A Helical Coolant Channel Design for the Solid Wall Blanket

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A HELICAL COOLANT CHANNEL DESIGN FOR THE SOLID WALL BLANKET

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ABSTRACT

A helical coolant channel scheme is proposed for the APEX solid wall blanket module. The self-coolant breeder in this system is FLIBE (LiF)2(BeF2). The structural material is the nanocomposited alloy 12YWT. The neutron multiplier used in the current design is either stationary or slow moving liquid lead. The purpose of this study is to design a blanket that can handle a high wall loading (5 MW/m^2). In the mean time the design provides means to attain the maximum possible blanket outlet temperature and meet all engineering limits on temperature of structural material and liquids. An important issue for such a design is to optimize the system for minimum pressure loss. For advanced ferritic steel (12YWT) an upper temperature limit of 800°C is expected, and a limit of 700°C at the steel/FLIBE interface is recommended.[1]

The blanket module is composed of two main continuous routes. The first route is three helical rectangular channels side–by-side that surround a central box. The helical channels are fed from the bottom and exit at the top to feed the central channels in the central box. The coolant helical channels have a cross sectional area with a length of about 10 cm and a width that changes according to the position around the central box. For instance: the width of the coolant channels facing the plasma is the narrowest while it is the widest in the back (farthest from the plasma).

In this design the coolant runs around the central box for only 5 turns to cover the total height of the first wall (6.8 m). The design is optimized with the FW channel width as a parameter with the heat transfer requirements at the first wall as the constraints.

I. INTRODUCTION

A helical coolant channel scheme is proposed for the APEX solid wall blanket module. The self-coolant breeder in this design is FLIBE (LiF)2(BeF2). The structural material is the nanocomposited alloy 12YWT and is chosen for its superiority in mechanical properties and compatibility with FLIBE and lead at elevated temperatures.[1,2] A neutron multiplier such as beryllium or lead should be used to enhance FLIBE capability of tritium breeding. Both multipliers have their own problems. For example, beryllium has problems such as swelling, large tritium inventory and toxicity, while lead produces bismuth which generates polonium and the effectiveness of this multiplier decreases with increasing distance from the first wall. However, a system can be engineered to avoid and deal with such a problem. Presently, liquid lead is used as the neutron multiplier. The development philosophy is to design a blanket that can handle a high wall loading (5 MW/m^2). In the mean time the design provides means to attain the maximum possible blanket outlet temperature and meet all engineering limits on temperature of structural material and liquid coolants. The design also aims at optimizing the coolant system to minimize the pressure loss. For advanced ferritic steel an upper temperature limit of 800°C is expected, and a limit of 700°C at the steel/FLIBE interface is recommended. At the first wall we have the highest thermal load, namely, the surface heat flux and the maximum volumetric heating. Thereby the first wall thermal condition requires the highest heat transfer coefficient. In this design the highest coolant velocity flows in the narrowest channels in the first wall. This combination results in the highest heat transfer coefficient in the system where it is needed. Figure 1 shows a sketch of a cross-section view at midplane and also shows the coolant flow direction.

II. BLANKET DESIGN

The suggested design uses slow flowing (or stationary) lead as a multiplier and FLIBE as a breeder/ multiplier coolant media. The blanket module is 30 cm in width and depth in the toroidal direction and in the radial direction respectively. The helical coolant channels have a rectangular cross sectional area with a length of about 10 cm and a width that changes according to the position around the central box. For instance: the width of the coolant channels facing the plasma is the narrowest while it is the widest in the back (farthest from the plasma). In this design the coolant runs around the central box for only 5 turns to cover the total height of the first wall (6.8 m). The helical pitch of each tube is about 1.20 m. Figure 2 shows the helical channels surrounding the central box of one module. The main reason for the helical coolant channels is to redistribute the heating to mitigate the thermal stresses.

II.A. Coolant Routing

The blanket module is composed of three main continuous routes. The first route is composed of twelve helical rectangular channels (three on each side of the central box), side–by-side that are continuous surrounding a central box. The helical channels are fed from the bottom and exit at the top. The second route follows the combined coolant that exits the three channels of the first wall (zone 1) and the coolant exits the three channels at the back (zone 2) to feed the central channel (zone 5). The central channel is straight in the poloidal direction. The third route follows the coolant that exits the side wall six channels (zone 3) (three channels on each side) and is directed to feed the straight coolant channel in the back of the lead zone. The central channel outflow coolant and the back of the lead outflow coolant are combined and mixed to feed the heat exchanger. Figure 3 illustrates the coolant routes. The FLIBE flows in the first wall, side wall and back wall, then in the other side wall in an upward direction in a helical fashion around the module.

The coolant in the central zone (zone 5) and in the back of the lead is moving in the downward direction. The coolant's (FLIBE) high speed in the first wall is needed to carry away the surface heat flux and the high volumetric heating. The FLIBE flows at slow speed in the side channels and even slower speed in the back channels to reduce the pressure drop associated with helical designs (longer path and more turns).

II.B. Input Data

The average reactor neutron wall loading is 3.84 MW/m^2. The OB average neutron wall loading is 4.61 MW/m^2. The peak OB surface heat flux is 1.0 MW/m^2. OB average surface heat flux is 0.9 MW/m^2.

Utilizing the neutronics data, the following table shows the thermal loads in various reactor components.

II.C. Thermal Loads

FW power (MW)	7
Central channel power (MW)	4.88
Side/back wall power (MW)	1.45

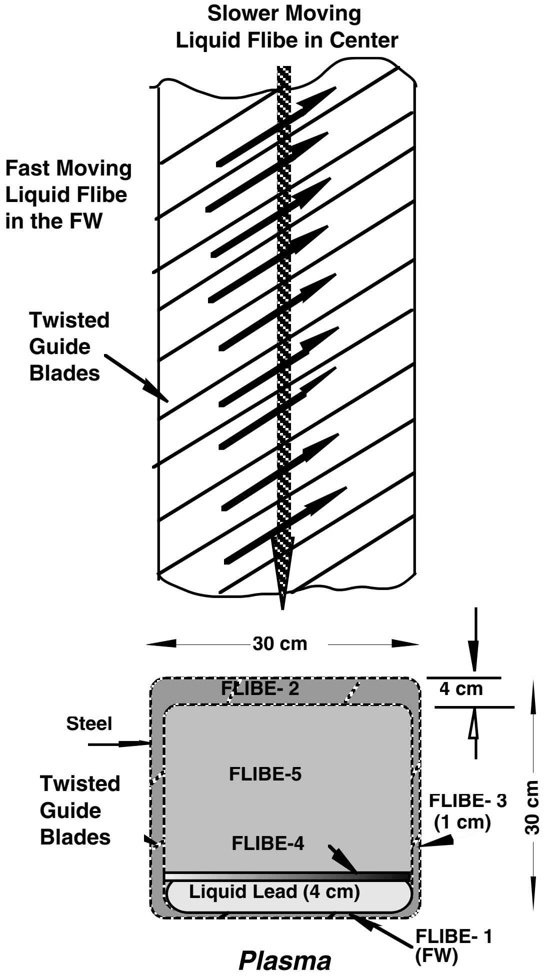


Figure 1. The flat-helical FLIBE/liquid lead/solid wall design.

II.D. Design Requirements

The maximum steel temperature is < 800°C, and the maximum steel/FLIBE interface temperature < 700°C.

II.E. Design Criteria

1. Maximum possible outlet temperature.
2. Minimum coolant velocity.
3. Minimum pressure losses.
4. Minimum pressure driven stresses.

III. DESIGN OPTIMIZATION

The design is optimized with the FW channel width as a parameter while the heat transfer requirements at the first wall are the constraints.

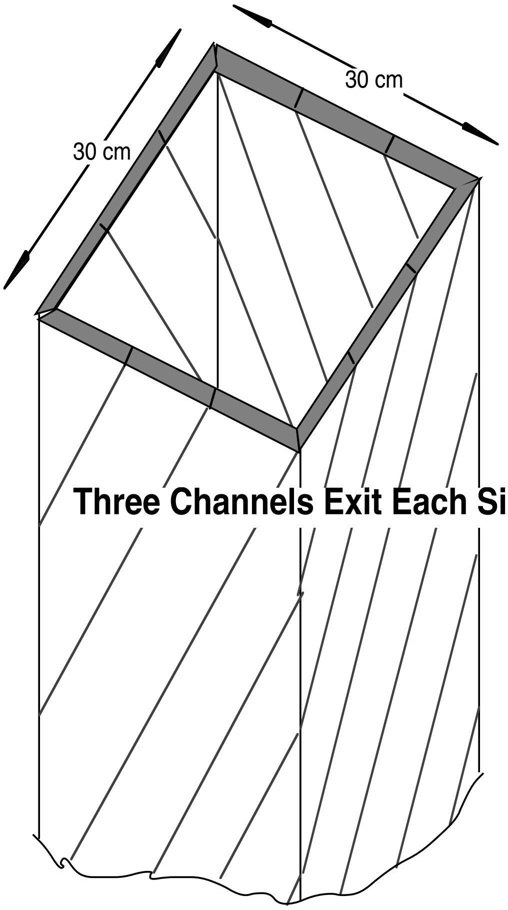


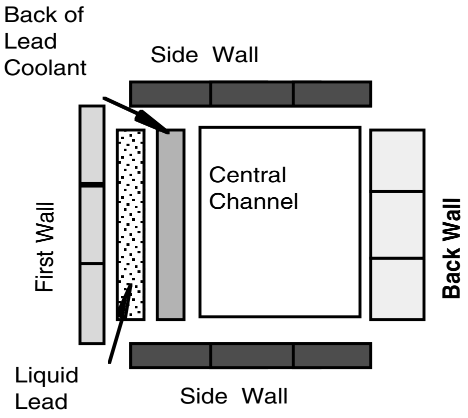
Figure 2. Twelve helical coolant channels surround the central box.

III.A. Assumptions

1- The temperature difference between the bulk FLIBE and the FLIBE steel interface is about 100°C. This restriction is to allow a reasonable lower FLIBE speed in the FW.

2- Choosing the FLIBE film ΔT with the given heat loads fixes the heat transfer coefficient in the FW coolant channel to be $\approx$ 10,000 W/m^{2}K.

Keeping the width of the side channels at 1.0 cm and the back channel of 4 cm, the optimization process is performed to obtain the best available design point/points under these assumptions. The objective function is to find the FW channel width that would minimize the frictional pressure drop. The average temperature used in this calculation (for fluid properties purposes) is 600°C. All steel walls are 3 mm in thickness.



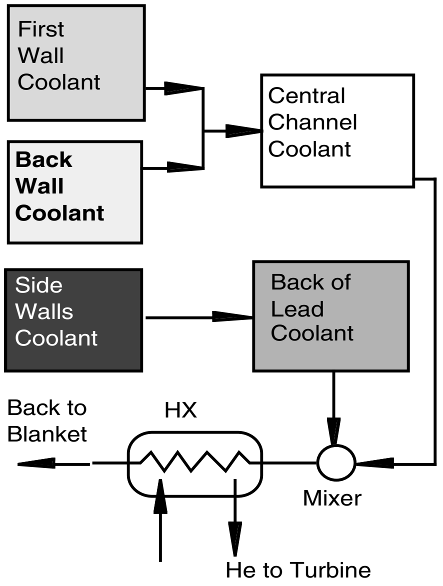


Figure 3. Routing scheme for the helical blanket.

III.B. Material Properties at 600°C

Thermal conductivity, k for steel = 33 W/m ·K and the thermal properties of FLIBE are as follows:

Density, ρ = 1987 kg/m^3

Heat capacitance, c_p = 2380 J/kg ·K

Thermal conductivity, k = 1 W/m ·K

Viscosity, μ = 0.0116 Pa ·s.

The heat transfer coefficient is calculated using $h = Nu \cdot k/d$. The recommended formula for Nu suitable for fluids with high Pr $(Pr>20)$ is:[3]

$$Nu = 0.0118\, Pr^{0.3}\, Re^{0.9}$$

The Blasius friction coefficient,

$$f = 0.3164/Re^{0.25}$$

Pressure drop in a vertically moving fluid:

$$\Delta P = \rho\, v^2/2 + f\, \rho\, L\, v^2/2d$$

where:

Nu is the Nusselt number,
Pr is the Prandtl number,
Re is the Reynolds number,
ρ is the fluid density,
v is the coolant velocity,
d is the coolant tube hydraulic diameter, and
L is the coolant tube length.

IV. RESULTS OF THE PARAMETRIC STUDY

A parametric study is performed with all the constraints and assumptions satisfied. Figure 4 shows the major results of this study. In examining Fig. 4 we notice that the total temperature rise in the FLIBE increases as the FW coolant channel thickness decreases. A temperature rise of about 100°C would mandate that the FW coolant channel thickness would be about 4 mm, and the coolant speed in the FW channel is about 5.5 m/s.

The total frictional pressure drop shows a minimum at FW channel width of 3.5 mm. Unfortunately, choosing FW channel width of 3.5 mm gives about a 70°C film temperature difference in the FLIBE at the Pb back coolant side and this will cause the steel/FLIBE temperature to be more than 700°C. Working near the minimum pressure point and choosing a FW channel width of about 4 mm gives a total temperature rise of 102°C, and about 5.75 atm total frictional pressure drop with 50°C film temperature difference in the FLIBE at the Pb back coolant side.

IV.A. Results Summary

General

Mass flow rate (kg/s)	49.56
Total temperature rise (°C)	102
Frictional pressure drop (atm)	5.75
Width/length of one module (cm)	30/30
FW thickness (steel) (mm)	3.0
Helix pitch (m)	1.2

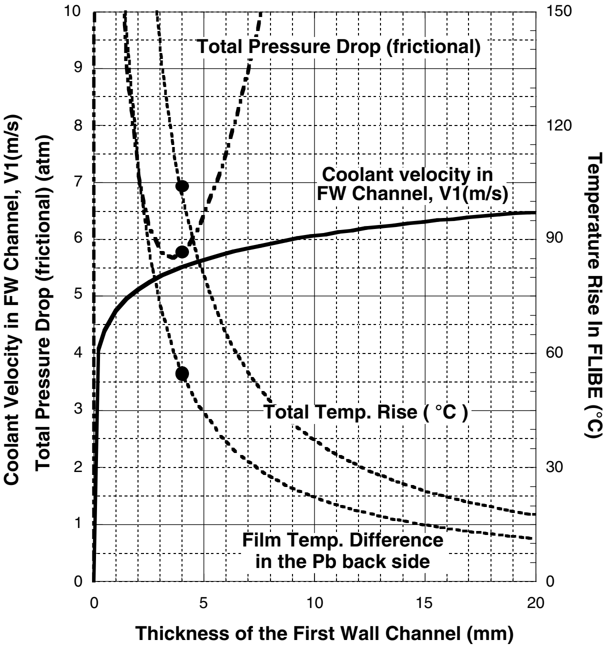


Figure 5. Coolant performance curves in the solid wall helical design.

IV.B. Parameters of different zones

Zone #	1	2	3	4	5
Coolant channel width, (cm)	0.4	4.0	1.0	1.0	19.0
Coolant Speed, (m/s)	5.5	0.55	2.2	4.4	0.26
Heat transfer coefficient, (W/m^2K)	12,400	-	-	9,100	1,030
Temperature rise (°C)	60	60	60	20	63
Inlet Temp. (°C)	580	580	580	640	640
Exit Temp. (°C)	640	640	640	660	703
Pressure Drop, (atm)	3.4	small	0.47	1.8	small
Coolant direction	up	up	up	down	down

The boundary layer film temperature differences, ($T_{interface} - T_{bulk}$), are as follows:

1. At the FW side is 100°C.
2. At lead first side is 37°C, and lead second side is 55°C because the heat transfer coefficient (h) of the coolant behind the lead channel (zone 4) is less than h of the coolant in front of the lead channel (zone 1).

Figure 6 shows a summary of the optimization results and the operating point of the design. The outlet temperature from the mixer at the blanket module = 682°C. Coolant is fed at the bottom of the module to zones 1, 2, and 3. Coolant exits zone 3 and feeds into zone 4. Coolant exits zones 1 and 2 and is combined to feed into zone 5. Coolant from zones 4 and 5 is fed into the mixer and then directed to the HX.

From Figure 6 we notice that the pressure and temperature at point I (top of the blanket) are the same from all directions. Pressures and temperatures at points II and III are not equal. Thermal hydraulics analysis shows that $T_{III} < T_{II}$, and $P_{III} > P_{II}$. Therefore, a pressure regulator and a mixer are needed at zones II and III exits in order to prepare the coolant flow for the power extraction cycle.

V. CONCLUSIONS

One round through the coolant loop gives the shortest coolant loop length (one upward and one downward), and results in reducing the frictional pressure drop. The coolant channels are tailored in order to insure adequate cooling where it is seriously needed. The coolant speed is fast at the FW channel where it is needed and slow in the back coolant channels where it is not needed and that also contributes to the pressure frictional loss reduction. There is simplicity in manufacturing a double-flat-straight wall with helical guide blades. The helical coolant scheme insures a homogenous temperature distribution across the entire blanket cross section. The temperature homogeneity would eliminate/reduce the thermal stresses. All the design guidelines for temperature are satisfied. However, the temperature at the lead/steel interface could reach more than 700°C, which is a concern. Two thinner lead layers (2 cm thick each) could be used and a FLIBE channel in between them would insure that the lead/steel interface temperature would be less than 700°C.

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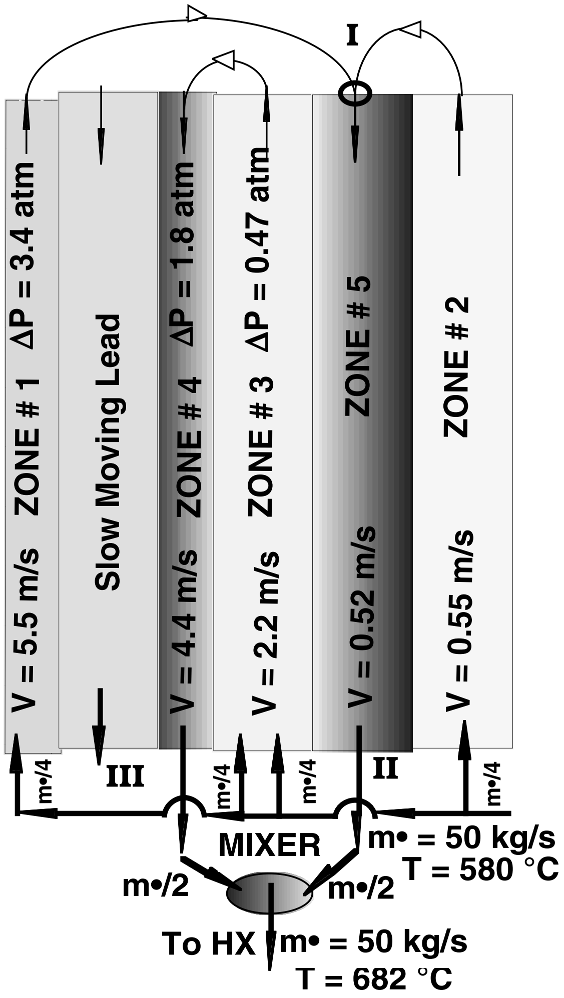

Figure 6. Parameters and flow direction in the optimized module.

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