

Flow balancing in liquid metal blankets

M.S. Tillack, N.B. Morley

Mechanical, Aerospace and Nuclear Engineering Department, UCLA, Los Angeles, CA 90024-1597, USA

Abstract

Non-uniform flow distribution between parallel channels is one of the most serious concerns for self-cooled liquid metal blankets with electrically insulated walls. We show that uncertainties in flow distribution can be dramatically reduced by relatively simple design modifications. Several design features which impose flow uniformity by electrically coupling parallel channels are surveyed. Basic mechanisms for “flow balancing” are described, and a particular self-regulating concept using discrete passive electrodes is proposed for the US ITER advanced blanket concept. Scoping calculations suggest that this simple technique can be very powerful in equalizing the flow, even with massive insulator failures in individual channels. More detailed analyses and experimental verification will be required to demonstrate this concept for ITER.

1. Introduction

Besides safety, the most serious concerns over the use of liquid metals as fusion reactor coolants relate to the effects of magnetic fields on fluid flow. The key issues can be categorized as: (1) large pressure drops leading to unacceptable pressure stresses, (2) local stagnation of the velocity profile within a channel leading to hot spots and/or high thermal stresses, and (3) non-uniform flow distribution between parallel channels sharing a common manifold.

These problems have been well documented in numerous studies [1,2]. The problems are particularly serious in reactors with high field strength and long poloidal path lengths. ITER, with a coolant path length of approximately 25 m and a field strength exceeding 12 T at the inboard blanket, is a difficult reactor configuration to cool with liquid metals, even with its relatively low power density of about 1 MW m^{-2} . In this regime, it becomes necessary to electrically decouple the fluid

from the load-bearing structures. Currently, the favored approach for the advanced blanket in ITER is the use of insulator coatings on all of the walls [3].

Insulation on the walls can reduce the pressure drop in straight ducts by orders of magnitude compared with thin conducting walls. Accounting for three-dimensional (3-D) effects at entrance/exit regions, bends and manifolding, the pressure drop is still likely to be lower than in thin conducting ducts by at least an order of magnitude.

While this appears to be a very attractive solution to the magnetohydrodynamics (MHD) issue, other problems arise. Long entry regions are found in insulated ducts due to the weaker influence of the field. Perturbations at the inlet can affect the flow over much or all of the channel length. This may or may not cause problems, depending on the nature of the flow perturbation. A more serious concern occurs due to the sensitivity of the flow to 3-D effects and imperfections in the coating. Since the pressure drop in the bulk of the channel is

reduced so greatly, localized perturbations could potentially dominate the flow field and pressure drop.

A number of past studies have highlighted the potential negative consequences of MHD phenomena. However, MHD forces also offer unique opportunities to control and even improve the heat transfer and pressure drop in blankets. Flow balancing is one such technique, which can be utilized to help enforce a uniform distribution of flow, even if defects or failures appear during the course of operation. Other methods of MHD flow control include flow tailoring [4], side layer flow enhancement and 2-D fluctuations [5,6]. The purpose of flow balancing is to maintain a relatively equal distribution of flow in multiple-duct configurations using either active or passive techniques.

Flow balancing is a generic concept; several methods may be possible. In this paper, we examine several techniques for flow balancing in liquid metal blankets with the ducts arranged in parallel with the magnetic field direction. The attractiveness, or even feasibility, will depend on the reactor parameters, blanket design and other factors. A possible design modification for the ITER advanced blanket is proposed and analyzed. This simple modification appears to offer significant advantages. However, the analysis here is somewhat elementary, ignoring 3-D effects which may alter the performance of the schemes presented. In addition, the possible negative effects on local velocity profiles are not considered. Therefore further, more detailed, analysis is recommended, together with validating experiments.

2. Discussion of flow balancing techniques

Manifolding is required to distribute coolant throughout any reactor. In some designs, individual blanket modules include internal manifolding to distribute flow in parallel channels. In the current US ITER design, individual modules consist of a single channel, but numerous modules are assembled in parallel [7]. Regardless of the design details, the total pressure drop between manifolds has a single value, which the fluid experiences regardless of its flow path. If different channels provide different flow resistance, then the bulk velocity will be different. Flow resistances can be affected by geometric effects, such as bends and changes in duct cross-section, or by electrical effects, such as changes in the wall resistance or magnetic field strength and orientation.

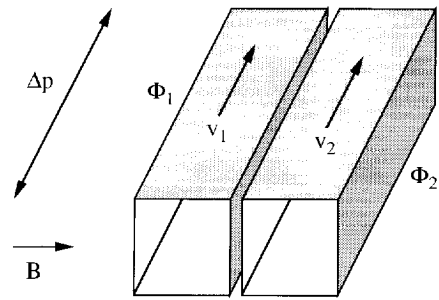


Fig. 1. Parallel channel idealized geometry.

2.1. The unbalanced case

Let us consider the two parallel channels shown in Fig. 1, which share a common inlet and outlet manifold. Without balancing, the bulk average velocity v in each parallel channel will be related to the total manifold pressure drop Δp by the approximate formula

$$\Delta p = \sigma_r v B^2 L \Phi \quad (1)$$

where σ_r is the fluid conductivity, B is the (assumed constant) magnetic field strength, L is the path length and Φ is the effective electrical conductance of the return current path (either through the coating and structural walls or through liquid metal boundary layers). If the two channels have different conductances Φ_1 and Φ_2 , then

$$\sigma_r v_1 B^2 L \Phi_1 = \sigma_r v_2 B^2 L \Phi_2 \quad (2)$$

$$\frac{v_1}{v_2} = \frac{\Phi_2}{\Phi_1} \quad (3)$$

In other words, the non-uniformity of flow is proportional to the non-uniformity in the path of electrical resistance.

2.2. Physical and MHD orifices

Imposing a large pressure drop at some point along the flow path, for example at the inlet, partially decouples the flow rates in parallel channels from smaller mismatched flow resistances over the remaining length of the duct. This technique can be very simple to apply, for instance by inserting a physical orifice into the channels.

More sophisticated applications of this technique involve the use of an MHD choke as a virtual orifice [8]. The choke is a region where additional electrical current is allowed across the channel in such a way as to

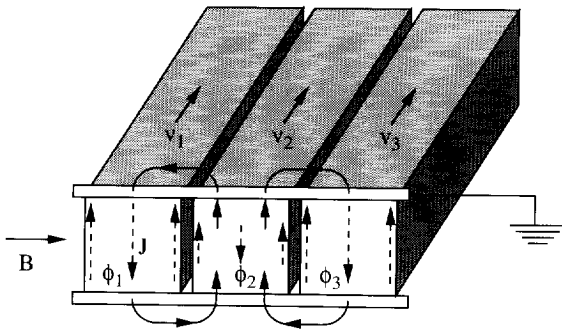


Fig. 2. Current paths in a flow-coupled configuration.

retard the flow strongly, providing the required pressure drop. Velocity feedback and active control of choke currents (or alternatively in situ pumping currents) may also be provided to control flow behavior precisely. However, this would require additional complicated control systems and current source circuitry.

To compare with the reference case above, let us consider an MHD choke with a pressure drop given by Eq. (1), with equivalent electrical conductivity $\Phi_o \gg \Phi_1$. The flow imbalance due to non-uniform channel conductances in this case is moderated by the choke

$$\frac{v_1}{v_2} = \frac{\Phi_2 + \Phi_o}{\Phi_1 + \Phi_o} \tag{4}$$

If a 20% change in resistance occurs in an insulated duct, but a choke provides three times the pressure drop of the entire insulated duct section, then the flow rate will be affected by only approximately 5%. Known non-uniformities (determined by analysis or testing) can be balanced by such techniques. The main disadvantages are that additional pressure drop and pumping power result, and the effectiveness of the technique is limited to relatively small imbalances.

2.3. Flow balancing by electrical coupling

Electrical coupling can have a much stronger effect than orificing. Prior to the description of possible coupling techniques, the general principles are discussed.

In an isolated symmetric duct, the liquid metal ensures uniform potential along field lines throughout the core region. This is dictated as a consequence of the relation

$$\nabla p = J \times B \tag{5}$$

If the potential along the sidewalls is able to equalize between adjacent channels, then Ohm's law tells us that

$$|j_1/\sigma| - |v_1 B| = |j_2/\sigma| - |v_2 B| \tag{6}$$

So a change that reduces the velocity in channel 1 (such as due to a downstream obstruction) requires that the current density, and thus the pressure gradient, drops as well.

Fig. 2 shows the current paths which result from imbalanced parallel channels that are electrically coupled with a high-conductivity electrode at the top and bottom. In this example, the flow in the central channel, v_2 , is assumed to fall temporarily below that of its neighboring channels due to an increased resistance which occurs for some reason. In balanced flow, only the "Hartmann" currents exist, as shown with broken lines. Since the central channel generates less electromotive force, it will experience lower Hartmann currents. The potential difference between the top and bottom wall will tend to fall below that of the two neighboring channels ($\phi_2 < \phi_1, \phi_3$). In that case, global currents form in such a way as to "pump" the central channel. The additional current in the central channel is opposite the direction of the Hartmann current in the core. As the velocity in the central channel recovers, the core current also recovers such that the average pressure drop $J \times B$ in all channels becomes balanced.

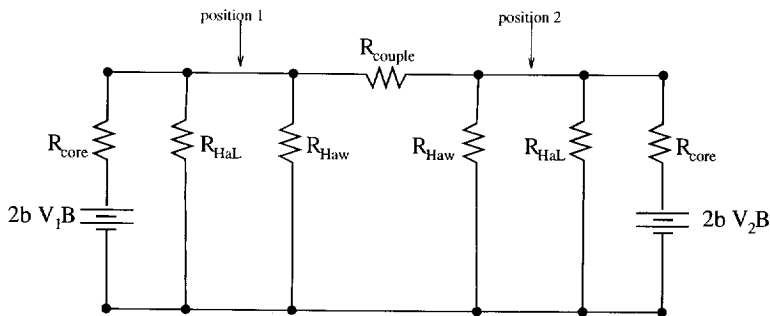


Fig. 3. Resistor network for fully developed flow in parallel channels.

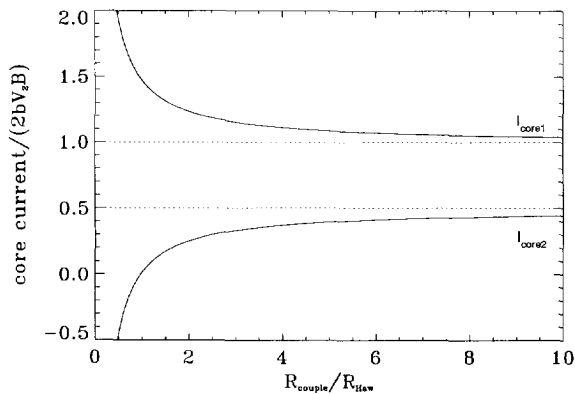


Fig. 4. Core current response for $v_1/v_2 = 0.5$, $\Phi = 0.01$ and $Ha = 10^5$.

The behavior of the core currents can be better understood quantitatively by modeling the situation of Fig. 2 with a resistor network such as that in Fig. 3. Here the problem has been further simplified to two channels only. The resistor R_{couple} allows us to vary the degree of coupling between the two channels, with the extreme cases of $R_{\text{couple}} \rightarrow 0$ giving perfect coupling and $R_{\text{couple}} \rightarrow \infty$ yielding the completely decoupled case. The resistors R_{HaL} and R_{HaW} represent the resistances of the Hartmann layers and Hartmann walls (the sidewalls are assumed to be infinitely conducting and so are not included), and R_{core} is the resistance of the core fluid region. The voltage sources are the generated electromotive forces proportional to $v \times B$ in each channel.

Supposing a large upstream disturbance causes the velocity in channel 2 to drop to half of that in channel 1, the core currents' responses are given in Fig. 4. Here we see that, as the degree of coupling increases ($R_{\text{couple}} \rightarrow 0$), the core current in the retarded channel 2 decreases from that expected for a purely decoupled case, indicating less MHD drag in the retarded channel. In fact, the current even reverses direction for this particular case, and pumping of the retarded channel is seen.

Similarly, the unretarded channel 1 experiences an increase in core current and thus a greater flow resistance. The net response in this perturbed flow distribution is to equalize the flow more so than the uncoupled case. This balancing response becomes extremely strong as R_{couple} drops below the parallel resistance of R_{HaW} and R_{HaL} .

2.4. Distributed electrical coupling: perforated ribs and conducting electrodes

Flow balancing requires that parallel channels be electrically connected in some way. One method to

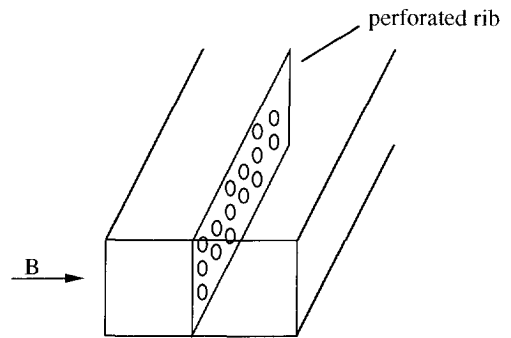


Fig. 5. Perforated rib in a multiple-duct assembly.

equalize potentials between insulated channels is the perforated wall scheme shown in Fig. 5. Small holes in the rib of a multiple-duct assembly allow equalizing currents to flow between channels through the liquid metal itself, rather than through external structures as indicated in Fig. 2. Insulation from the conducting channel walls is maintained if the multiple duct is assembled and then subjected to the wall coating process. Additionally, the wall perforations equalize pressure differentials so that the pressure gradient ∇p is constant along the entire channel length. This, as a consequence of Eq. (5), indicates that the core currents are always equal. The constancy of core current and Eq. (6) imply that in this case imbalanced flows are not even possible. This case is similar to a single channel elongated along the magnetic field, but with ribs that support the wide channel sidewalls lending further structural stability to the elongated channel design.

Design constraints may disallow the use of multiple adjacent perforated walls to distribute electrical potential. In this case it may be possible to use internal electrodes in contact with the liquid metal but insulated from the structure. Electrodes in separate channels would have to be connected together in some way, possibly by means of insulating feedthroughs penetrating the channel walls at specific locations.

2.5. Localized electrical coupling: manifold electrodes and locally uncoated channels

Distributed coupling is attractive for several reasons. With such a design, we could even apply current to the electrodes and stimulate in situ pumping. In situ pumping has the relatively exciting potential to eliminate completely the MHD pressure drop, regardless of the wall conductance. This occurs because the force of the MHD pressure gradient (against the flow) is every-

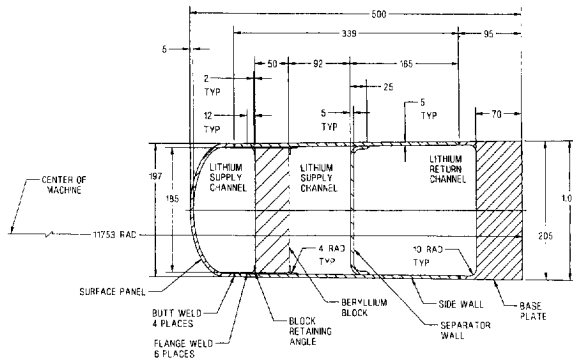


Fig. 6. US ITER liquid metal blanket design concept.

where balanced by the MHD pumping force (in the direction of the flow). However, localized coupling may be more practical to apply in many instances. It may not be feasible to install insulated feedthroughs and bonded electrodes throughout the entire channel length; designs with perforated walls may also prove impractical. However, even a very short length of coupled channel is adequate to balance the flow effectively.

One way to apply localized coupling is by installing electrodes near manifolds within the region of strong magnetic field. Extending electrodes into the manifolds allows balancing currents to flow between neighboring electrodes through the liquid metal in the manifold region with little resistance. The length of influence into the channels would depend on the conductance of the electrode and the liquid metal. A certain degree of natural balancing is to be expected at manifolds even if the electrode is not present; this effect could be enhanced by the presence of a highly conducting floating electrode.

Another flow balancing design concept is to introduce a short section of channel, without insulator coatings, that has highly conducting sidewalls to distribute the electrical potential. This is a simple technique to apply, but will result in an increased pressure drop, varying in severity with the relative conductance of the Hartmann walls. For this reason a thin, poorly conducting Hartmann wall used in combination with a thick, highly conducting sidewall is the ideal arrangement. This is the method proposed in the following section for the ITER advanced blanket.

2.6. "Natural" flow balancing

The possibility of natural flow balancing, where imperfect insulator coatings on conducting structural walls of electrically coupled channels tend to equalize

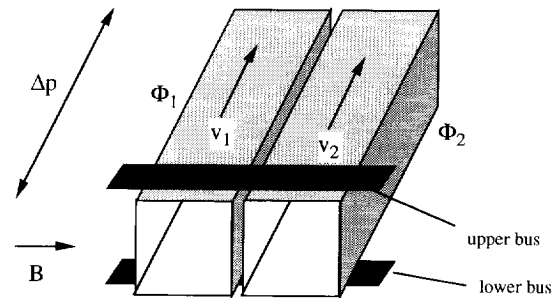


Fig. 7. Locally coupled ducts.

potentials, was considered. This situation would occur naturally in ducts with flawed coatings and electrically connected structural walls.

The introduction of equal coating resistances at positions 1 and 2 in Fig. 3 reduces the effectiveness of the coupling since now the fluid potentials can float more easily with respect to each other. An increase in coating resistance ultimately leads to the totally decoupled insulated wall case, which has very little tendency to equalize the flow rates. Calculations show that, if the coating resistances are unequal, then the tendency exists to make the flow imbalance even worse than the totally decoupled case. Therefore, little or no credit can be taken for natural flow balancing in reactor-relevant regimes.

3. A proposal for the ITER advanced blanket

A recent US design for an advanced liquid metal-cooled blanket for ITER is shown in Fig. 6 [7]. The figure shows an inboard module of a poloidal flow concept. The design features modules mounted on a common "strongback". Each module contains a single flow path. The coolant enters at the top, passes along the front side (facing the plasma) through dual supply channels, turns 180° at the bottom, and then exits by a return channel at the back.

A possible flow balancing scheme for this blanket concept, depicted in Fig. 7, imposes localized coupling by means of high-conductivity bus bars located near a manifold. The bus bars maintain equal potential difference between the top and bottom of each channel, thereby enforcing equal flow rates. As shown above, they must remain in good electrical contact with the fluid. Any insulator coating must be avoided at this location.

It is likely that some type of joining or welding must occur in these manifolds inside the magnetic field. This

would be a good location to insert electrodes which are constructed of, or coated with, a material that resists oxidation and/or nitridation, or to simply not aluminize this region so that the insulator coating does not form. The manifold region could be located away from the plasma in an area of low radiation and thermal gradients, even including shielding to prevent neutron degradation of any bonds, joints or conductivity of the bus bar.

A simple analysis is provided below to show the effectiveness of the technique and the additional pressure drop experienced under normal operation.

3.1. Basic performance

The total pressure drop in both channels shown in Fig. 7 is given by

$$\Delta p = \Delta p_e + \Delta p_b \quad (7)$$

where Δp_e comes from the electrode region and Δp_b comes from the remainder of the blanket. The pressure drop in the electrode region is

$$\Delta p_{e1} = \sigma_r B L_e (E + v_1 B) \quad (8)$$

$$\Delta p_{e2} = \sigma_r B L_e (E + v_2 B) \quad (9)$$

where E is the electric field, which is forced to be constant between channels at the electrode. The pressure drop in the remainder of the duct is

$$\Delta p_{b1} = \sigma_r v_1 B^2 L_b \Phi_{b1} \quad (10)$$

$$\Delta p_{b2} = \sigma_r v_2 B^2 L_b \Phi_{b2} \quad (11)$$

For insulated ducts, $\Phi = 1/Ha$. If we add the pressure drops in each duct and equate the total pressure drop between the two, we obtain

$$\frac{v_1}{v_2} = \frac{L_e + L_b \Phi_{b2}}{L_e + L_b \Phi_{b1}} \quad (12)$$

This expression indicates that the non-uniformity of the flow is reduced compared with the case without balancing, depending on the ratio of lengths and the flow path resistance. For effective flow balancing, we require

$$\frac{L_e}{\Phi_b L_b} \gg 1 \quad (13)$$

The minimum electrode length is determined by assuming $\Phi_b \approx 10^{-4}$. This value of conductance is about one order of magnitude lower than that achievable in thin conducting ducts, and one order of magnitude higher than would be obtained in a perfectly insulated

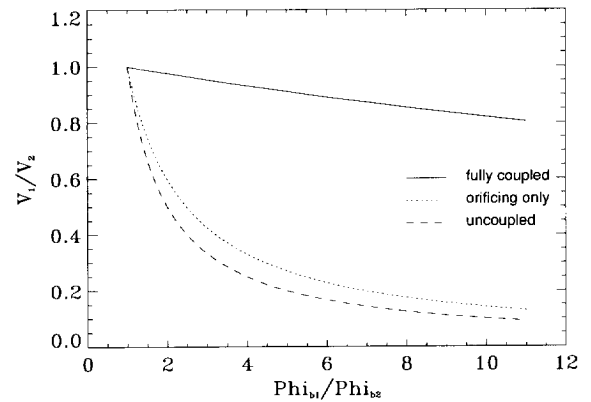


Fig. 8. Velocity ratio in two channels with and without coupling.

duct with fully developed flow and $Ha = 10^5$. In this case, assuming $L_b \approx 25$ m, we require $L_e \gg 2.5$ mm. In other words, a very short length of tightly coupled duct can balance 25 m of moderately insulated channel. We will use a very conservative safety factor and assume that the electrode length is 10 cm for the calculations of the pressure drop below.

3.2. Pressure drop

The presence of the high-conductivity bus bars will influence the local pressure drop if they electrically contact the Hartmann walls—even if the flow is balanced. Since the length of the electrodes is short, the additional pressure drop will come primarily from 3-D effects. However, in order to make a simple estimate of the magnitude, we assume fully developed flow in a thin-walled duct at the location of the electrodes.

If we make the requirement that the pressure drop in the electrode region is small compared with that in the blanket region, we can use Eq. (1) to obtain

$$\frac{\Delta p_e}{\Delta p_b} = \frac{L_e \Phi_e}{L_b \Phi_b} \ll 1 \quad (14)$$

so that the total design window for the electrode region is

$$1 \ll \frac{L_e}{L_b \Phi_b} \ll \frac{1}{\Phi_e} \quad (15)$$

The first inequality is necessary for effective flow balancing, and the second for acceptably small additional pressure drop. For vanadium walls 5 mm thick and a channel half-width of 10 cm, we obtain $\Phi_e = 1.6 \times 10^{-2}$. In that case, the pressure drop over a

Table 1
Parameters used in the pressure drop estimate

Wall thickness	$t = 5 \text{ mm}$
Channel half-width	$a = 100 \text{ mm}$
Fluid conductivity	$\sigma_f = 3 \times 10^6 \text{ 1}/\Omega \text{ m}$
Wall conductivity	$\sigma_w = 1 \times 10^6 \text{ 1}/\Omega \text{ m}$
Wall conductance ratio	$\Phi_w = 1.6 \times 10^{-2}$
Field strength	$B = 12 \text{ T}$
Electrode length	$L_e = 10 \text{ cm}$
Channel length	$L_b = 25 \text{ m}$
Fluid mean velocity	$v = 1 \text{ m s}^{-1}$

10 cm path length (using the values in Table 1) is approximately 0.7 MPa, or 40% of the blanket region pressure drop. This value is somewhat high, and indicates that the electrode length should be shortened (which is possible given the flow balance constraints above) and/or the wall conductance ratio reduced. Even at this level of pressure drop, flow balancing due to the orificing effect is much less than that due to coupling currents.

Fig. 8 shows the ratio of the velocities in two parallel channels with different effective wall conductances, Φ_{b1} and Φ_{b2} . The 10 cm electrode as described above is added to the system. The results show that, even with a factor of ten difference in channel flow resistance, the variation in velocity with flow coupling is only 20%, whereas the velocities in the completely uncoupled case are proportional to the conductances. The middle line shows the amount of flow balancing which occurs with the electrodes in place due only to the increased pressure drop (the orificing effect). Virtually all of the balancing is due to current redistribution.

4. Conclusions

The generic concept of flow balancing has been described, and shown to have various possible embodiments in reactor blanket designs. A flow balancing proposal for ITER was shown to be a practical “self-regulating” device which provides minimal additional pressure drop, and responds instantaneously to any imbalances which may occur. Flow obstructions in any one channel are equally shared amongst many channels, reducing the pressure drop by the number of coupled

channels. A very short coupling length is needed of the order of 5–10 cm. The complexity added to the blanket appears to be very modest considering the clear advantages. The entire modification could be made away from the plasma in a region near an existing manifold, provided that it is within the region of the strong magnetic field.

The simple calculations presented above assume fully developed pressure drops in all cases, even though it is likely that 3-D effects and developing flow may dominate the total pressure drop. A more detailed assessment of these flow balancing techniques requires further more sophisticated modeling, including pressure drops due to non-uniform magnetic fields, entry regions, manifolds and abrupt changes in wall conductivity. Simple relatively inexpensive experiments are needed to verify the performance of the device at high magnetic fields.

References

- [1] M.A. Abdou, M.S. Tillack and A.R. Raffray, Thermal, fluid flow and tritium release problems in fusion blankets, *Fusion Technol.*, 18 (2) (1990) 165–200.
- [2] S. Malang, H. Deckers, U. Fischer, H. John, R. Meyder et al., Self-cooled blanket concepts using Pb–17Li as liquid breeder and coolant, *Fusion Eng. Des.*, 14 (1991) 373–399.
- [3] Detail of the ITER Outline Design Report: The ITER Machine, ITER-TAC-4, January, 1994.
- [4] J.S. Walker and B.F. Picologlou, Comparison of three MHD flow control methods for self-cooled liquid metal blankets, *Fusion Technol.*, 10 (2) (1986) 866.
- [5] O.V. Andreev and Yu.B. Kolesnikov, Possibilities of heat transfer intensification to the MHD problems of liquid metal fusion blankets, 7th Beer-Sheva Seminar on MHD Flows and Turbulence, Jerusalem, February, 1993.
- [6] C.B. Reed and B.F. Picologlou, Sidewall flow instabilities in liquid metal MHD flow under blanket relevant conditions, *Fusion Technol.*, 15 (2) (1989) 705.
- [7] L. Green, M.D. Carelli, F. Stefani, G.D. Morgan, V.D. Lee and R.F. Mattas, A review of ITER blanket designs, 11th Topical Meeting on the Technology of Fusion Energy, June, 1994, *Fusion Technol.*, to be published.
- [8] Tokamak power systems studies—FY1986, a second stability power reactor, Argonne National Laboratory Rep., ANL/FPP/86-1, Argonne National Laboratory, March, 1987.