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COMPARISON OF THREE MHD FLOW CONTROL METHODS FOR SELF-COOLED LIQUID METAL BLANKETS*

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ABSTRACT

The heat deposition in a blanket is concentrated near the first wall. Uniform liquid-metal velocity in a self-cooled blanket is unattractive, because it leads to low mixed-mean temperature rise through the blanket and reduced power conversion efficiency. The objective of MHD flow control is to use the electromagnetic forces to produce a non-uniform velocity distribution which gives a uniform temperature distribution over the thickness of the blanket. Three methods of MHD flow control are presented here and the MHD pressure drops corresponding to the three methods are compared. One of the methods, although successful at achieving nonuniform velocity profiles, permits a large circulation of electric current which produces a high pressure drop. The analytical results do not indicate a clear choice between the other two methods. The analytical results do point to possible difference in heat transfer performance with the two methods.

INTRODUCTION

In a self-cooled, liquid-metal blanket, liquid lithium or lithium-lead circulates through the reactor where it collects energy and breeds tritium. Part of the energy from the plasma is deposited directly on the first wall by radiation, and the rest is deposited by nuclear reactions in the structure, coolant, and shielding. The reaction rate and the resultant strength of the distributed volumetric heat source in the liquid metal decrease exponentially with distance from the first wall. As a result, the fluid near the first wall receives a great deal more heat per unit time than does fluid removed from the first wall. In a magnetic confinement reactor, the required strong magnetic fields effectively suppress turbulence, so that there is very little or no turbulent mixing. If the liquid-metal velocity is uniform throughout the blanket, thermal conduction alone is too weak to prevent the development of

large radial temperature differences. At the blanket exit, the average fluid temperature is far below the temperature near the first wall, considerations. Optimal thermal performance which is limited by first wall materials considerations. Optimal thermal performance requires a high average exit temperature. Thus, uniform velocity leads to poor thermal performance. The objective of magnetohydrodynamic (MHD) flow control is to produce non-uniform fluid velocity distributions within a single duct, with a large velocity near the first wall and a much smaller velocity away from the first wall. With such appropriately shaped velocity distributions the temperature distribution across the duct can be made much more uniform.

In 1985, we proposed two methods of MHD flow control¹. At that time, an analysis² existed for one of the proposed methods, which is called Method I here. Since then, the analysis for the other proposed method, called Method II here, has also been completed³. In the present paper, we propose a third method with several variations, and we compare the pressure drops required in each method to achieve specific non-uniform velocity distributions. The analysis for Method III represents an extension of previous analyses^{2, 3, 4} and is not presented here.

In a simple tokamak blanket design, the liquid metal flows in the poloidal direction and is confined by the first wall, a second wall parallel to the first wall, and a series of walls perpendicular to the first and second walls, which separate adjacent flow ducts and support the first wall. The principal magnetic field is in the toroidal direction, so that it is perpendicular to the separating walls and parallel to the first and second walls.

The flow across magnetic field lines produces an electromotive force (EMF) which drives a circulation of electric current. For fully developed flow in a straight duct, the electric currents circulate through the liquid metal, first wall, second wall and separating walls. If the structural metal walls can be insulated

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electrically from a much thinner metal liner in contact with the liquid metal, then the structural stresses are decoupled from the MHD pressure drop. This allows for the development of much more attractive blanket designs with lower pressure drops and peak material stresses. Such a design solution was utilized in the liquid metal blanket of the Blanket Comparison and Selection Study⁵, and more recently, and more extensively, in the liquid metal blankets of the Tokamak Power Systems Studies⁶. An attractive way of implementing the insulating liner solution by means of appropriate "inserts" in the coolant ducts has been proposed recently⁷. An insert is fabricated from a sheet laminate composed of two thin metal sheets separated by an electrical insulator. The space between the inserts and the walls is occupied by thin layers of the liquid metal coolant. There is no need for the inserts to cover the entire surface of the walls, as long as the covered parts of the structural walls are symmetric relative to the axis of symmetry of the cross section which is normal to the B field. The liner can cover the inside surface of the first wall with little adverse effect on the heat transfer from this wall to the liquid metal, because the required insulator thickness is very small and the thermal conductivity of most candidate insulators are within an order of magnitude of the thermal conductivity of the structural material.

Although MHD flow control does not depend on the availability of laminated walls, the comparison between the three proposed methods is affected by the presence of insulated liners. In all the cases treated here, we assume that there is an insulated liner as part of an insert covering the inside surface of the first wall and at least part of the remaining inside surface.

METHOD I: CONTROL WITH FULLY DEVELOPED FLOW

The cross section of a typical poloidal duct of the blanket is shown in Figure 1. The first and second walls are separated by a distance of $2L$, where L is used as the characteristic length to non-dimensionalize all the lengths. The inside metal liner of the insert of thickness t , covers the first wall and extends a distance sL along each separating wall. Because each of both adjacent ducts, the electric current from each duct occupies half of its thickness. The cross section does not change in the poloidal direction, so that the flow is fully developed, i.e., independent of x , except near elbows or other three-dimensional disturbances.

For the analysis, the interior of the duct is divided into an inviscid core region and viscous boundary layers adjacent to each wall². The most important boundary layer is the one adjacent to the liner of the first wall in Figure 1. This layer has a thickness which is comparable to $LM^{-1/2}$, where $M = B_0 L (\sigma/\mu)^{1/2}$ is the Hartmann number (typically $10^4 - 10^5$), (σ and μ are the electrical conductivity and

Fig. 1 Cross Section of Poloidal Duct with Partial Insulating Liner

viscosity of the liquid metal). The electric currents and the corresponding voltage gradients along the first wall liner result in axial velocities in this boundary layer comparable to $U_0 M^{1/2}$. Here, U_0 is the average axial velocity for the entire cross section and is used to non-dimensionalize all the velocities. The fraction of the total flow carried by the large velocity in the thin boundary layer adjacent to the first wall is denoted by Q , whereas the fractions of the total flow carried in the core of the regions $-1 < z < (-1 + s)$ and $(-1 + s) < z < 1$ are denoted by Q_1 and Q_2 . The fraction of the total flow carried by the boundary layer adjacent to the second wall is Q/r_3 , which is negligible if $r_3 \gg 1$. Because a high velocity jet here is counterproductive, the second wall is made very thick ($r_3 \gg 1$).

The dimensionless axial velocity corresponding to Q_1 is V_1 and that corresponding to Q_2 is $V_2 = V_1/r_2$. The step in the core velocity is matched by a viscous interior layer which lies along the magnetic field line at $z = (s-1)$ and which also has a thickness that is comparable to $LM^{-1/2}$. This interior layer has a simple error function structure which provides the transition between V_1 and V_2 . The sum of the flow fractions Q , Q_1 and Q_2 must of course equal one, which determines V_1 for a given set of values for s , r_2 , "a" and α . Here "a" is the aspect ratio of the duct's cross section, and $\alpha = cM^{1/2}$, where $c = \sigma_w t / \sigma L$ is the wall conductance ratio for the inner liner, and σ_w is the electrical conductivity of the metal

walls. The liner and the boundary layer near the first wall are electrical resistors in parallel for the vertical currents, and α is the ratio of their electrical resistances. For all the results presented in this paper we take $a = 1$ (square cross section) and $\alpha = 3$ (e.g., $c = 0.01$ and $M = 90,000$). Then $Q = 0.12V_1$. The dimensionless axial pressure drop Δp is defined as the pressure drop for duct length equal to L_a , divided by the characteristic pressure drop, $\sigma c U_0 B_0^2 L_a$. For Method I, L_a is arbitrary because the pressure gradient for fully developed flow is constant, and $\Delta p = V_1$.

The results for Method I are presented in Table 1. For $s = 2$, the insert completely covers the separating walls, $V_1 = 0.89$ throughout the core, and 11% of the flow is carried by the high-velocity sheet jet adjacent to the first wall. As s is decreased or r_2 is increased, V_1 and Q increase. The final results in Table 1 indicate that it is theoretically possible to get 45% of the flow in the first wall sheet jet and a core velocity near the first wall which is roughly four times the average velocity.

TABLE 1. RESULTS FOR METHOD I FOR
 $a = 1$, $\alpha = 3$, and $r_3 \gg 1$

s	r_2	$V_1/\Delta p$	Q	V_2
2	—	0.89	0.11	—
1	5	1.39	0.17	0.28
0.5	5	1.92	0.23	0.38
0.2	5	2.49	0.30	0.50
0.1	5	2.77	0.34	0.55
1	10	1.49	0.18	0.15
0.5	10	2.24	0.27	0.22
0.2	10	3.21	0.39	0.32
0.1	10	3.75	0.46	0.38
0.2	20	3.75	0.46	0.19

The values for L , s , r_2 , α and " a " and the corresponding values for V_1 , and Q depend on the particular reactor parameters and are limited by practical considerations. A typical set of parameters for a Tokamak reactor could be as follows: Duct size 10 cm x 10 cm, inner liner thickness: 0.2 mm, thickness of separating walls: 2 mm ($r_2 = 5$), and radial extent of insert 1 cm ($s = 0.2$). Under such conditions, 30% of the total flow will be concentrated in a very high velocity jet adjacent to the first wall and an additional 25% of the flow is carried by the 1 cm wide core flow, with velocity two and one-half times higher than the average velocity. One should also bear in mind that the predicted velocity distributions in the jets are parabolic in y with a peak at $y = 0$. The heat transfer consequences of this fact need to be carefully considered and verified experimentally before full credit for first wall cooling is taken.

METHOD II: CONTROL WITH RECTANGULAR AND TRAPEZOIDAL CROSS SECTIONS

For Methods II and III, the cross sectional area of each poloidal duct increases and decreases periodically as we move in the poloidal direction. The duct length for one complete period of the changes is taken as L_a . For both Methods II and III, the cross section of any duct at $x = 0$, $0.5L_a$ and L_a is identical to that shown in Figure 1 for $s = 2$.

For Method II, the distance between the separating walls at the first wall is kept equal to $2aL$, but we gradually and symmetrically increase and decrease the distance between the separating walls at the second wall to maximum and minimum values of $2(a \pm 2b)L$, as shown in Figure 2.

Fig. 2 Adjacent Poloidal Ducts for Method II
($a = 1$, $b = 0.25$, $L_a = 8L$)

The axial velocity is now a function of x and z , so we define V_1 as the average over one period ($0 < x < L_a$) of the dimensionless core velocity adjacent to the first wall. Similarly, Q is the average over one period of the fraction of the total flow carried by the large velocity in the viscous boundary layer adjacent to the first wall. The results for Method II with $a = 1$, $\alpha = 3$, $c = 0.01$ and $r_3 \gg 1$ are presented in Table 2. The U_0 used to define the dimensionless V_1 and Δp is always the average axial velocity for the basic rectangular cross section, i.e., the total volumetric flow rate divided by $4aL^2$. The only role of c here is in the definition of L_a/L . For other values of c , the values of

L_a/L in Tables 2, 3 and 4 should be multiplied by $0.1 c^{-1/2}$, with no changes in the other results. Comparison of the results in Tables 1 and 2 shows that Method II requires more than twice the pressure drop for given values of V_1 and Q , than does Method I.

TABLE 2. RESULTS FOR METHOD II FOR
 $a = 1, \alpha = 3, c = 0.01$ and $r_3 \gg 1$

b	L_a/L	$\Delta p/V_1$	V_1	Q
0.50	4	2.71	2.49	0.30
0.50	8	1.97	1.93	0.23
0.25	4	1.97	1.93	0.23
0.25	8	1.56	1.50	0.18
0.15	4	1.65	1.60	0.19

Method II is based on certain characteristic surfaces which guide the flow so that it is more concentrated near the first wall¹. However, the complete analysis³ for this method reveals that it permits a relatively large circulation of electric current. This current circulates in planes perpendicular to the toroidal field and is not forced to flow through the thin liners. The axial current in the liquid metal is distributed over virtually the entire cross section, so that the electrical resistance here is small. The only controllable resistance in the circuit is that of the second wall. If the second-wall thickness is reduced, Δp does decrease, but V_1 and Q decrease as well, because an undesirable high-velocity wall jet develops along the second wall. Any benefit in the reduction of Δp is lost because of the decrease of V_1 and Q , so there is no advantage to reducing the thickness of the second wall.

METHOD III: CONTROL WITH RECTANGULAR EXPANSIONS AND CONTRACTIONS

For Method III, the cross section of each duct is always a rectangle. A series of expansions and contractions are created by symmetrically diverging and converging the separating walls. The distance between these walls varies periodically between the values $2(a + b)L$, as shown in Figure 3. Again the cross section of any duct at $x = 0, 0.5L_a$ and L_a is the same as that shown in Figure 1, with $s = 2$. For both Methods II and III, b is defined so that both methods have the same changes in cross sectional area for the same values of a and b . Again V_1 and Q represent averages over one period.

The results for Method III with $a = 1, \alpha = 3, c = 0.01$ and $r_3 \gg 1$ are presented in Table 3. Comparison of the results in Tables 2 and 3 indicate that Method III is a vast improvement over Method II. As in Method II, an electric current circulates in planes perpendicular to the toroidal magnetic field. The axial current in the liquid metal is now confined to a thinner current sheet adjacent to the first wall. As a result, the total current circulation and the

pressure are smaller for Method III than for Method II.

Fig. 3 Adjacent Poloidal Ducts for Method III
($a = 1, b = 0.25, L_a = 8L$)

Comparison of the results in Tables 1 and 3 indicates that Method III does not quite achieve the ratio of $V_1/\Delta p = 1$ which is true for every case of Method I. However, for the smaller values of b , Method III approaches a ratio of $V_1/\Delta p = 1$. For $b = 0.5$ and $L_a = 4L$, 54% of the total flow is carried by the high-velocity sheet jet adjacent to the first wall, while the core velocity adjacent to the first wall is $5.6U_0$. Such a flow concentration near the first wall is probably not practical with Method I. Note that, in comparing the three methods, the ratio $\Delta p/V_1$ is taken as the figure of merit. The lower this value the lower the price in Δp that must be paid to achieve a given V_1 .

TABLE 3. RESULTS FOR METHOD III FOR
 $a = 1, \alpha = 3, c = 0.01$ and $r_3 \gg 1$

b	L_a/L	$\Delta p/V_1$	V_1	Q
0.50	4	1.30	5.62	0.54
0.50	8	1.29	3.82	0.37
0.25	4	1.06	3.26	0.38
0.25	8	1.06	2.02	0.23
0.15	4	1.02	2.24	0.27

The values of V_1 in Table 3 are averages over one period. Figure 4 presents the value of the local core velocity adjacent to the first wall for the first case in Table 3. The value varies from 2.27 to 14.64, which is a much larger variation than would occur just because of the change in cross sectional area. In each expansion and contraction, there is a transverse velocity away from and towards the first wall, respectively. This periodic transverse motion provides a heat transport away from the first wall which is absent in Method I.

Fig. 4 Variation of Core Velocity at Edge of First Wall Boundary Layer over a Period $L_a = 4L$ ($a = 1$, $b = 0.5$, $c = 0.01$, $\alpha = 3$) and Corresponding Variation of Duct Dimension in Toroidal Direction

ADDITIONS OF STRAIGHT DUCTS

For both Methods II and III, the ratio of Δp to V_1 can be decreased by adding straight ducts with the appropriate trapezoidal or rectangular cross sections. These straight ducts are added between the expansions and contractions at their junctions, which were previously at $x = 0.25L_a$, $0.75L_a$, $1.25L_a$, etc. For Method III, the series

of expansions and contractions becomes an expansion, a straight large rectangular duct, a contraction, a straight small rectangular duct, an expansion, etc. The duct length for a complete period is now equal to the lengths of the original expansion and contraction, plus the lengths of the two added straight ducts. The total pressure drop increases slightly but L_a increases much more, so that Δp decreases significantly. A slightly larger total pressure drop occurs over a doubled total duct length.

In the straight ducts, the non-uniform velocity profile at the two ends decays toward a uniform velocity near the center but, even with this decay, the overall effect of adding the two straight ducts to each complete period is a slight decrease in both V_1 and Q (averaged over a now lengthened period) and a much more significant decrease in Δp .

For Method II, the benefit of adding straight ducts is, at best, to make Method II comparable to Method I³. Method I is still preferable because of its simplicity. For Method III, we consider only one case: the addition of straight ducts with lengths of $2L$ at each junction of a contraction and expansion. With the same expansions and contractions, $L_a = 4L$ and $L_a = 8L$ become $L_a = 8L$ and $L_a = 12L$, respectively. This straight duct length has been chosen arbitrarily; there has been no attempt to optimize the results by varying the lengths of the expansions, contractions and straight ducts. The result for the modified Method III are presented in Table 4, where each line corresponds to the same line in Table 3. The ratios of Δp to V_1 are all smaller than one. There is relatively more benefit for the more severe expansions and contractions with $b = 0.5$ than for those with smaller values of b . With $b = 0.5$, we create a very large core velocity near the first wall at the smallest cross section. With the original Method III, we get relatively little benefit from this large velocity because we immediately enter an expansion. Hence the velocity is only very large for a short duct length. By adding the straight duct with this smallest cross section, the decaying velocity in the straight duct has a large value for a much longer duct length. Once we provide the pressure drop needed to create this large velocity, we want it to persist for the longest possible distance.

TABLE 4. RESULTS FOR METHOD III WITH THE ADDITION OF STRAIGHT DUCTS WITH LENGTH $2L$ AT EACH JUNCTION OF AN EXPANSION AND CONTRACTION FOR $a = 1$, $\alpha = 3$, $c = 0.01$ and $\gamma_3 \gg 1$

b	L_3/L	$\Delta p/V_1$	V_1	Q
0.50	8	0.85	5.53	0.48
0.50	12	0.92	3.60	0.34
0.25	8	0.79	2.87	0.33
0.25	12	0.87	1.85	0.21
0.15	8	0.81	1.98	0.24

CONCLUSIONS

The analytical results indicate that Methods I and III are much better than Method II. In addition, they indicate how Method III can be improved to have a higher ratio of V_1 or Q to Δp than Method I. However, a blanket design utilizing Method I is intrinsically simpler than that utilizing Method III.

There is a possible advantage of Method III over Method I. The streamlines for Method I are all straight, while those for Method III move periodically away from and toward the first wall. The benefit of this transverse motion on the heat transfer through the blanket needs to be evaluated by introducing the analytical solutions for the velocity components as functions of x and z into a two-dimensional heat transfer code. A three-dimensional code would be required if the variation of Q with y is also included.

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