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Magnetohydrodynamic Flows in Ducts with Insulating Coatings

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Abstract

An effective insulation of the electrically conducting channel walls leads to tolerable magnetohydrodynamic (MHD) pressure drop in liquid metal flows in self–cooled fusion reactor blankets. Such insulation prohibits closed current circuits over conducting walls and reduces total current, which determines pressure drop and flow distribution, caused by the interaction of the flowing liquid metal and the strong plasma–confining magnetic field.

Several kinds of insulation are currently under development. One is the so called flow channel insert technique, where the insulating ceramic is protected against the liquid metal by thin steel sheets. Recently, direct insulating ceramic coatings have been proposed, which should resist corrosion during the whole operation time of a fusion blanket. It is not necessary that these coatings provide a perfect insulation, because even a finite coating resistance is enough to reduce the pressure drop by orders of magnitude. The aim of this paper is to provide material scientists or blanket designers with sufficient data on MHD insulation requirements. Reduced insulation properties, which may arise during blanket live time by impurities, corrosion, irradiation damage or by small cracks, can be allowed up to a certain limit. The increase in pressure drop and the change in flow pattern are quantified, if the coating resistance falls below this limit.

Magnetohydrodynamische Strömungen in Kanälen mit isolierenden Beschichtungen

Zusammenfassung

Magnetohydrodynamische (MHD) Druckverluste in Flüssigmetallströmungen selbstgekühlter Blankets von Fusionsreaktoren werden durch eine wirksame elektrische Isolation der Kanalwände auf ein akzeptables Maß reduziert. Eine solche Isolation verhindert geschlossene Stromkreise über elektrisch leitende Wände und reduziert die gesamte Stromdichte. Die Wechselwirkung elektrischer Ströme mit den starken Magnetfeldern, die das Plasma einschließen, bestimmt den Druckverlust und die Strömungsverteilung der Flüssigmetallströmung.

Momentan werden verschiedene Isolationsmöglichkeiten untersucht. Eine ist die sogenannte Strömungskanal–Einsatz–Technik, bei der die keramische Isolationsschicht durch dünne Stahlschichten vor dem Flüssigmetall geschützt wird. In jüngster Zeit werden direkt isolierende keramische Beschichtungen vorgeschlagen, die während der gesamten Betriebszeit eines Blankets Korrosionsprozessen widerstehen. Dabei ist es nicht notwendig, daß diese Beschichtungen eine vollständige Isolation erreichen, da selbst endliche Schichtwiderstände die Druckverluste um Größenordnungen reduzieren. Ziel dieser Arbeit ist es, Materialwissenschaftlern oder Blanket–Designern Daten über erforderliche Isolationswerte zu liefern. Reduzierte Isolationseigenschaften, die während der Lebensdauer eines Blankets durch Verunreinigungen, Korrosion, Strahlungsschäden oder durch feine Risse verursacht werden, sind bis zu einer gewissen Grenze zulässig. Die Zunahme des Druckverlustes und die Änderung der Strömungsverteilung werden quantifiziert, falls der Schichtwiderstand unter diese Grenze fällt.

Magnetohydrodynamic flows in ducts with insulating coatings

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1 Introduction

The idea to use insulating coatings to provide sufficient pressure drop reduction in fusion blanket components is very old. Recently Malang (1991, 1992) defined required coating resistance, to decrease pressure drop by more than one order of magnitude compared to the other insulation method (flow channel inserts). These coatings prohibit a closed current circuit over good conducting channel walls, which results in very small total current, induced inside the fluid, and in a strong reduction of magnetohydrodynamic (MHD)–pressure drop.

Blanket concepts with poloidal flow direction suffered in the past by unacceptable pressure drop. With insulating coatings they become very attractive because of their much simpler design (see Malang *et al.* 1992) compared especially to the poloidal–radial–toroidal–radial–poloidal one, currently considered as the reference concept at KfK (Malang *et al.* 1991).

In reality, however, a perfect insulation can not be achieved. Even ceramic insulation materials have small but still finite conductivity σ_i or large but not infinite resistivity $\rho_i = 1/\sigma_i$. The efficiency of an insulating layer of thickness δ_i can be measured by the product $\rho_i\delta_i$, called throughout this report as *coating resistance*. As an example alumina is considered as insulating material for blankets with Pb17Li as liquid metal (Malang *et al.* 1992). Its specific resistance $\rho_i > 10^{10}\ \Omega\cdot m$ in the relevant temperature range of 400^oC together with a layer thickness of $10\mu m$, which seems to be a suitable value for technical applications, would provide almost perfect insulation conditions with $\rho_i\delta_i = 10^5\ \Omega\cdot m^2$. However this value may be reduced significantly by metallic impurities in the ceramic layer, by corrosion processes, by irradiation damage or by small cracks. Promising insulation materials for Li as liquid metal are proposed by Sze *et al.* (1992).

A reduction of the coating resistance has an influence on the pressure drop. Rough estimates of this influence have been made by Malang 1991 and by Sze *et al.* 1992. They considered the MHD–flow in a geometry, relevant to poloidal flow concepts, namely the rectangular duct with two walls parallel to the orientation of the magnetic field $\boldsymbol{B}$, and the other two perpendicular to it, called ***side walls*** and ***Hartmann walls***, respectively. In their simplified model they supposed a slug flow velocity profile and considered mainly the influence of finite coating resistance at the side walls on pressure drop.

The present analysis shows that there is a strong dependence of the pressure drop on coating resistance, but only in a certain range of it. Furthermore, there is a strong influence of the coatings at Hartmann walls on the flow structure. Over a large range of coating resistance the velocity distribution even in fully developed channel flow is neither of slug flow type, nor similar to other fully developed MHD–velocity profiles. In a special range of parameters, as shown in this report, this may lead to unfavorable conditions, where nearly the whole core is stagnant and all volume flux is carried by jets at the side walls.

2 Formulation

Consider the steady flow of a viscous conducting incompressible fluid in a duct in a strong uniform external magnetic field $\boldsymbol{B} = \boldsymbol{B}_0$.

The dimensionless inertialess and inductionless equations governing the problem are

$$M^{-2}\nabla^2\boldsymbol{v} + \boldsymbol{j}\times\boldsymbol{B}_0 = \nabla p, \qquad (2.1a)$$

$$\boldsymbol{j} = -\nabla\phi + \boldsymbol{v}\times\boldsymbol{B}_0, \qquad (2.1b)$$

$$\nabla\cdot\boldsymbol{v} = 0, \qquad (2.1c)$$

$$\nabla\cdot\boldsymbol{j} = 0, \qquad (2.1d)$$

where the fluid velocity $\boldsymbol{v}$, the electric current density $\boldsymbol{j}$, the electric potential ϕ and the pressure p are normalized by v_0 (the average fluid velocity at a fixed cross section of the duct), $\sigma v_0 B_0$, $v_0 B_0 L$ and $\sigma v_0 B_0{}^2 L$, respectively; $M = B_0 L\sqrt{\sigma/\rho\nu}$ is the Hartmann number.

The boundary condition for fluid velocity at each wall is the non–slip condition

$$\boldsymbol{v} = \boldsymbol{0}. \qquad (2.1e)$$

To obtain the conditions for the electrical variables consider a thin conducting wall covered by an insulating coating (see fig.2.1). The curvilinear coordinate system (n, s, t) is induced by the inside surface of the wall. The boundary condition on the wall–coating interface reads

$$\boldsymbol{j}\cdot\boldsymbol{n} = \nabla_w\cdot(c\nabla_w\phi_w). \qquad (2.1f)$$

It is equivalent to the thin–wall condition, derived by Walker (1981) for flows in ducts with no coating. In equation $(2.1f)$ $\phi_w(s,t)$ is the wall potential; $c(s,t) = \sigma_w h_w(s,t)/\sigma L$ is the wall conductance ratio; σ_w, h_w are the conductivity and the thickness of the wall; ∇_w is the gradient in the plane (s,t) of the wall; $-\boldsymbol{j}\cdot\boldsymbol{n}$ is the current, entering the wall from the coating.

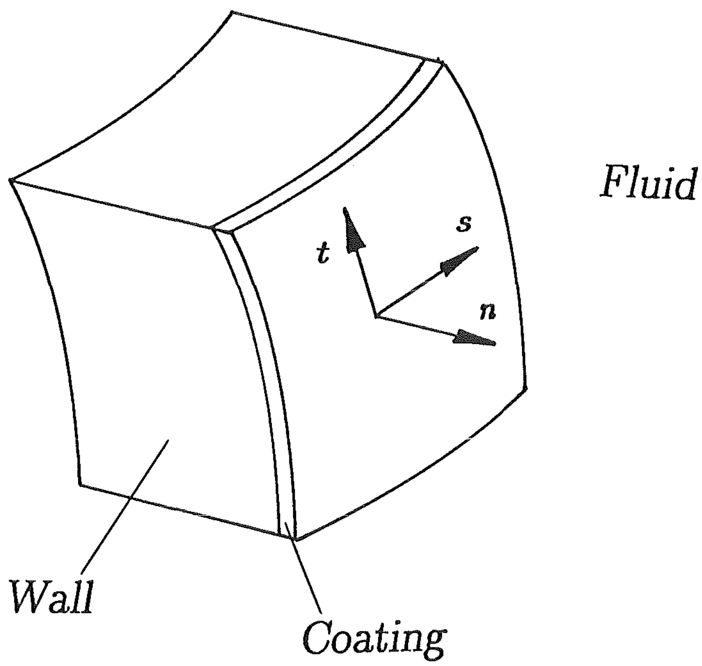


Fig. 2.1 Curvilinear coordinates

Since the coating is very thin, it can conduct current only in the normal direction, so that

$$\boldsymbol{j}\cdot\boldsymbol{n} = \frac{1}{\kappa}(\phi_w - \phi) \qquad (2.1g)$$

on the wall, and $-\boldsymbol{j}\cdot\boldsymbol{n}$ in both equations (2.1f) and (2.1g) denotes the current, entering the wall with coating from the fluid; $\kappa = (\rho_i\delta_i)\sigma/L$ is the nondimensional ***coating resistance.***

The conditions (2.1f,g) are to be used simultaneously. In principle, if it does not lead to a confusion in some limiting cases, a single condition can be obtained from the two in order to exclude either wall potential, or the current.

For the fully developed flow in rectangular duct the conditions (2.1f,g) at the top, for example, read (see fig.2.2)

$$j_y = -c\frac{\partial^2\phi_w}{\partial z^2}, \quad j_y = \frac{1}{\kappa}(\phi-\phi_w), \quad \text{at } y = 1. \qquad (2.2a,b)$$

Excluding wall potential from (2.2a,b) gives

$$j_y = -c\frac{\partial^2\phi}{\partial z^2} + c\kappa\frac{\partial^2 j_y}{\partial z^2} \quad \text{at } y = 1. \qquad (2.3)$$

Excluding the current from (2.2a,b) leads to the condition

$$\phi - \phi_w = -c\kappa\frac{\partial^2\phi_w}{\partial z^2}. \qquad (2.4)$$

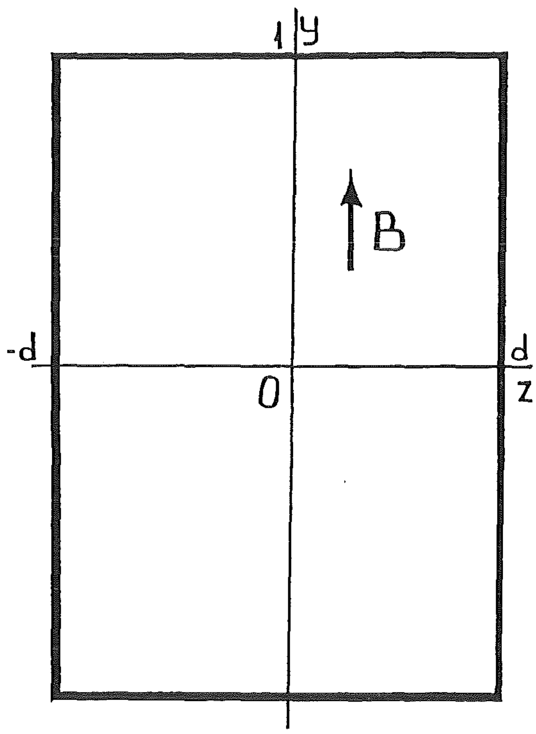


Fig. 2.2 Rectangular duct geometry

3 Numerical solution

To study the influence of the coatings on pressure drop and flow distribution consider a fully developed MHD–flow in a square duct. Under relevant fusion blanket conditions the conductivity of the channel walls is much higher than those of the Hartmann layers $(c >> M^{-1})$ and even higher than those of side layers $(c >> M^{-\frac{1}{2}})$. In this chapter the MHD–channel flow in a perfectly conducting duct $(c \rightarrow \infty)$, covered by the coating, is considered, because the effect of finite coating resistance should be most expressed in this case. Preliminary results were presented by Bühler (1992).

For a numerical solution the ***General Core Flow Solution*** code is used (see Bühler 1991). The ***thin wall boundary condition*** which is used in this code as electrical boundary condition was extended to the conditions *(2.1f,g)*.

The influence of finite coating resistance on the pressure drop is shown in fig.3.1 for the range of the Hartmann number $M = 10^2 \div 10^4$. As expected, for small values of κ the nondimensional pressure drop tends to that in MHD–flows in good conducting channels $(k = -\partial p/\partial x \rightarrow 1,\ \text{as}\ \kappa \rightarrow 0)$. As the insulation is improved to values $\kappa >> 0.1$ the pressure drop significantly reduces. Increasing of the coating resistance by one order of magnitude gives a reduction of pressure drop also by one order of magnitude. A considerable reduction of pressure drop is only possible until the limiting case of perfect insulation is reached. A further improvement of the insulation has no effect on pressure drop. Nearly perfect insulation conditions are reached if κ is related to the Hartmann number by

$$\kappa >> M. \qquad (3.1)$$

This relation determines the required condition for ceramic coatings to provide pressure drop as in insulating channels.

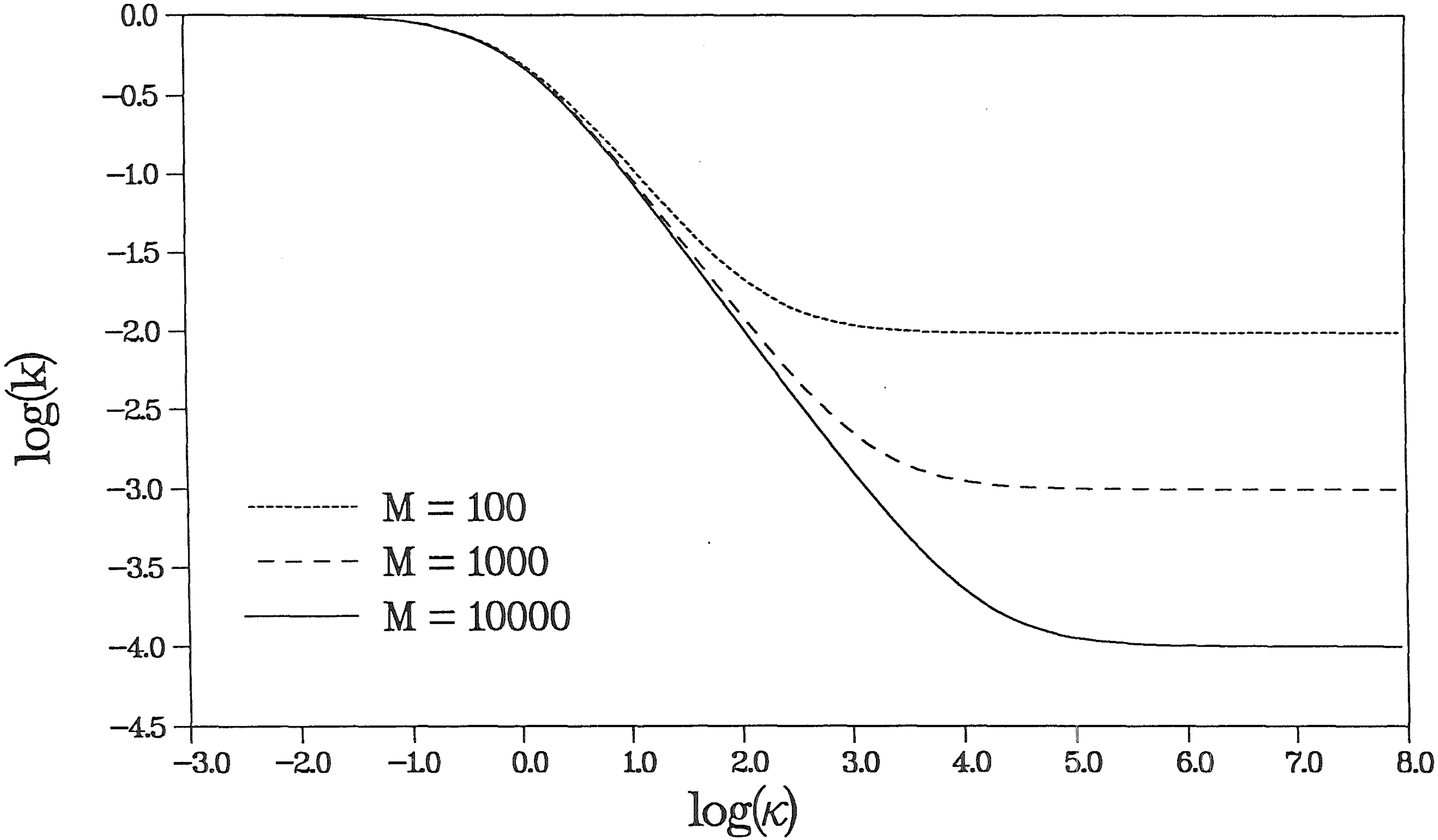
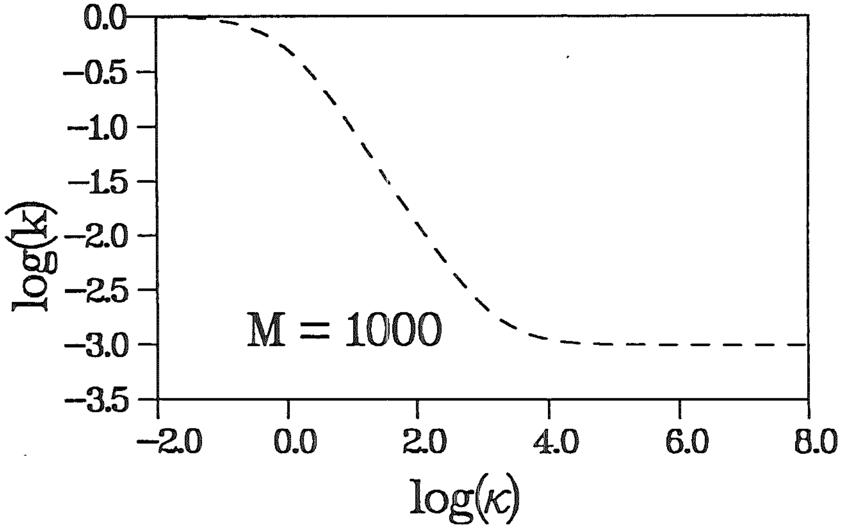
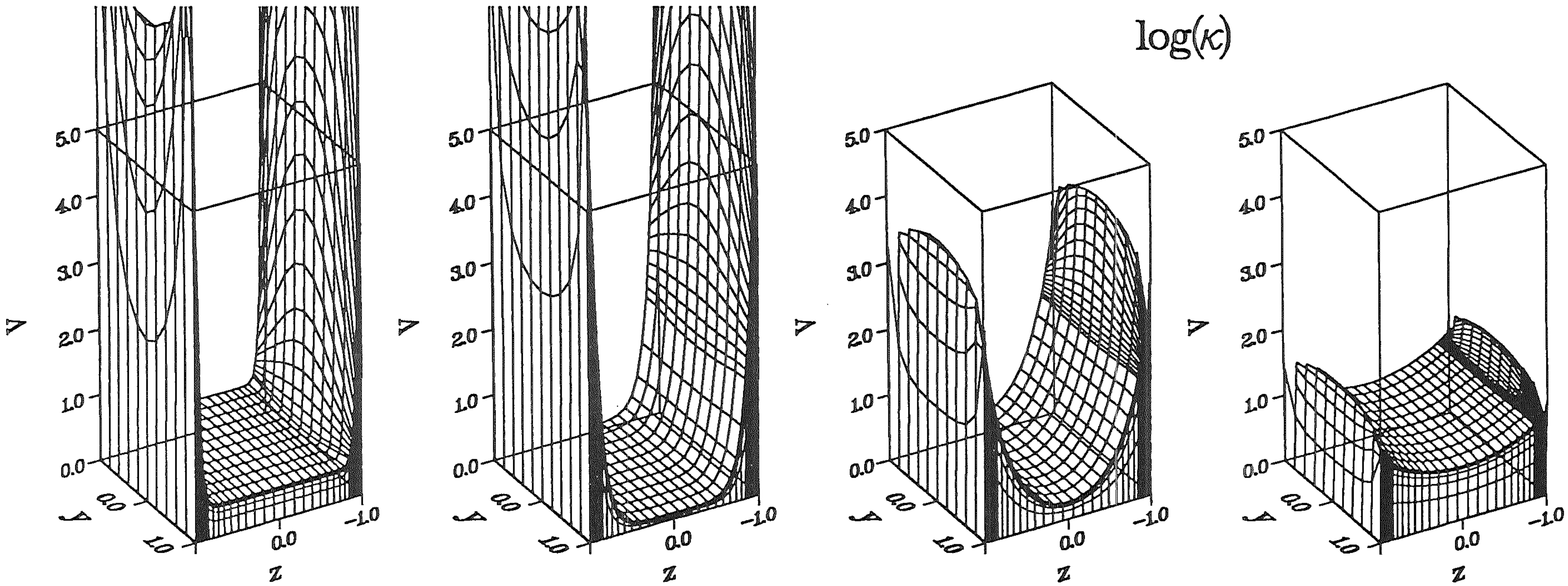


Fig. 3.1 *MHD Pressure drop as a function of the coating resistance coefficient in a perfectly conducting channel, covered by insulating coatings.*

Fig. 3.2 *MHD Velocity profiles in a perfectly conducting channel, covered by insulating coatings. Variation of velocity profiles as a function of the coating resistance coefficient κ.*





κ =	1	10	100	1000
Fig. 3.2	a	b	c	d

From fig.3.1 one may conclude that it is possible to find a suitable value for the coating resistance κ, smaller than those required for perfect insulating conditions, if some acceptable pressure drop is allowed. However this choice has to be done carefully, taking into account flow distribution over the cross–section (see fig.3.2). If $\kappa << 1$ or $\kappa >> 10^3$, the velocity profiles (not shown on fig.3.2) are of slug–type, corresponding to the insulating and perfectly conducting limits, respectively. If the coating resistance is small (fig.3.2a), thin high–velocity jets form along the side walls. As the coating resistance increases, the amount of fluid, carried by these jets increases and the core velocity decreases at the same time. The velocity profile on fig.3.2b is similar to that in a channel with insulating side walls and highly conducting top and bottom (see Hunt 1965). The core is virtually stagnant and all volume flux is carried by the two jets at the side walls. When κ increases further, the thickness of the side layers increases, and the velocity profile in the core no longer is of slug–type. At $\kappa = 100$ there is no distinct core and layers (fig.3.2c). The velocity in the center of the duct increases. At $\kappa = 1000$ (fig.3.2d) the velocity profile is of almost slug–type.

In fully developed flows in symmetric rectangular ducts with thin conducting walls without coatings the velocity in the core is always of slug–type. Velocity profiles on fig.3.2 are very unusual, especially that at $\kappa = 100$. To clarify the physical reasons for the effects described in this chapter an asymptotic solution has been developed as $M \longrightarrow \infty$.

4 Asymptotic solution

First, a particular case of completely insulating side walls is considered. The resistance of the coatings on Hartmann walls is supposed to be high $(\kappa >> 1)$. The symmetric problem with respect to z and y, formulated for the fluid velocity v and the induced magnetic field b (these are both in the x-direction) reads (see Shercliff 1965)

$$\Delta v + M\frac{\partial b}{\partial y} = -kM^2, \qquad (4.1a)$$

$$\Delta b + M\frac{\partial v}{\partial y} = 0 , \qquad (4.1b)$$

$$v = 0,\ b = 0,\ \text{at}\ z = d, \qquad (4.1c,d)$$

$$\frac{\partial v}{\partial z} = 0,\ \frac{\partial b}{\partial z} = 0,\ \text{at}\ z = 0, \qquad (4.1e,f)$$

$$\frac{\partial v}{\partial y} = 0,\ b = 0,\ \text{at}\ y = 0, \qquad (4.1g,h)$$

$$v = 0,\ c\frac{\partial b}{\partial y} + b = c\kappa\frac{\partial^2 b}{\partial z^2},\ \text{at}\ y = 1. \qquad (4.1i,j)$$

Here, $k=-\partial p/\partial x$; c is the wall conductance ratio of the top; $\Delta=\partial^2/\partial y^2+\partial^2/\partial z^2$.

The boundary condition $(4.1j)$ can be obtained from the condition (2.3) and the Ampère's and Ohm's laws, which read

$$j = \frac{1}{M}\nabla\times(be_x) = \frac{1}{M}(\frac{\partial b}{\partial z}e_y - \frac{\partial b}{\partial y}e_z), \qquad (4.2a)$$

$$\nabla\phi = -j + (ve_x)\times e_y = -\frac{1}{M}\frac{\partial b}{\partial z}e_y + (\frac{1}{M}\frac{\partial b}{\partial y} + v)e_z . \qquad (4.2b)$$

The condition of constant average velocity in duct cross–section requires that

$$\int_0^1 dy\int_0^d v dz = d \qquad (4.1k)$$

An exact solution to the problem *(4.1)*, similar to that of Hunt(1965) for the duct with no coating, has been obtained by Shishko (1988) in terms of Fourier series. The exact solution is difficult to analyze at large Hartmann numbers. The direct application of matched asymptotic expansions to the problem *(4.1)* leads to a solution in a compact form with less effort.

At large Hartmann numbers the flow exhibits the following subregions (see fig.4.1):

– the inviscid core C;

– the Hartmann layer H at the top with $O(M^{-1})$ thickness,

– the side layer S with $O(M^{-\frac{1}{2}})$ thickness.

The other subregions, not shown on fig.4.1, are not important for the present analysis.

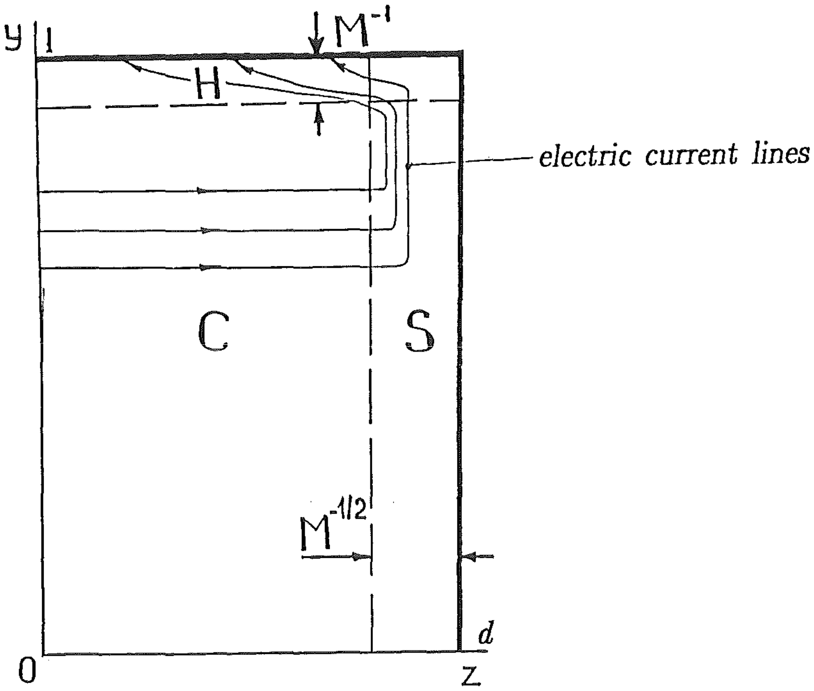


Fig. 4.1 Flow subregions at large Hartmann numbers and sketch of electric current lines.

4.1 The core

Neglecting viscous terms in the eqs. $(4.1a,b)$ gives

$$v_C = f(z), \quad b_C = -kMy, \qquad (4.3a,b)$$

where $f(z)$ is an integration function. The symmetry conditions $(4.1e\text{-}h)$ have already been taken into account.

In the core the current is uniform and flows only in the z-direction, since

$$j_C = k\mathbf{e}_z \qquad (4.3c)$$

4.2 The Hartmann layer

The solution in the Hartmann layer, which satisfies the non–slip condition $(4.1i)$and the conditions of matching the core variables reads

$$v_H = f(z)\left[1 - e^{y_H}\right] , \qquad (4.4a)$$

$$b_H = -kMy + f(z)e^{y_H} , \qquad (4.4b)$$

where $y_H{=}M(y-1)$ is the stretched Hartmann–layer variable.

Substituting $(4.4b)$ into boundary condition $(4.1j)$ determines the unknown function $f(z)$ to give

$$f(z) = A\cosh\beta z + k\eta , \qquad (4.5)$$

where

$$\beta = \sqrt{\frac{cM+1}{c\kappa}} \; ; \; \eta = \frac{c+1}{c+M^{-1}};$$

A is a constant of integration. It has to be determined from the conditions of matching the solution (4.4) with the solution in the side layer.

From the analysis of the flow in the side layer and adjacent Hartmann layer for the range of κ considered here it follows that there is no jump in the induced magnetic field on the top across the layer, so that the boundary condition *(4.1d)* is applied to the function *(4.4b)* directly. This gives

$$f(z) = k\left\{ (M-\eta)\frac{\cosh\beta z}{\cosh\beta d} + \eta \right\} \qquad (4.6)$$

The electric current density in the Hartmann layer is

$$j_H = j_{yH}e_y + j_{zH}e_z \;, \qquad (4.7a)$$

where

$$j_{yH} = \frac{1}{M}f'(z)e^{y_H} \;, \quad j_{zH} = k - f(z)e^{y_H} \;. \qquad (4.7b,c)$$

Variation of functions $f(z)$ and $f'(z)$ with κ is shown on fig.4.2 and fig.4.3.

4.3 Flow rate and pressure gradient

The velocity in the side layer is of the same order as in the core, so that the side layer carries no volume flux to the main order. Thus, it is not considered here in detail.

Since all volume flux is carried by the core, the flow rate is calculated by integrating the expression *(4.3a)* over the duct's cross–section. This gives

$$Q = \int_0^1 dy \int_0^d f(z)\,dz = k\left\{ \frac{1}{\beta}\tanh\beta d\,(M-\eta) + \eta d \right\} . \qquad (4.8)$$

Substituting *(4.8)* into *(4.1k)* determines the pressure gradient. This gives

$$k = \frac{\beta d}{\tanh\beta d\;(M-\eta) + \eta\beta d} \;. \qquad (4.9)$$

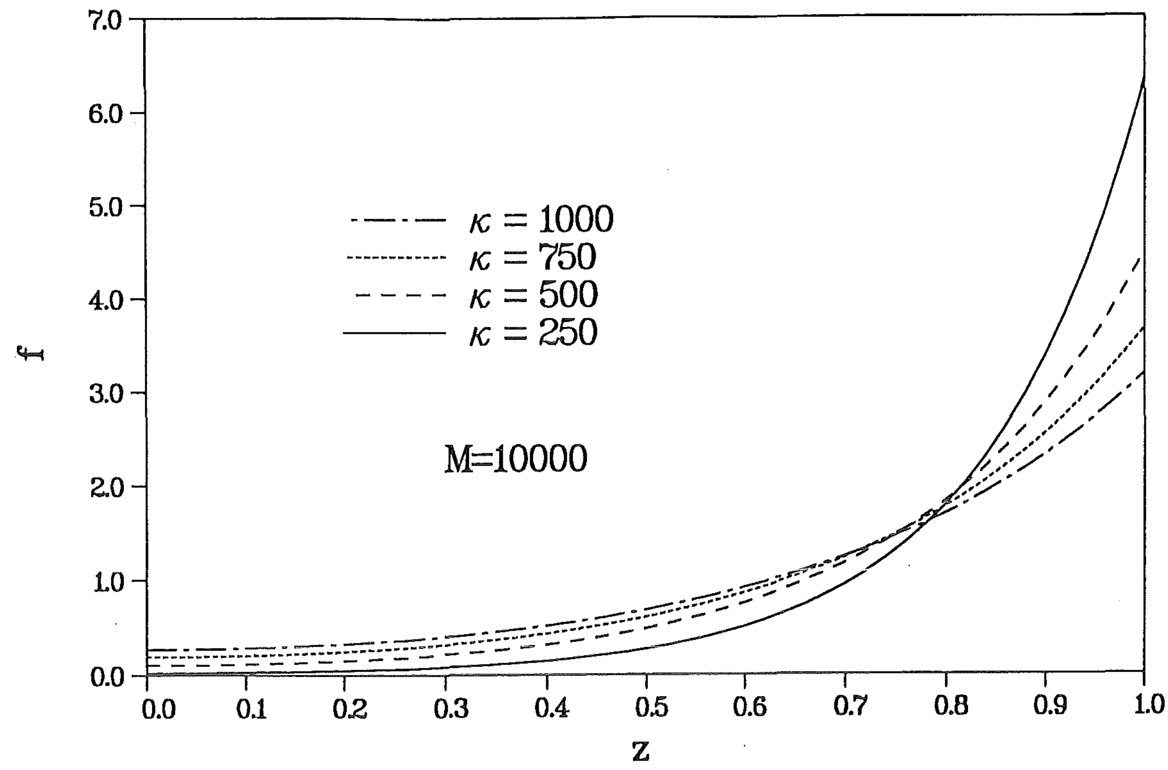


Fig. 4.2 Function $f(z)$, determining the core velocity, at different values of κ.

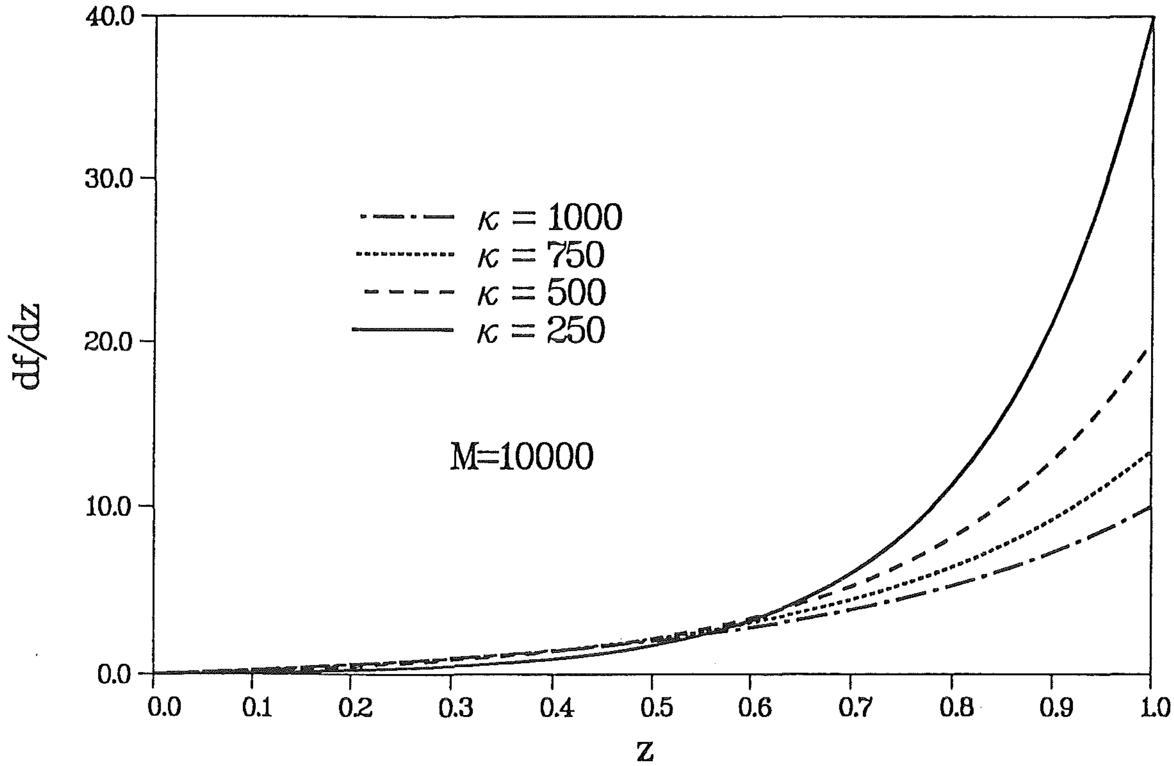


Fig. 4.3 Function $f'(z)$, determining the current, entering the top from the Hartmann layer, at different values of z.

4.4 Flow structure

When an electrically conducting fluid flows across magnetic field lines, a uniform current is induced in the core in the z-direction (see fig.4.1 and eq. $4.3c$). It enters the layer S at the side wall at $z=1$. Since the side wall is insulating, the current turns and flows within the layer almost along magnetic field lines. When the current approaches the corner $z=d$, $y=1$, it splits into two parts. The first part enters the conducting top through the coating with high resistance. The second part flows along the Hartmann layer in the $-z$-direction. The resistance of the Hartmann layer is also high, and equal to M. If there was no coating, all current would enter the top directly from the side layer. Only negligible amount of current would flow along the Hartmann layer. Since the coating is present, parts of current conducted by the top and the Hartmann layer are determined by the values of κ^{-1}, the conductance of the coating, and M^{-1}, the conductance of the Hartmann layer, provided $c \gg M^{-1}$, i.e. the top is much better conductor than the Hartmann layer. Since part of current leaves the Hartmann layer to the top at any cross–section $z=const$, the amount of current, flowing in the $-z$-direction in the former, decreases with z. This leads to variation of j_{zH} with z, and since $\boldsymbol{j}\times\boldsymbol{B}$ is to be balanced by viscous term (eq. $4.1a$), it results in variation of the velocity with z in the Hartmann layer and in the core.

If $\kappa \gg M$, the resistance of the insulating coating becomes very high. All current is conducted by the Hartmann layer. The channel may be considered as fully insulated with

$$k = M^{-1}, \qquad (4.10a)$$

$$v_C = f(x) = 1 . \qquad (4.10b)$$

If $\kappa=O(1)$ and $c \gg M^{-1}$, only a part of the top, which is above the side layers is affected by the presence of the coating (fig. 3.2a). The core velocity decreases to zero (to be more precise, it is of the order of $M^{-\frac{1}{2}}$), as in the case of no insulation.

If $c \gg M^{-1}$ and $1 \ll \kappa \ll M$, the core velocity reads

$$v_C = f(z) = kM \exp\left[\sqrt{\frac{M}{\kappa}}\,(z-d)\right] , \qquad (4.11a)$$

where

$$k = \frac{dc}{c\sqrt{M\kappa} + d(1+c)} . \qquad (4.11b)$$

The velocity profile is virtually like that with thick layers of thickness $O(\sqrt{\kappa/M})$. According to the terminology used by Walker (1981), these "layers" may be called as outer ones, while the usual side layers of thickness $O(M^{-\frac{1}{2}})$ are called as inner ones. We would like to stress, however, that if κ is treated as being of the order M, these "outer layers" are obtained from the consideration of the equations governing the flow in the *core* under the boundary (and matching) conditions applied to the *core* variables with the only reference to the Hartmann layer. Hence, the "outer layers" are nothing special but parts of the core (eq. 4.6): in the center of the channel there is a uniform part, and the exponential functions describe the flow closer to the side walls.

Consider now a duct with all walls conducting. If side walls are conducting, the boundary condition

$$c\frac{\partial b}{\partial z} + b = c\kappa\frac{\partial^2 b}{\partial y^2} \ \text{at } z=1 \qquad (4.12)$$

holds. After introducing the stretched variable $\xi=\sqrt{M}(z-d)$, and assuming that $c>>M^{-\frac{1}{2}}$ it reads

$$\sqrt{M}\frac{\partial b}{\partial \xi} = \kappa\frac{\partial^2 b}{\partial y^2} \ \text{at } \xi=0 . \qquad (4.13)$$

The order–of–magnitude arguments show that if $\kappa<<\sqrt{M}$ the side wall is not affected by the coating and may be considered as perfectly conducting. Only a part of the top above the side layer is affected. This may lead only to the different profile of the side–wall jet along magnetic field lines, with respect to the case of no insulation. If κ becomes much higher then $\sqrt{M}$, the side wall becomes insulating, but the top wall is still good conductor, except in the vicinity of the side wall of thickness of the order $\sqrt{\kappa/M}$, where the outer layer is formed (see eq. 4.6). This gives a velocity profile a) on fig. 3.2. Then the asymptotic solution, derived in this section and the discussion apply with all consequences for changes of the velocity profile reflected on fig. 3.2. Hence, when κ increases from zero to infinity, first the side wall becomes insulating, and then the flow structure is determined by the Hartmann layer.

5. Conclusion

Insulating coatings at channel walls reduce the pressure drop by orders of magnitude, even if no perfect insulation is achieved. MHD–flow conditions close to the perfect insulating case are achieved, if the nondimensional coating resistance κ is one order of magnitude larger than the Hartmann number M $(\kappa >> M)$. The nondimensional MHD—pressure drop is of the order of M^{-1} which is extremely small for fusion relevant applications, where the Hartmann number is of the order $M = 10^4 \div 10^5$. Under such conditions poloidal blanket concepts become very attractive, due to their simpler design.

However, one should be careful if the value of κ may fall below the value of M initially or during the operation time of a fusion blanket. A reduction of κ can be caused for example by impurities in the ceramic, by corrosion, by irradiation damage or by small cracks. If κ lies in the intermediate range $1 << \kappa << M$ the pressure drop may still be at acceptable values. However, the velocity distribution in the channel cross section may become unsuitable for efficient convective heat removal. If κ approaches the order $\sqrt{M}$ nearly the whole core becomes almost stagnant. For smaller values of κ $(\kappa << 1)$ the velocity profile tends to the slug flow profile as in highly conducting channels, but at the same time the pressure drop exceeds the tolerable limit.

In the intermediate range of k one of the suggestions to the designers is to use ducts with cross section other than rectangular, or to turn rectangular ducts at certain angle to the magnetic field. This allows to avoid undesirable velocity profiles with stagnant regions. The cost for this is only relatively small increase in pressure drop.

The flows in ducts with non–perfect insulation can be considered from another point of view, namely as flows in ducts with contact resistance on the fluid–wall interface. These may be present in laboratory experiments, if electrical contact between the fluid and the walls is poor. It especially holds for such working fluids as mercury. The most probable reason for the deviation between some classical theoretical and experimental results on fully developed flows in rectangular ducts (see Branover 1978) is the contact resistance between mercury and copper, so that the deviation is caused by the effects described in this paper.

In the present paper we present only the results on fully developed flows in rectangular ducts. Flows in ducts with more general geometries and three–dimensional flows will be considered in a journal paper.

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