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Fusion Breeder Tokamak Reactor Blanket

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PRESSURE DROP CONSIDERATIONS OF A LITHIUM COOLED
FUSION BREEDER TOKAMAK REACTOR BLANKET

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Liquid lithium was selected as one of the coolants for the 1983 fusion breeder blanket used on the magnetically confined tokamak fusion reactor, and as a result, the thermal-hydraulic calculations were dominated by magnetohydrodynamic (MHD) considerations. The applicable sets of MHD equations for the engineering thermal-hydraulic design were reviewed and compared. Special attention was given to the MHD calculations for the fertile material zone, a packed bed of composite beryllium and thorium balls, since this region can dominate the thermal-hydraulic behavior of this blanket module. To keep the pressure drops acceptable, fertile fuel balls were omitted in the inboard blanket.

Introduction

The fusion breeder program is a DOE-funded program directed by Lawrence Livermore National Laboratory; the other participants in this hybrid fusion reactor design are TRW Company, GA Technologies Inc., Westinghouse Corporation, and EG&G Idaho, Inc. GA is responsible for the blanket thermal-hydraulics, blanket and reactor safety designs. The MHD pressure drop considerations of a lithium-cooled fusion breeder tokamak reactor are reported in this paper.

The 1983 fusion breeder program is a fusion hybrid reactor study based on the tokamak reactor confinement concept and uses the neutronics approach of fission-suppression to produce fissile fuel for LWRS [1,2]. Fission-suppression is an approach to minimize the number of fast and thermal fissionings in a fusion hybrid blanket in order to optimize the overall safety characteristics of the blanket system and to maximize the amount of fissile material produced for a given thermal power. The lower half of the tokamak reactor inboard/outboard blanket arrangement is illustrated in Fig. 1. The vertical trough arrangement was selected to facilitate the feeding and removal of fuel balls from the blanket.

During the scoping phase of this study, the direct flow of lithium through a packed bed blanket configuration was selected as one of the blanket designs for the 1983 fusion breeder blanket study. The fluid dynamics and heat transfer aspects of using liquid lithium as the coolant for a magnetic fusion reactor blanket are of key concern because of the large MHD effects that can occur. In this paper, sets of liquid metal MHD pressure drop equations are reviewed and compared. A model for MHD pressure drop through a packed bed was developed, results are presented, and critical design issues are discussed.

Blanket Design Considerations

A key problem in the design of lithium-cooled blankets for a tokamak reactor is the calculation of the blanket MHD pressure drops. Although the set of MHD equations for the calculation of pressure drops through B-field gradients, turns, contractions, and entrance and exit flows are still uncertain, available sets of equations were used and compared to determine feasibility of the design. The first design approach

to minimize pressure drop is to minimize the flow velocity by maximizing the flow cross-sectional area wherever necessary. This leads to the selection of a nonfissile fuel breeding blanket for the inboard side of the reactor where the magnetic field strength is high. The second design approach used is to insulate the coolant flow channels where possible, like inlet/outlet pipes and distribution plenums. The selected insulation method is the use of an 0.25 mm thick stainless steel clad lining the inside of the coolant flow channel, separating the ceramic insulation and the coolant.

A blanket configuration similar to the UWMAK-I [3] design was used in the inboard side as shown in Fig. 2. Two lithium streams are used in the outboard blanket, as illustrated in Fig. 3. In order to handle the surface heat flux of the tokamak reactor at 0.25 MW/m^2 , the design approach was to minimize the amount of coolant flowing at the first wall to keep the total pumping power low but to maximize the coolant velocity to keep the coolant temperature rise within specific material temperature limits.

The following summarizes the approach in the blanket MHD calculations:

- Calculate and compare the pressure drops using the equations from Hunt and Holroyd [4,5], and from Picologlou [6] when applicable.
- Assume the pressure drop for turns is negligible when both legs are normal to the B-field.
- Assume the pressure drop through an expansion flow is negligible.
- Calculate the pressure drop through contractions by using the equations recommended by Hunt and Holroyd.

MHD Equations Comparison

Key sets of applicable MHD equations are given in Table 1. The set of equations recommended by Hoffman and Carlson [7] was used for the 1982 fusion breeder study [8]. The constant K, used for the flow through varying B-field strength, has to be determined graphically, and is supported by limited experimental results. The set of equations supplied by Hunt and Holroyd gives distinct recommendations for the calculations of inlet, gradient-B, turning, expansion, and contraction pressure drop calculations. The latest set of equations supplied by Picologlou also has detailed specifications. The only agreement between these three sets of MHD equations is for straight pipe flow normal to the magnetic field. Since the sets of equations given by Hunt and Holroyd, and Picologlou are more complete, they will be the only sets compared in this paper.

Blanket

Figures 2 and 3 give the inboard/outboard blanket configurations for the Fusion Breeder Study. In order to keep the module pressure and coolant pressure drop

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to acceptable levels in the high field inboard region of the tokamak reactor, we recommend that the packed-bed fertile material be omitted in this region. The UMMAK-1 type of blanket module was selected, because the plenum region is relatively simple in geometry, thus allowing the possibility of using thin-clad insulated walls. The module is designed to take different surface wall loadings by adjusting the front lobe dimension thus adjusting the length of the liquid metal flow path and liquid metal channel depth for material temperature control. For the outboard region, the configuration as shown in Fig. 3 was selected. Separation of the first wall and fertile zone coolant routing will reduce the total blanket pressure drop and allow the adjustment of the first wall flow speed by changing the coolant gap dimension to handle the surface loading. A potential design simplification is to combine the two outlet streams into one.

Figure 4 is a schematic of the inboard/outboard coolant routings illustrating the key dimensions and magnetic field strengths (numbers in bracket) at different reactor radial positions.

Packed Bed MHD Pressure Drop

The packed bed outboard blanket design schematic is shown in Fig. 3. It shows the direction of the incoming lithium from one side of the module as it flows along the first wall. Another stream of lithium also flows toward the first wall and then turns and flows radially outward through the packed bed of spherical beryllium pebbles. The lithium then flows out of the blanket module through the outlet plenum and the outlet pipes.

The key difficulty in the calculation of the pressure drops for liquid metal flow through a packed bed in the presence of a magnetic field is the lack of analytical support from the literature. The coolant paths formed by the close-packed pebbles are very tortuous and coolant flow in and out of magnetic field lines is unavoidable. Because of the relatively high electrical conductivities of lithium, beryllium, and thorium metal, induced currents will be formed inside the blanket, which will in turn generate body forces against the direction of fluid flow. Precise analysis of the aggregate or cancelling effects of these body forces as formed by surrounding coolant paths is impossible because of the 3-D geometric complication and the unspecified packing structure of the pebbles (which is a function of the method of packing and the packed-bed characteristic dimensions). Because of the difficulties associated with modeling the complex packed bed configuration, simplified assumptions were made in considering the pressure drops through the packed-bed. The results can be used as indications of design feasibility. To begin, an order of magnitude determination comparing the MHD-induced pressure drop to the pressure drops which exist regardless of the magnetic field (i.e., viscous and packed bed momentum transfer), was made by starting from basic principles using the momentum equation. It was shown that at a coolant ΔT of 150°C and a pebble diameter of 3 cm, the MHD pressure drop due to the 4 T B-field is at least four orders of magnitude higher than the zero field packed bed and viscous pressure drops. This allows us to concentrate on the contribution of pressure drop from MHD losses.

A model was constructed by considering the potential current paths and calculating the pressure drops accordingly. It was noted that at a temperature of 400°C the electrical conductivity of beryllium metal is 6.2×10^6 (ohm-m)⁻¹, about twice as high as lithium at 3.2×10^6 (ohm-m)⁻¹. Assuming perfect electrical contact of the lithium with the beryllium pebbles, the induced currents would flow in both the lithium and in

the beryllium pebbles. Considering the radial flow through individual cusp and the configuration and the orientation of the magnetic field, it can be seen that the induced currents, which result from flow among adjacent pebbles, would form a matrix of current flowing among the pebbles. Considering the blanket as a whole as shown in Fig. 5, the local currents in the fluid among the pebbles can form poloidal currents that flow in the fluid around the blanket and return through the conducting walls.

Based upon the above observation, it is possible to estimate the pressure drop through the bed by starting with the magnetic field contribution to the momentum balance equation:

$$\vec{\nabla} p = \vec{J} \times \vec{B} \quad (1)$$

where $\vec{\nabla} p$ is the pressure gradient vector, $\vec{J}$ is the induced current vector, and $\vec{B}$ is the magnetic field vector. In the above equation, $\vec{J}$ is given by

$$\vec{J} = \sigma \vec{\nabla} \times \vec{V} \quad (2)$$

where σ is the lithium electrical conductivity and $\vec{V}$ is the coolant velocity vector. Considering only the bulk radial flow velocity in a cylindrical geometry, the velocity vector is given by

$$\vec{V} = V_r \vec{r} \quad (3)$$

where

$$\vec{V}_r = \frac{R_0}{V_0 r} \quad (4)$$

In the above equation, V_0 is the average radial bulk velocity of the coolant at radius R_0 . The bulk radial velocity is determined by the flow area available in the bed (i.e., between the pebbles).

Substituting Eqs. (4), (3), and (2) into Eq. (1) and recognizing that $\vec{B} = B_z \vec{z}$ yields

$$\frac{\Delta p}{\Delta r} = \sigma V_0 R_0 B_z^2 / r \quad (5)$$

Integrating Eq. (5) over the blanket thickness yields

$$\begin{aligned} \Delta p &= \sigma V_0 R_0 B_z^2 \int_{R_0}^{R_1} \frac{dr}{r} = \sigma V_0 R_0 B_z^2 \ln \left(\frac{R_1}{R_0} \right) \\ &= \sigma V_0 R_0 B_z^2 \ln \left(\frac{R_1}{R_0} \right) \\ &= \frac{\sigma}{\rho C_p} \frac{HMB^2}{(\Delta T) F} \ln \left(\frac{R_1}{R_0} \right) \end{aligned} \quad (6)$$

where Δp = packed bed MHD pressure drop,
 σ = electrical conductivity of lithium, (3.2×10^6 ohm-m⁻¹),
 ρ = fluid density, (5.5 kg/m³),
 C_p = fluid specific heat, (4200 J/kg),
 H = neutron wall loading, (3 MW/m²),
 M = blanket energy multiplication, (2),
 B = magnetic field strength, (3.3 T),
 ΔT = coolant inlet-outlet temperature differential, (340° to 430°C),
 R_0 = packed bed inner radius, (10.2 m),
 F = coolant flow cross-sectional area fraction, (0.4),
 R_1 = packed bed outer radius, (10.7 m),

V_0 = fluid velocity at R_0 ,
 z = direction of mirror reactor axis.

V_0 has been substituted by $TM/\rho C_p \Delta T$ ($1/F$), in balancing the power generated in blanket and the power carried away by the coolant.

Inputs and Results

Table 2 summarizes the input parameters for the blanket MHD calculations.

TABLE 2
 THERMAL-HYDRAULIC CALCULATION INPUT PARAMETERS

Reactor thermal power	5000 MW
Neutron wall loading	3 MW/m ²
Surface wall loading	0.25 MW/m ²
Coolant - lithium	
T_{in}/T_{out}	340°/430°C
Blanket energy multiplication	2
Inboard power fraction	0.325
Magnetic field strength	$B = 33/r$ Tesla

With reference to Fig. 4, the channel characteristic dimensions and the pressure drops for respective channels and turns are given in Tables 3 through 5. The pressure drops for the inboard blanket, outboard first wall and blanket sections are also given in Tables 3 through 5, respectively. The results calculated by using the Hunt and Holroyd, and Picologlou sets of equations are presented. Comparing the two sets of calculations different results were obtained for the gradient B-field and turning calculations, yet the total pressure drops for the whole loop are similar, since they are dominated by the pressure drop due to straight channel flow across field lines, which is the only calculation that is agreed upon by the different authors. The pressure drop results indicate that the first wall contribution is relatively small. The magnitudes of the inboard/outboard blanket pressure drops are approximately equal. For the outboard blanket, the pressure drop is dominated by the packed bed pressure drop. A similar design for the inboard blanket would not be acceptable because the high magnetic field strength at the inboard region would result in a pressure drop in excess of 5 MPa (800 psi).

Considering the first wall heat flux and the volumetric power generations in the first wall and the lithium, the maximum first wall temperature was calculated conservatively from the conduction of heat through the first wall and lithium while taking the maximum coolant temperature at the outlet of the first wall. For the inboard and outboard blankets, these maximum temperatures are 551°C and 469°C, respectively. From design feasibility considerations, these temperatures are acceptable, since they are located at the outlet end of the first wall where the structural loading requirement is much reduced. In addition, channel dimensions can be adjusted to reduce this coolant temperature drop in the channel, thus reducing the structural material maximum temperature.

Conclusions and Recommendations

Considering the MHD pressure drops and the estimated maximum temperatures for the inboard and outboard blankets, the following conclusions and recommendations can be made:

1. The present blanket design approach of breeding fissile material only in the

outboard blanket is acceptable both from pressure drop and temperature considerations.

2. As indicated in Table 4, the key differences in the two sets of MHD equations are on gradient B-field and turning calculations. Although the total pressure drops predicted by the two sets of equations are similar, the individual terms differ significantly and experiments will be needed to understand the differences.
3. It should be noted that if the blanket flow plena are not insulated by the use of a 0.25 mm thick stainless steel liner, the increase in pressure drop would be proportional to the channel wall thickness. At a wall thickness of 3 mm, just the channel (plenum) pressure drop for the inboard/outboard blankets would be 2574 kPa (373 psi)/1308 kPa (190 psi), respectively, which would be unacceptable when other pressure drops are considered. This also indicates the importance of developing the insulated metallic liner or other wall electrical insulation, as a way of reducing the Hartmann flow pressure drops [9].
4. Tables 3 and 5 show that the pressure drop due to contraction can be significant. Because there is large uncertainty associated with contraction calculations, experimental verification of this is needed.
5. As indicated in Table 5, the packed bed pressure drop contributes significantly to the total outboard blanket pressure drop. Experimental verification of the packed bed MHD pressure drop will be needed.

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TABLE 4
OUTBOARD FIRST WALL PARAMETERS AND PRESSURE DROPS

	Characteristic Dimension (m)	Magnetic Field Strength (T)	Wall Thickness (m)	Channel Length (m)	Fluid Velocity (m/s)	Conductance Ratio (C)	Hunt and Holroyd (kPa)	Picologlou (kPa)
J - Inlet(a)	0.75	2.4	2.5×10^{-4}		0.98	1.7×10^{-4}	34.2	34.2
JX - B gradient(a)	0.75	$2.4 + 3.2$	2.5×10^{-4}	3.5	0.98	1.7×10^{-4}	61.0	14.1
K - Turn	(Both legs are normal to B-field)						0	0
K - Expansion	(Assumed to be zero)						0	0
KO - Channel	0.15	3.2	3×10^{-3}	6.5	0.11	0.01	225.0	225.0
L - Turn	(Both legs are normal to B-field)						0	0
L - Expansion	(Assumed to be zero)						0	0
LM - B gradient	0.005	$3.2 + 3.4$	3×10^{-3}	0.5	0.02	0.3	0.4	78.7
M - Turn	0.005	3.4	3×10^{-3}		0.02	0.3	3.6	0.7
MN - B gradient	0.005	$3.4 + 3.2$	3×10^{-3}	0.5	0.02	0.3	0.4	78.7
N - Expansion	(Assumed to be zero)						0	0
N - Turn	(Both legs are normal to B-field)						0	0
N - Contraction(a)	0.15	3.2	2.5×10^{-4}		$0.02 + 0.11$	0.84×10^{-3}	12.4	12.4
O - Turn	(Both legs are normal to B-field)						0	0
O - Contraction(a)	0.15	3.2	2.5×10^{-4}		$0.11 + 0.98$	0.84×10^{-3}	120.1	120.1
OP - B gradient(a)	0.75	$3.2 + 2.4$	2.5×10^{-4}	3.5	0.98	1.7×10^{-4}	61.0	14.1
Total							518.1	578.0
Blanket Maximum Pressure @ K							422.9	530.0
							(61.3 psi)	(76.9 psi)

(a) The design assumes the use of a 0.25 mm thick stainless steel clad lining the inside of the channel.

TABLE 5
OUTBOARD FERTILE ZONE BLANKET PARAMETERS AND PRESSURE DROPS

	Characteristic Dimension (m)	Magnetic Field Strength (T)	Wall Thickness (m)	Channel Length (m)	Fluid Velocity (m/s)	Conductance Ratio (C)	Hunt and Holroyd (kPa)	Picologlou (kPa)
J - Inlet	0.75	2.4	2.5×10^{-4}		0.98	1.7×10^{-4}	34.2	34.2
JQ - B gradient(a)	0.75	$2.4 + 3.2$	2.5×10^{-4}	3.5	0.98	1.7×10^{-4}	61.0	14.1
Q - Turn	(Both legs are normal to B-field)						0	0
Q - Contraction(a)	0.75	3.2	2.5×10^{-4}		$0.98 + 1.26$	1.7×10^{-4}	87.0	87.0
QU - Channel(a)	0.15	3.2	2.5×10^{-4}	6.5	1.26	0.84×10^{-3}	218.0	218.0
R - Turn	(Both legs are normal to B-field)						0	0
R - Expansion	(Assumed to be zero)						0	0
RS - B gradient	0.15	$3.2 + 3.4$	3×10^{-3}	0.5	0.24	0.1	8.2	337.4
S - Turn	0.15	3.4	3×10^{-3}		0.24	0.1	40.8	4.0
ST - Packed Bed	0.09	$3.4 + 3.2$	3×10^{-3}	0.5	0.055	0.02	906.0	906.0
T - Turn	(Both legs are normal to B-field)						0	0
T - Contraction	0.09	3.2	3×10^{-3}		$0.055 + 1.26$	0.02	487.0	487.0
U - Turn	(Both legs are normal to B-field)						0	0
U - Expansion	(Assumed to be zero)						0	0
UP - B gradient(a)	0.75	$3.2 + 2.4$	2.5×10^{-4}	3.5	0.98	1.7×10^{-4}	61.0	14.1
Total							1903.2	2101.8
Blanket Maximum Pressure @ Q							1808.0	2053.0
							(262 psi)	(298 psi)

(a) The design assumes the use of a 0.25 mm thick stainless steel clad lining the inside of the channel.

CL TOKAMAK

BLANKET

MAGNET

BALL CHUTE

MAJOR
AXIS

INBOARD BLANKET

OUTBOARD BLANKET