and uniform fluid speed throughout the cell. The uniform-speed assumption is adequate in view of the high transverse Hartmann numbers and small Peclet numbers encountered in this design. The calculation was done as in Reference 4, by an implicit finite-difference method with a two-dimensional point mesh conforming to the streamlines. The surface and volumetric heat input rates were taken from neutronics calculations as shown in Figure 6. For simplicity, the heat generation for the header region was set to zero, and an equal heat input was added to the radial flow cells; thus the calculated temperature gradients in the radial flow cells are conservative (larger than actual) by about 20%.

The calculated coolant temperatures in a radial flow cell are summarized in Figure 7. The main conclusion to be drawn is that the coolant can be discharged at a temperature quite close to the structural material corrosion limit of 500°C. The temperature approach is closer than in Reference 4 because the coolant residence time is more nearly optimal.

Cooling of the Shield

The shield of the reactor contains a large amount of lead, which melts at 327°C. Therefore, the temperature in this zone was designed to be kept below 200°C for safety reasons. The heat load is small and easily removed by pressurized helium in coils imbedded in the shield.

A gap is required between the blanket and the shield for thermal insulation. This will allow the blanket to be a hot zone while the shield is relatively cool. Helium enters at 50°C and 53 kg/cm^2 (760 psi) makes three passes in each heat transfer unit before it exits at 200°C. The pressure drop of the helium is only 5×10^{-4}kg/cm^2 ($<5 \times 10^{-3}$psi), and the pumping requirement is only 7 kW.

The temperature distribution from the first wall to the edge of the shield is shown in Figure 8.

Conclusions

An efficient design has been proposed for a lithium cooled reactor blanket. The major parameters of this design are listed on Table 1. The same type of design is also adaptable to higher wall loadings and magnetic fields. The following points are the unique features of this design:

1. Maximum utilization of the available space for the coolant flow to minimize the velocity.
2. Proper orientation of the coolant channels to avoid interaction of the eddy currents.
3. U-bend design to provide radial mixing of the blanket coolant.

The limiting factor of this design is probably the high internal pressure in the blanket. The high pressure requires a thick first wall which will cause stress problems. The heat transfer performance power requirements are very satisfactory.

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Notation

a	effective half-width of the flow cross-section in the direction of $B_\perp$
$B_\perp$	transverse component of the magnetic field
b	effective half-width of the cross-section in the direction perpendicular to $B_\perp$ ($a = b = \pi D/8$ for a pipe of diameter D)
C	$= \sigma_w t_w / \sigma a$, ratio of wall and fluid conductances
K_plE	dimensionless function of geometry and wall conductance ratio C, given in Figure 14 of Reference 9
p	coolant pressure
t_w	wall thickness
V	Volumetric flow rate
v	coolant velocity
σ	electrical conductivity of the coolant
σ_w	electrical conductivity of the wall material

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Table 1

Summary of Important Parameters for Heat Transfer

Total Thermal Load	5000 MW_T
Major Radius	13 m
Minor Radius	5.5 m
Total Thermal Wall Loading	1.77 MW/m^2
B axis	3.86 Tesla
Structural Material	316 SS
Blanket Coolant	Lithium
Maximum Lithium Temperature	500° C
Lithium Temperature Rise	200° C
Lithium Flow Rate	6 x 10^3 kg/sec
Maximum Lithium Pressure Drop	281,900 kg/m^2 (401 psi)
Maximum First Wall Pressure	200,800 kg/m^2 (300 psia)
Lithium Pumping Required	22 MW
Shield Coolant	He
He Pressure	5.2 x 10^5 kg/m^2(50 atm)
He Temperature Rise	150° C
He Flow Rate	64.5 kg/sec
He Pumping Required	7 kW

Table 2

Summary of Li Pressure Drop Calculations
(Inner zone of the blanket)

	v,m/s	a,m	b,m	$L_{F/b}$	K_{PIE}	t_w,mm	L,m	$B_\perp$,Tesla	$\Delta P_E, \frac{kg}{m^2}$	$\Delta P_H, \frac{kg}{m^2}$	$\Sigma\Delta P \frac{kg}{m^2}$
			For unit nearest reactor axis								
Feed pipe; Discharge pipe	.18	.196	.196	5.1	.05	2.0	1.83	5.9	31,400	11,600	43,000 (x 2)
Toroidal headers	.705	.196	-	-	-	4.0	3.4	.6	-	1,000	1,000 (x 2)
Poloidal headers	.083	.15	.25	2	.11	3.0	16.0	6.5	48,400(x2)	95,600	192,400
Radial cells	.038	0.5	-	-	-	3.0	1.6	6.5	-	1,500	1,500
											281,700 (=401 psi)
			For units on top and bottom of the torus								
Feed pipe	.235	.196	.196	10.2	.025	2.0	8.0	3.9	9,000	28,200	37,200
Toroidal headers	.939	.196	-	-	-	4.0	6.8	.5	-	3,200	3,200
Poloidal headers	.092	.15	.15	2.0	.11	2.0	8.0	4.2	6,700(x2)	17,100	30,500
Radial cells	.038	0.5	-	-	-	3.0	1.6	5.0	-	1,100	1,100
Toroidal headers	.939	.196	-	-	-	4.0	6.8	.3	-	1,200	1,200
Discharge pipe	.235	.196	.196	5.1	0.05	2.0	5.0	2.64	7,900	8,100	16,000
											89,200 (=127 psi)
			For unit farthest away from reactor axis								
Feed pipe; Discharge pipe	.235	.196	.196	5.1	0.5	2.0	5.0	2.6	7,700	7,900	15,600 (x 2)
Toroidal header	.939	.196	-	-	-	4.0	6.8	.3	-	1,100	1,100 (x 2)
Poloidal header	.092	.15	.15	2.0	.11	2.0	8.0	2.6	2,800(x2)	6,500	12,100
Radial cells	.038	0.5	-	-	-	3.0	1.6	2.6	-	500	500
											46,000 (=65 psi)

Table 3

Summary of Pressure Drop Calculations
(Outer zone of blanket)

For unit nearest reactor axis

	v,m/s	a,m	b,m	$L_{F/b}$	K_{PIE}	t_w,mm	L,m	B_-,Tesla	$\Delta P_E, \frac{kg}{m^2}$	$\Delta P_H, \frac{kg}{m^2}$	$\Sigma \Delta P \frac{kg}{m^2}$
Feed pipe (discharge pipe)	.24	.196	.196	5.1	.05	2.0	1.83	5.9	41,800	15,400	57,200(x2)
Toroidal headers	.235	.196	-	-	-	4.0	3.4	.6	-	300	300(x2)
Coolant channels	.276	.60	.025	2	.11(x2)	4.0	16.0	7.0	18,700(x2)	122,900	160,300
											275,300 (=391 psi)

For units on top and bottom of the torus

	v,m/s	a,m	b,m	$L_{F/b}$	K_{PIE}	t_w,mm	L,m	B_-,Tesla	$\Delta P_E, \frac{kg}{m^2}$	$\Delta P_H, \frac{kg}{m^2}$	$\Sigma \Delta P \frac{kg}{m^2}$
Feed pipe	.313	.196	.196	10.2	.025	2.0	8.0	3.9	12,000	37,600	49,600(x2)
Toroidal headers	.313	.196	-	-	-	4.0	6.8	.5	-	1,100	1,100(x2)
Coolant channels	.184	.60	.025	2	.11	4.0	8.0	4.2	2,200(x2)	17,100	21,500
Discharge pipe	.313	.196	.196	5.1	.05	2.0	5.2	2.64	10,500	10,800	21,300
											94,600 (=135 psi)

For unit farthest away from reactor axis

	v,m/s	a,m	b,m	$L_{F/b}$	K_{PIE}	t_w,mm	L,m	B_-,Tesla	$\Delta P_E, \frac{kg}{m^2}$	$\Delta P_H, \frac{kg}{m^2}$	$\Sigma \Delta P \frac{kg}{m^2}$
Feed pipe (Discharge pipe)	.313	.196	.196	10.2	.025	2.0	8.6	2.6	10,500	10,800	21,300(x2)
Toroidal headers	.313	.196	-	-	-	4.0	6.8	.3	-	1,000	1,000(x2)
Coolant channels	.184	.60	.025	2	.11	4.0	8.0	2.6	800(x2)	6,600	8,200
											52,800 (=75 psi)