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MHD FLOW TAILORING IN FIRST WALL COOLANT CHANNELS OF SELF-COOLED BLANKETS*

by

B. F. Picologlou, C. R. Reed and T. Q. Hua

Fusion Power Program
Argonne National Laboratory
9700 S. Cass Ave.
Argonne, IL 60439

L. Barleon, H. Kreuzinger
Institut fur Reactorbauelemente
Kernforschungszentrum Karlsruhe
Karlsruhe, FRG

J. S. Walker
Department of Theoretical and Applied Mechanics
University of Illinois
Urbana, IL 61801

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Kernforschungszentrum Karlsruhe
Karlsruhe, FRG

J. S. Walker
Department of Theoretical and Applied Mechanics
University of Illinois
Urbana, IL 61801, USA

ABSTRACT

MHD flow tailoring, the use of salient features of MHD flows in strong magnetic fields to create desirable velocity profiles in single ducts, presents the possibility of significant reduction in blanket complexity and cost, and enhancement of thermal hydraulic performance. A particular form of flow tailoring, involving ducts with alternating expansions and contractions lends itself to the design of first wall coolant ducts. The potential benefits of this configuration and its immediate applicability to blanket design have made it the choice as the first joint Argonne National Laboratory (ANL)/Kernforschungszentrum Karlsruhe (KfK) test on liquid metal MHD. Testing is being carried out at ANL's ALEX facility on a test article fabricated at KfK. A description of the test article, its important features, and the associated instrumentation are presented. A fully 3-D code capable of treating MHD flows in ducts of complex geometry has been developed and used in the flow trailoring experiments. The features and capabilities of the code are discussed and a sample of the code predictions for the geometry and conditions of the experiments are presented. A sample of the preliminary test results from the ongoing testing is also given.

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1. INTRODUCTION

In liquid-metal self-cooled blankets of magnetically confined fusion reactors, the electromagnetic (EM) body force acting on the liquid metal is several orders of magnitude larger than the viscous and inertia body forces everywhere with the exception of thin boundary layers and, in some instances, free shear layers. Outside these layers, the EM force is balanced by the pressure gradient. This balance, in conjunction with Ohm's law, determines not only the pressure distribution within the liquid metal but also the velocity distribution. Because magnetohydrodynamic (MHD) effects in liquid metal blankets result in large overall pressure drops and material stresses and in unconventional velocity distributions, the EM force has been largely viewed as an unavoidable shortcoming of liquid metal blankets that has to be dealt with, rather than a dominant factor that can be used to good advantage to simplify blanket design and improve thermal hydraulic performance. The latter view was advanced by Walker and Picologlou[1][2] under the general term of "MHD Flow Control". A particular type of MHD flow control, named flow tailoring, can achieve desirable non-uniform velocity profiles within a single duct by proper variation of duct wall thickness, duct cross sectional dimensions, and/or shape. Flow tailoring is particularly attractive in first wall coolant channels.

For blanket designs considered by Smith et al.,[3] and Ehst et al.,[4] the thickness of the thermal boundary layer on the first wall (which depends on the heated duct length and the average coolant velocity) is of the order of 1 cm. If the cross sectional dimension of the first wall coolant channels is much larger than 1 cm, the high average velocity required for proper cooling of the first wall will result in low average coolant temperature rise and lower energy conversion efficiency. Coolant ducts near the first wall channels must also have rather small cross sectional dimensions so that the coolant flow rate can be tailored to the spatially varying local volumetric energy deposition rate. Therefore, the combined requirements of high energy conversion efficiency and maximum allowable first wall material temperatures result in a large number of coolant ducts of small cross sectional area near the first wall. This increases blanket complexity and cost and tends to decrease reliability.

If flow tailoring is used in the first wall coolant channels, a desirable velocity distribution can be established within a single duct, thus reducing drastically the total number of required coolant ducts. A practical design using flow tailoring at the first wall coolant channels involves a series of adjacent poloidal ducts with expansions, contractions, and uniform cross section segments, such as the one shown in Figure 1. This arrangement guides the flow towards the first wall. The velocity adjacent to the first wall changes in the downstream direction, but it remains always higher than the average velocity, thus improving heat transfer. Further heat transfer enhancement is possible due to the non-zero transverse velocity component. In addition, flow tailoring results in increased volumetric flow in the first wall high velocity jets, which already carry a significant fraction of the total flow under normal circumstances, and may, under certain conditions, create flow instabilities in the vicinity of the first wall. Both these effects increase significantly heat transfer rates at the first wall.

The potential benefits of this configuration and its immediate applicability to blanket design have made it the choice as the first joint Argonne National Laboratory (ANL)/Kernforschungszentrum Karlsruhe (KfK) test on liquid-metal MHD. Testing is being carried out at ANL's ALEX facility with a test section fabricated at KfK. The design of the test section and the MHD analysis carried out by a 3-D computer code are presented. The code is an extension of the codes already developed by ANL/University of Illinois for treating 3-D MHD effects in round and square ducts. The codes, the first of their kind, have been validated by experiments carried out at ALEX. Samples of preliminary results of the testing are also presented.

2. ANALYSIS

Consider the steady flow of an incompressible liquid metal along a conducting duct with thin metal walls. The duct is aligned with the x-axis and is in a transverse magnetic field $B_y(x)$. The parameters governing the MHD flow in the duct are the Hartmann number, $M = B_y L \ (\sigma/\rho\nu)^{1/2}$, the interaction parameter, $N = \sigma B_y^{\ 2} \ L/\rho U_o$, the magnetic Reynolds number, $R_m = \mu\sigma U_o L$ and the wall conductance ratio, $C = \sigma_w t/\sigma L$. Here, L is a characteristic transverse dimension of the duct, t is the duct wall thickness, U_o is the average velocity in the duct, σ_w is the electrical conductivity of the duct wall, and μ, σ, ρ, ν are the magnetic permeability, the electrical conductivity, the density, and the kinematic viscosity of the liquid metal.

The product $C^{1/2} \ R_m$ gives a measure of the ratio of the induced to the applied magnetic field. Under blanket conditions $C^{1/2} \ R_m$ is at most $0 \ (10^{-2})$ and the induced magnetic fields can be ignored. Also, under tokamak blanket conditions N and M are $0(10^3)$-$0(10^5)$, making viscous and inertia effects unimportant throughout most of the flow except in very thin boundary and free shear layers. Therefore, the inviscid, inertialess equations and appropriate boundary conditions are used to solve for the flow outside these layers.

We will concentrate our attention on ducts of rectangular cross section with two sides parallel to the transverse magnetic field and we will confine the present discussion to the uniform field case where $B_y \ (x) = B_o$. Let the duct dimension in the z-direction be constant and equal to 2L and the duct dimension in the y-direction be 2La(x) where a(x) is the variable aspect ratio. The top and bottom walls at $y = \pm La(x)$, have equal thickness t. The side wall at z/L = -1 has thickness equal to t_1 and that at z/L = +1 has a thickness of t_2. The corresponding wall conductance ratios are C, C_1, and C_2.

Viscous effects are confined in thin Hartmann layers at the top and bottom walls whose thickness is $O(M^{-1})$ and side layers with $O(M^{-1/2})$ thickness at the side walls.[5] In fully developed flow, the core velocity outside these layers, U_c, is uniform and the voltage distribution is uniform in y and linear in z with a slope equal to U_cB_o. For $M^{-1} << C$, the current in the core closes through the top and bottom walls via the side walls and side layers. The side walls and side layers represent electrical resistances in parallel. For $C_1, C_2 >> M^{-1/2}$ the resistance associated with the side layer is much higher than that of the side wall and the core current flows across the side layer unchanged. Under these conditions, the details of the structure of the side layer are not important in determining the variables in the core. It is a straight forward matter to show that then the total flow carried by the side layer adjacent to the side wall of thickness t_1 is equal to $Q_c ta/6t_1(1 + C)$, where Q_c is the flow in the core. For a square duct (a = 1), equal wall thicknesses, $t = t_1$, and $C << 1$, the flow in the side layer is 1/6 of the flow in the core. The flow in the side layers is distributed parabolically in y.

If the aspect ratio of the duct changes in the downstream direction the core velocity, U_c, will also change. Then, axial voltage differences will be created and fully developed flow can no longer be sustained. The axial voltage differences will drive axial currents, both in the liquid metal and the conducting walls, which will adjust the fully developed voltage distributions. The velocity distributions in the core will also be adjusted so that Ohm's law in the liquid metal is satisfied as are all the conservation equations. The adjusted velocity distribution has higher velocities near the side walls and lower velocities near the center. In general, the higher the C of the side wall the lower the velocity shift toward the side wall and the lower the flow rate carried by the associated side wall layer. If, as would be the case in a first wall coolant channel, a higher velocity is required only on one side, a skewed velocity profile can be created by making C_1 and C_2 unequal.

The governing equations and boundary conditions are discussed in detail by Hua et al.[6][7] Briefly, for the inertialess, inviscid core of the flow, the fully 3-D solution for the pressure, the voltage, the three components of the current density and the three components of the velocity is reduced to solving four coupled partial differential equations for four unknown functions of two space variables, namely the pressure p (x,z), the potential at the top wall ϕ_t (x,z), the potential of the first side wall ϕ_1 (x,y), and the potential of the second side wall ϕ_2 (x,y). The necessary boundary conditions for solving the four partial differential equations are supplied by boundary conditions at two different x stations, matching conditions for electric potential and current at the corners, and the requirement that the total flow rate in the core and the two side layers be constant at all axial locations.

A numerical code for treating arbitrary variations of the aspect ratio with x, arbitrary values of C, C_1, and C_2, and arbitrary variations of B_y with x has been developed. At present the code is limited to cases with identical top and bottom wall thicknesses, and cases for which the axial magnetic field distribution, which must accompany any non-uniform transverse field distribution, is negligible. Moreover, it has been assumed that t, t_1, $t_2 \ll L$ and $M^{-1} \ll C$. Finally, the general treatment for spatially varying magnetic fields requires that $M^{-1/2} \ll C_1, C_2$. For cases of uniform transverse magnetic fields, this restriction has been relaxed. To do so, existing analytical solutions of the side layers derived by Walker[5] have been used to compute the current entering the side wall and that which flows in the y direction through the side layer. It was important to relax this condition because for the experimental conditions to be discussed later and for many practical applications the assumption $M^{-1/2} << C_1, C_2$ is not satisfied. For these cases, the solution depends on the Hartmann number (the interaction parameter does not enter into consideration here because the solution is inertialess). As the Hartmann number increases, the solution becomes less sensitive on M. Beyond the point where $M^{-1/2} << C_1, C_2$ is satisfied, the solution becomes independent on M.

The chosen geometry for the test article of the joint ANL/KfK testing of the flow tailoring concept is shown in Figure 1. Figure 2 shows in more detail the segment between x/L = -4.8 and x/L = 0.0. The segment for x/L $\leq$ -4.8 as well as the segment for $0.0 \leq x \leq 4.8$ are given by the mirror image of Fig. 2. Note that since the solution is for inertialess flow, the direction of the flow is unimportant. The values of the conductance ratios corresponding to the actual test article are $C = C_1 = 0.014$ and $C_2 = 1.65$ and the value of L is equal to 5 cm. The solution is given in terms of non-dimensionalized coordinates x/L, y/L, and z/L. The scale of the test article, i.e., the actual value of L, enters into the solution only through the value of M.

It is possible to obtain a solution for the entire configuration from a large negative x/L, where the flow is fully developed in the large uniform cross section duct, to a large positive x/L, where the flow is fully developed in the smaller uniform cross section duct. This would require considerable computational time as a result of the large number of nodes in the finite differencing scheme. Instead, the problem is solved as a composite of three different solutions: a) A solution from x/L =-18.5, where fully developed solution is assumed, to x/L = -4.8, where a symmetry boundary condition (no axial current density) is assumed; b) A solution from x/L = -4/8 to x/L = 0, where at both axial locations a symmetry boundary condition is applied; and c) A solution from x/L = 0, where a symmetry boundary condition is applied, to x/L = 11.5, where a fully developed flow boundary condition is assumed.

The validity of this scheme was demonstrated by comparing solutions a) and b) at their common station $x/L = -4.8$, and solutions b) and c) at their common station $x/L = 0.0$. Differences were virtually imperceptible. This fact lends support to the method of composite solutions used here. It also provides a demonstration that, even for small conductance ratios of the order of 10^{-2}, three dimensional effects do not extend beyond distances of a few characteristic lengths. This is of practical importance in the blanket design process, in that it may allow several interconnected duct segments to be treated separately.

The solution provides a complete description of all variables. A few samples are shown here. Figure 3 shows the transverse top wall voltage distribution at $x/L = -2.4$, i.e., at the middle of the expanding section. Solutions are given for nominal Hartmann numbers of 6,000, 3,000, and 1,500, corresponding to experiments at magnetic flux densities of 2 T, 1 T, and 0.5 T. Note that, as explained earlier, the solutions are functions of the Hartmann number. The case for $M = \infty$ is that for which $M^{-1/2} \ll C_1$, C_2. Figure 4 shows transverse top wall voltage distributions at several stations. Note that because, for all practical purposes, the solutions are symmetric about $x/L = 0.0$, only negative x's need to be included here. For clarity, Figure 4 includes only the curves for $M = \infty$. In Figs. 4 and 5, the reference voltage for each x/L is taken to be that at the corner at $z/L = 1$. The characteristic velocity U_o used in the non-dimensionalization is the average velocity at the average cross sectional area ($x/L = -2.4$).

Figure 5 shows the transverse voltage distribution at the thin side wall at $x/L = -2.4$. The voltages are given with respect to the mid-point of the side wall. Note that, as M decreases, the thickness of the side layer increases. Therefore, more current flows in the side layer, and less current flows in the side wall. As a result, the voltage drop in the side wall decreases with decreasing M.

Figure 6 shows the axial velocity distribution at x/L = -2.4 at the plane y = 0. Note that as M decreases and the side wall voltages decrease (as shown in Fig. 5) the flow rate in the side layer decreases and the flow in the core is increased. Figure 7 shows the evolution of the axial velocity profiles with axial location. Figure 8 shows for x/L = -2.4 the transverse pressure distribution relative to the pressure at z/L = -1. Finally, Figure 9 provides the axial distribution of pressure at z/L = -1 over an entire cycle for the flow tailoring geometry, from x/L = -4.8 to x/L = +4.8. The pressures shown in Figs. 8 and 9 are non-dimensionalized by $\sigma B_o^2 U_o L$.

3. TEST PROGRAM

Testing is conducted at ANL's ALEX facility described by Reed at et al.[8] The test article fabricated at KfK is of the configuration given by Figs. 1 and 2. The overall length of the test article is 614 cm. Flow tailoring testing is confined to 54 cm, between x/L = -6 and x/L = +4.8. The cross sectional dimensions at x/L = -4.8 are 10 cm x 6 cm and those at x/L = 0.0 are 10 cm and 14 cm. The top, bottom and one of the sides are made of 1.5 mm thick austenitic stainless steel. Because a high wall conductance ratio was required for the other side, a laminated wall, fabricated by explosively bonding electolytic copper (3.8 mm thick) to stainless steel (6 mm thick), was used. The copper is facing the liquid metal side. The top and bottom plates are welded to the 6 mm SS plate.

Because the pressure rating of the test article was set at 1 MPa, a strongback to support all the 1.5 mm thick walls was designed. The test section must be electrically insulated from the strongback so as to preserve its electrical characteristics. This was done by using silicone rubber sheets cut to shape. Special procedures and fabrication methods allowing welding of small pressure taps and fine electrode wires on thin SS plates were developed at KfK.

The instrumentation of the test section includes the following: electrodes for measurement of the voltage distribution on the test section at the ten stations shown in Fig. 1 (9 electrodes at the top wall and 3 to 7 electrodes at the thin side wall). Ten pressure taps at the thin wall at x/L = -4.8, -3.6, -3.0, -2.4, -1.8, -1.2, 0.0, 1.0, 2.4, and 4.8 for the measurement of axial pressure distribution (e.g. see Figure 9); eight pressure taps at the top wall at z/L = 0 at the stations x/L = -4.8, -3.0, -2.4, -1.8, 0.0, 1.0, 2.4 and 4.8 for the measurement of transverse pressure differences (e.g. see Figure 8 for x/L = -2.4); and four flanges at x/L = -3.0, -1.8, 0.0, and 1.8 for insertion of probes traversing along the z-direction for the measurement of velocity profiles. The types of measurements and experimental techniques are the same as those reported by Reed et al.[9] for testing of previous test articles at ALEX.

The ongoing test program is divided into three phases. In the first phase, which has been completed, all the voltage distributions were measured for all test conditions. In the second phase, transverse velocity distributions (e.g. Figure 6) are being obtained at selected axial locations. The third phase, in which all pressure measurements will be performed, will conclude the test program. Measurements are taken at three different magnetic fields and six different flow rates, each differing from the previous one by a factor of 2. This scheme provides a range of M from 1,500 to 6,000 and a range for N from 2.10^2 to 10^5, with measurements at the same N but different M's included in the test matrix.

Data reduction and evaluation from the first phase of the experimental program is currently under way. Although final conclusions can only be drawn after a thorough study and evaluation of the data is completed, a preliminary assessment is that agreement between measured and predicted voltage distributions is very good. This is demonstrated by the data given in Figs. 3 and 5 for the middle of the expanding section at M = 6,000, and N = 1.2×10^4

The flow tailoring test article contains two instrumented locations (with electrodes, pressure taps, and penetration flanges) at the uniform duct segments upstream and downstream of the flow tailoring segment. Following completion of the flow tailoring test program, testing at these locations, both in uniform and non-uniform magnetic fields, will be performed. Such testing, conducted on rectangular ducts with unequal side wall thicknesses and different aspect ratios, will complement similar testing completed on a square duct at ALEX and reported by Reed.[9]

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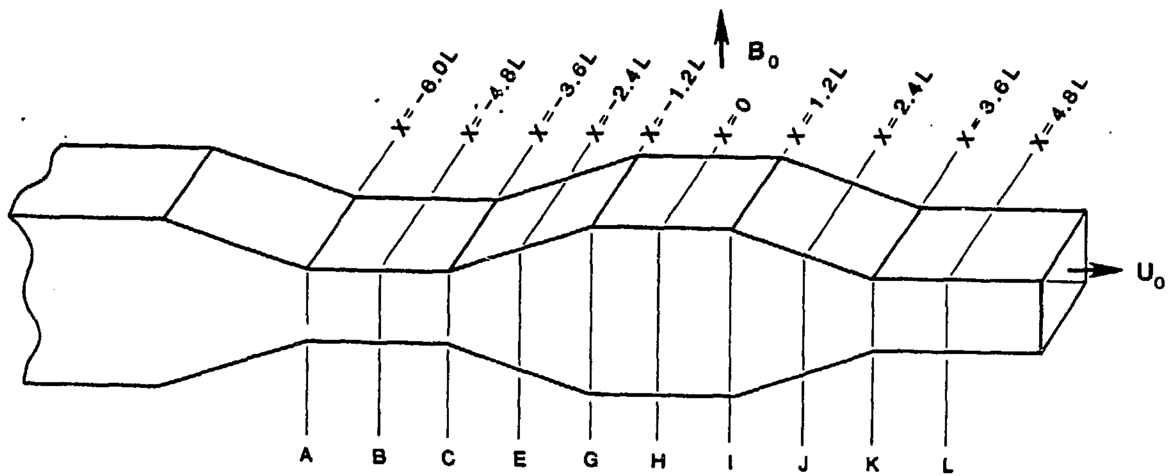
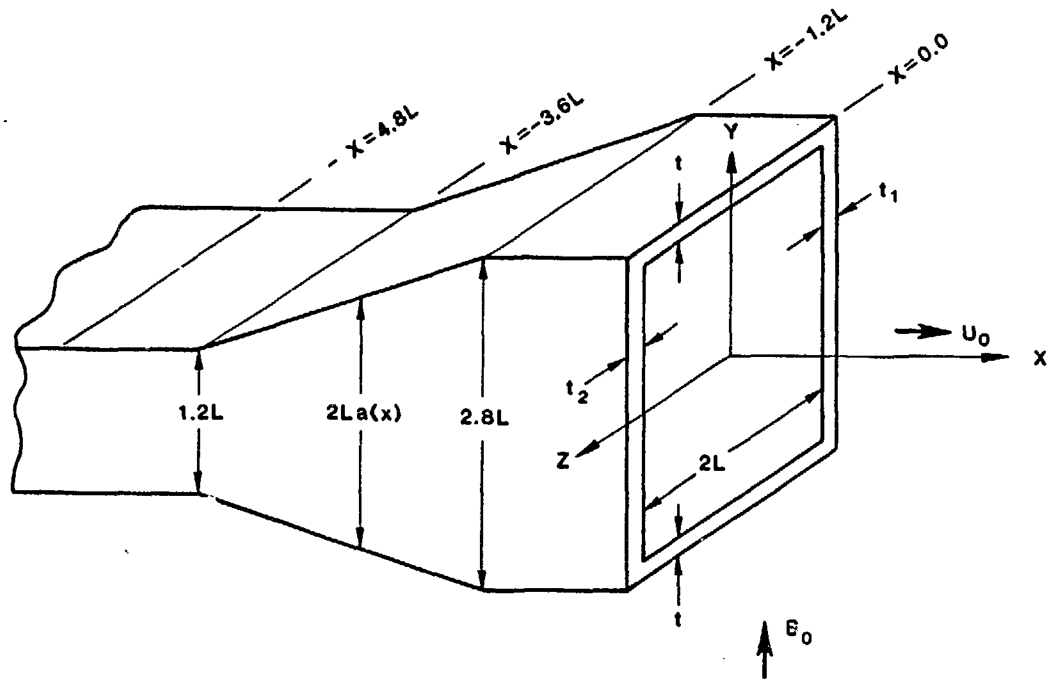


Figure 1. Picologlou et al



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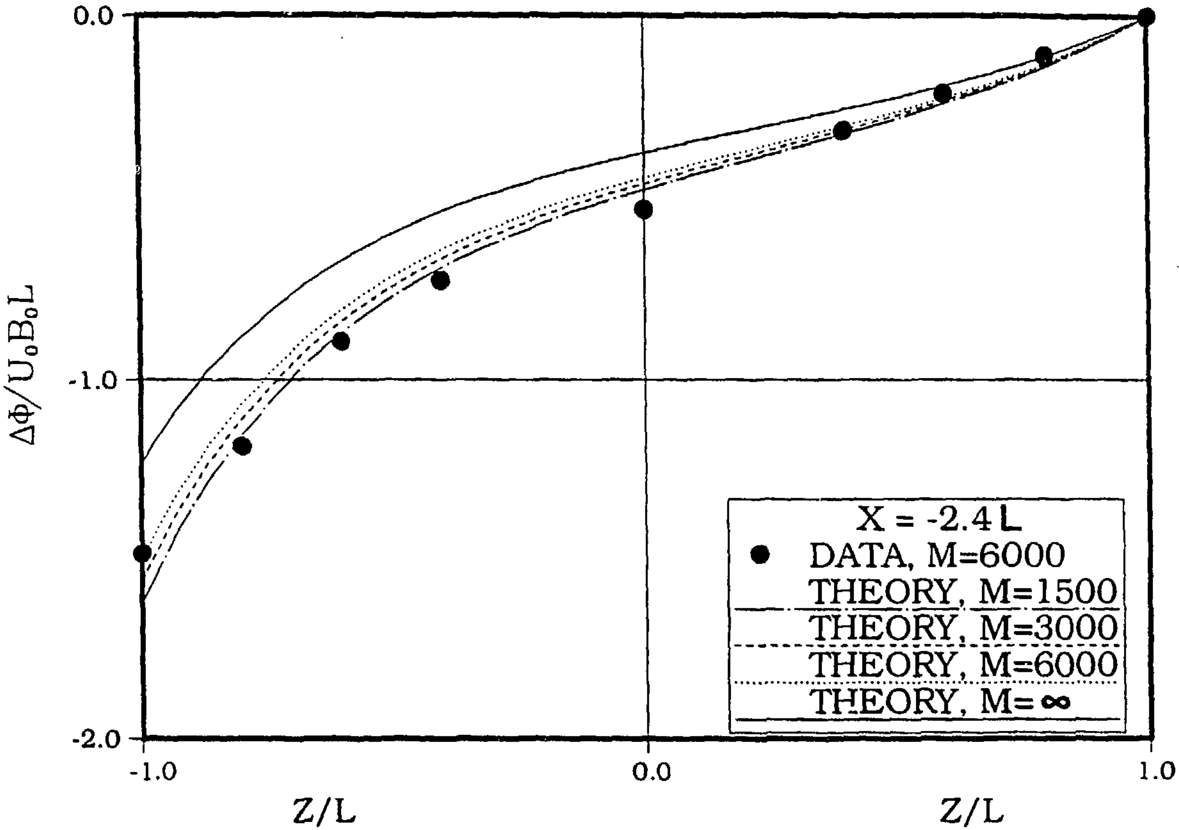

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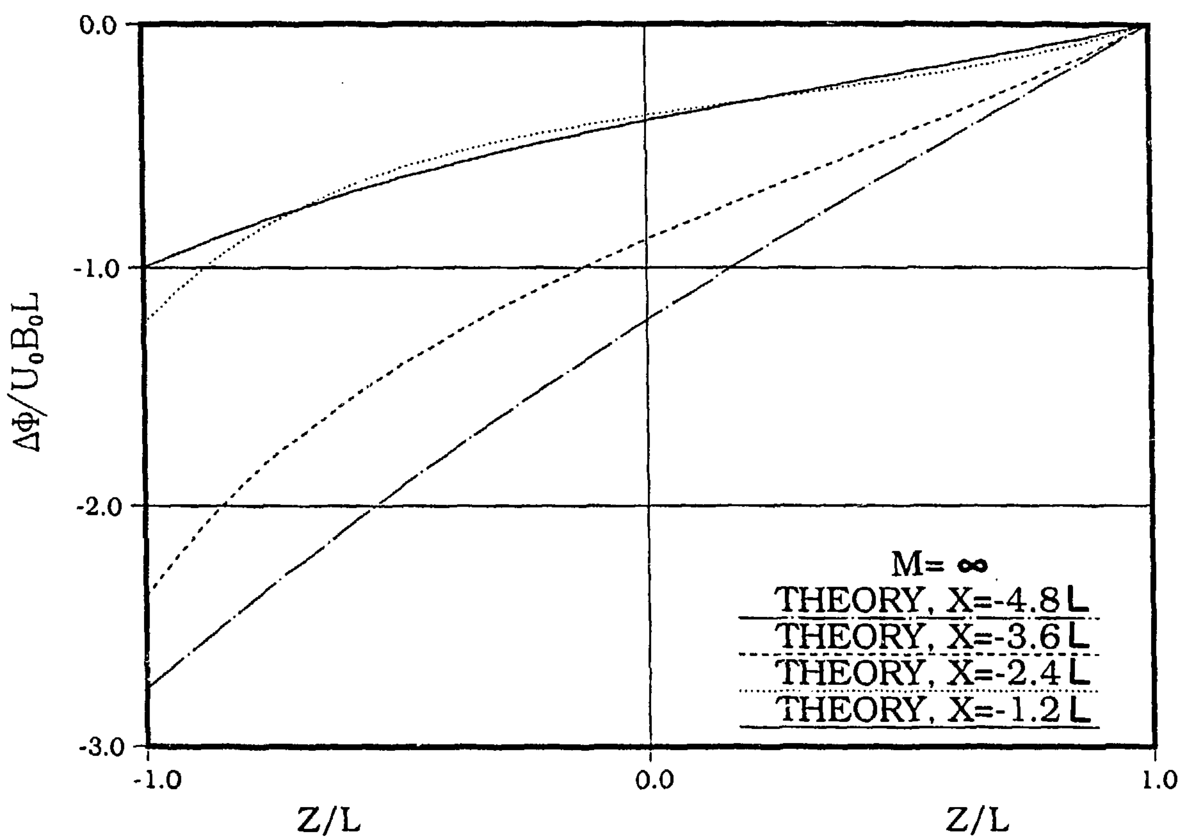

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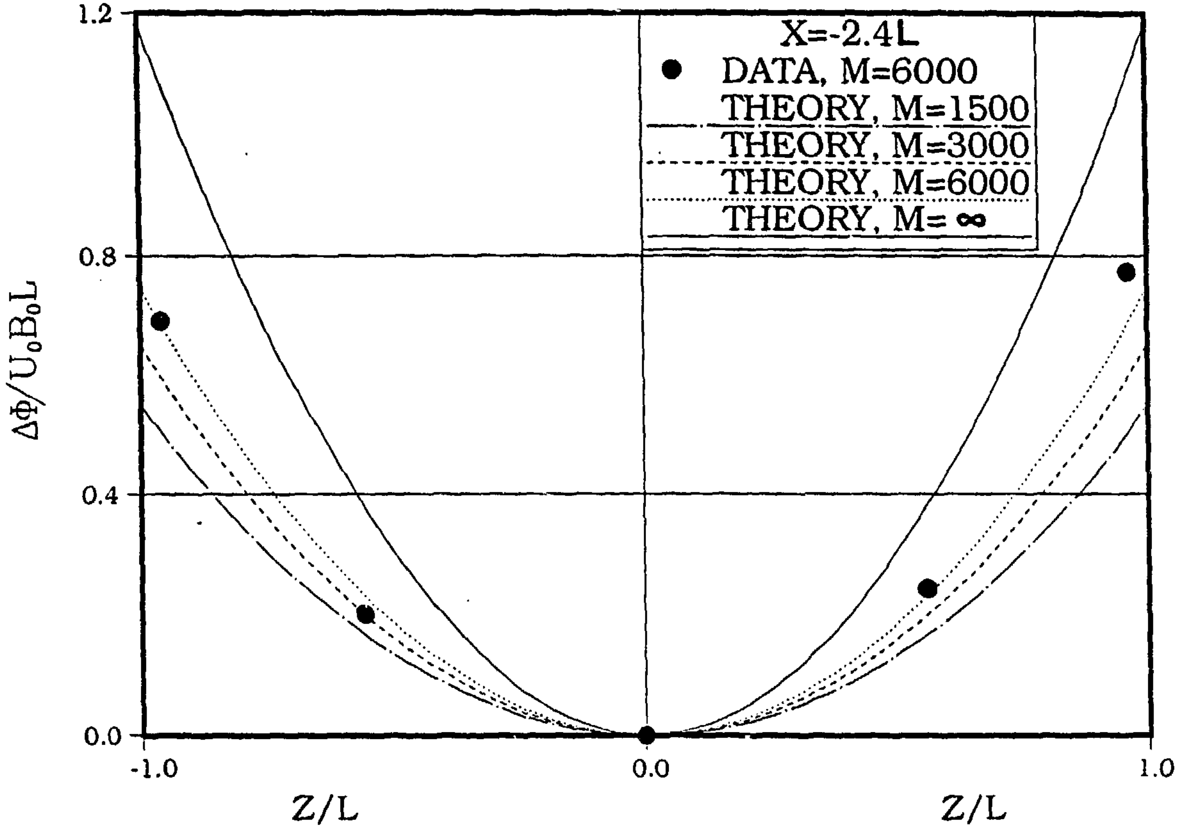

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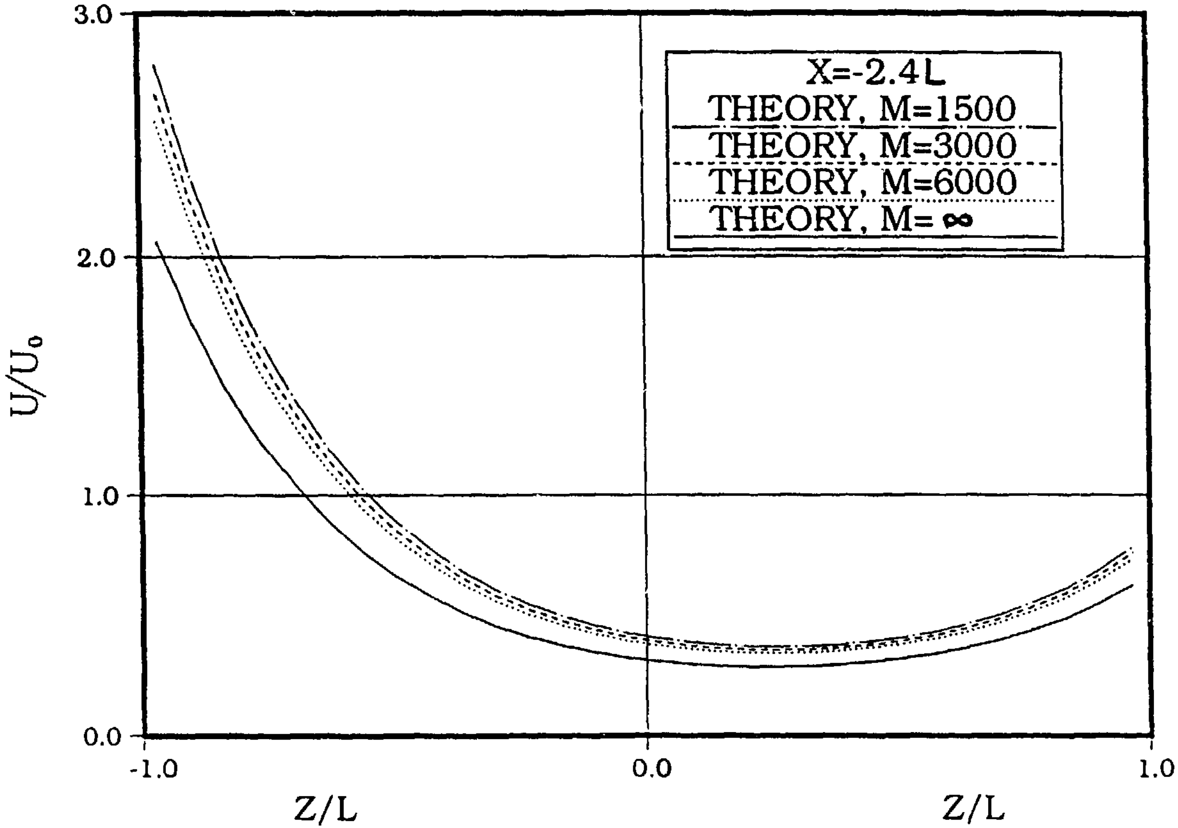

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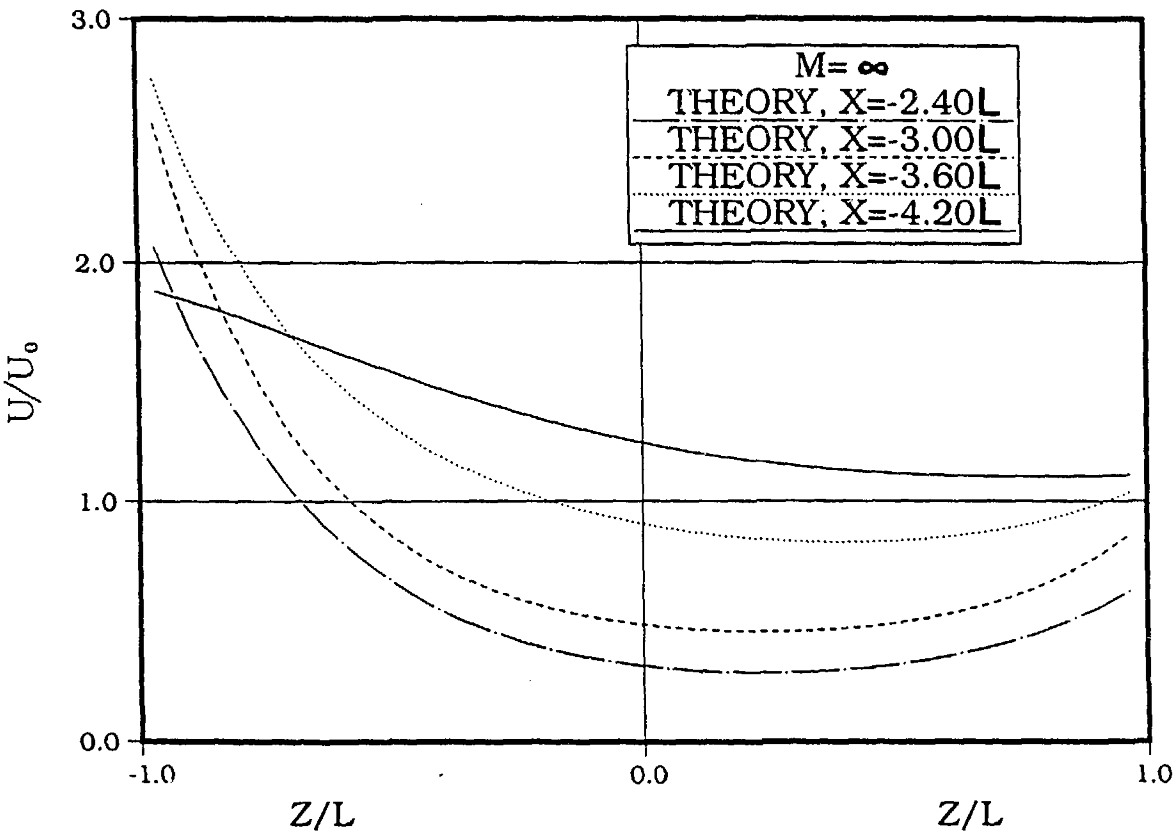

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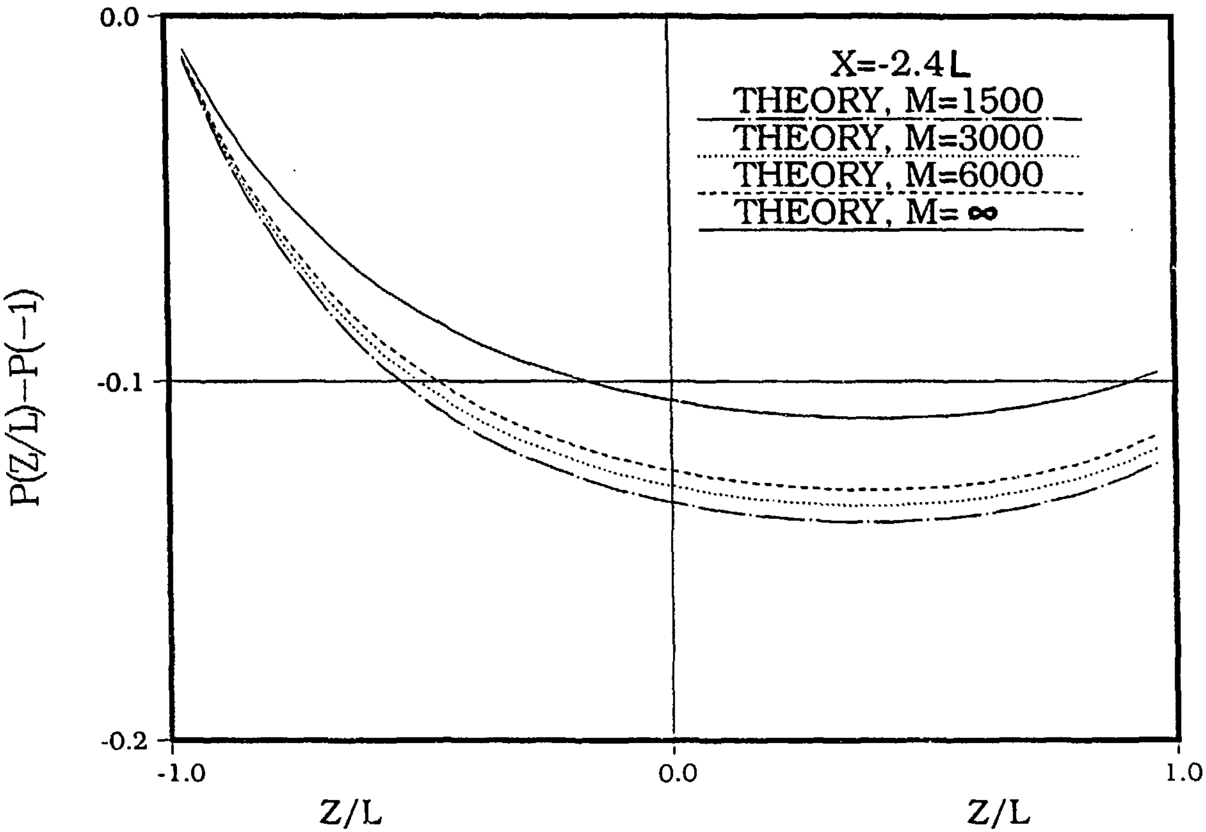

Figure 8. Picologlou et al

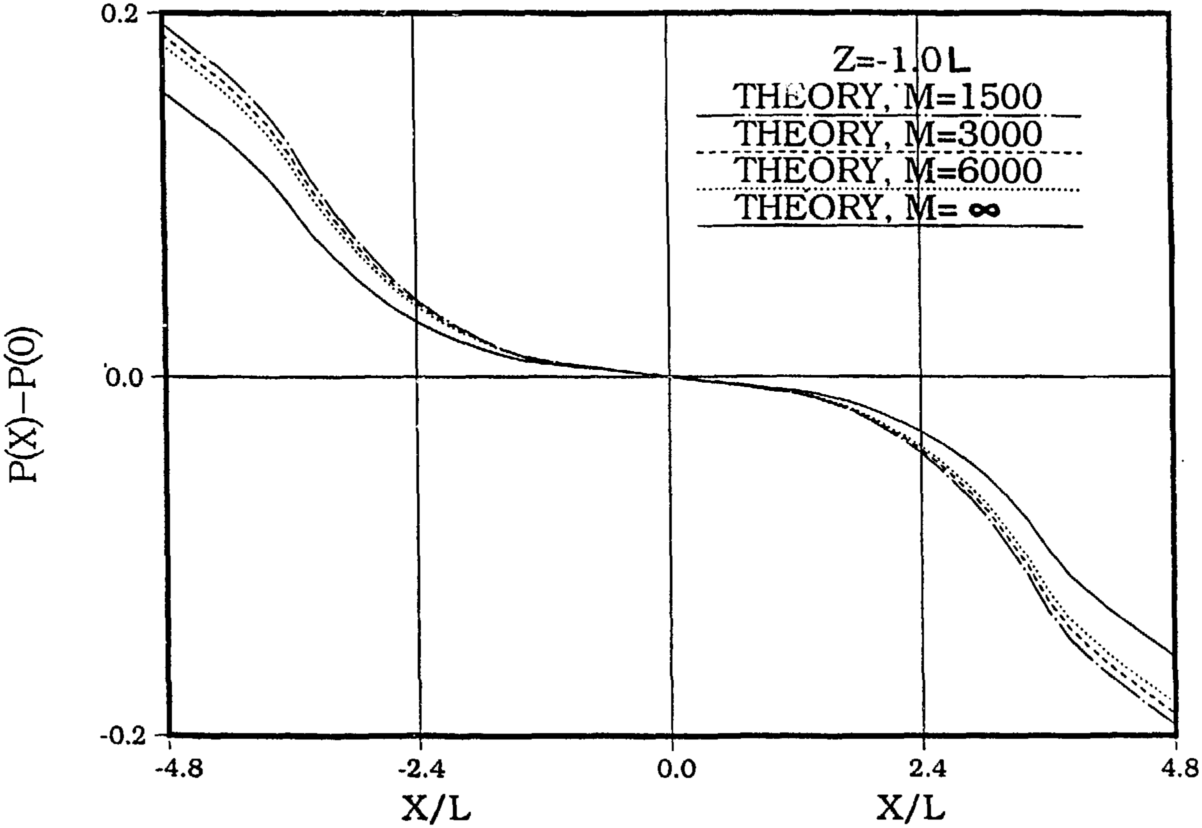

Figure 9 Picolyclou et al