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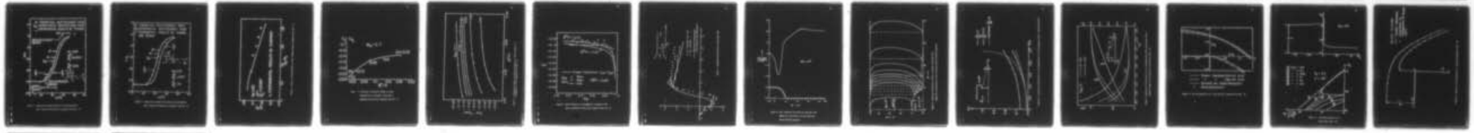

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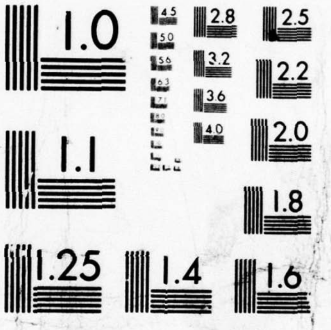

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The base pressure associated with supersonic axisymmetric flow past a backward facing step employing previously developed analysis of recompression, reattachment, and redevelopment processes, has been calculated for small supersonic approaching flow Mach numbers with thin initial boundary layers. The model of dealing with transonic flow past a backward facing step in two-dimensional or axisymmetric configuration has been successfully developed. Large scaled calculations of the turbulent Navier-Stokes equation based on the "two-equation model" has been carried

over

20. ABSTRACT CONTINUED

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SEPARATED FLOW PROBLEMS WITHIN THE TRANSONIC AND SUPERSONIC FLOW REGIMES

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FOREWORD

This is the final report prepared for U.S. Army Research Grant DAAG 29-76-G-0199. Dr. Robert E. Singleton of the Army Research Office served as technical monitor, and Dr. Donald J. Spring of the Army Missile Research and Development Command served as scientific liaison representative for this grant.

SUMMARY

Research activities carried out under the support of the U.S. Army Research Grant DAAG29-76-G-0199 are briefly described under the following four categories:

1. The base pressure associated with supersonic axisymmetric flow past a backward facing step employing previously developed analysis of recompression, reattachment, and redevelopment processes, has been calculated and reported for small supersonic approaching flow Mach numbers with thin initial boundary layers.
2. The model of dealing with transonic flow past a backward facing step in two-dimensional or axisymmetric configuration has been successfully developed.
3. Large scaled calcualtions of the turbulent Navier-Stokes equation based on the "two-equation model" has been carried out for the low speed flow past a two-dimensional backstep where a considerable amount of hot-wire data is available for compression and good description of the overall flow pattern has been obtained.
4. Numerical calculations of the potential flow after hodograph transformation have been proved to be fruitful by solving many previously unsolved problems where the effect of gravitation predominates.

Additional future work related to these topics have been mentioned and discussed.

1. Introduction

In the summer of 1975, a research proposal entitled "Separated Flow Problems within the Supersonic and Transonic Flow Regimes" was prepared by the author and submitted to the U.S. Army Research Office. It was felt at that time that

A. The component analysis of studying turbulent separated flows has been improved as a result of detailed study of recompression and reattachment process[1,2];

B. This analysis was built up on a firm and valid foundation;

C. The same study may be readily employed for separated flow problems in any other flow regimes; and

D. Its application to problems within the transonic flow regime would have considerable practical merits.

After the grant DAAG 29-76-G-0199 was awarded, research on separated flow problems was carried out with the emphasis on the transonic flow problems. Indeed, a model was developed specifically for problems of a transonic flow past a backward facing step in the two-dimensional or axisymmetrical configurations. Based on this study, it has also been verified that the base drag increases drastically as the free stream Mach number approaches sonic. The present report serves to present a brief account of activities carried out under the sponsorship of this grant. No attempt will be made to review these research activities in detail. References of publications will be mentioned and cited whenever possible.

A brief review of these research activities is given in the next section.

2. Research Activities carried out under the Support from the Army Research Office through Research Grant DAAG 29-76-G-0199

Research conducted within the last three years under the sponsorship of the Army Research Office may be categorized in the following areas:

A. Base pressure problems of axisymmetric supersonic flow

B. Base pressure problems within the transonic flow regime

C. Large scale calculations of the turbulent Navier-Stokes equation based on the two-equation model

D. Numerical calculations after the hodograph transformation

They are briefly described in the following sections.

2.1 Base Pressure Problems of Axisymmetric Supersonic Flow

Since the detailed study of recompression and reattachment of a turbulent free shear layer was carried out[1], it was obvious that this integral analysis was very useful in describing the process of recompression and reattachment for any separated flow problems. However, it was also shown that due to the streamline curvature effect during recompression which is important for supersonic turbulent base pressure problems, the pressure across the shear layer is no longer uniform, and a correction to the Prandtl boundary layer concept is necessary in turbulent recompression process when the external flow is supersonic. It would be naturally expected that the process of redevelopment after reattachment is also a process of relaxation of this pressure difference across the shear layer[2]. This study has been extended to treat the axisymmetric supersonic flow[3]. Although this method seems to yield good estimation of the base pressure and the pressure distribution throughout the recompression region for cases of thin initial boundary layer (Figs. 1, 2, and 3), it has been recognized that the quenching of turbulence due to the expansion around the corner, would introduce considerable "rotation" of the "inviscid stream" for relatively thick initial boundary layers and this effect has not been accounted for. This phenomenon would also be much pronounced for relatively high approaching Mach numbers. Future activities in this area should strive to improve this aspect of the problem.

2.2 Base Pressure Problems within the Transonic Flow Regime

Concurrent with the improved study of turbulent recompression and reattachment, the capability of calculation of transonic flows has been tremendously improved (see Ref. 4 and the materials cited therein). The validity of these calculations may be verified even when the situation of strong viscous interaction occurs[5,6]. Naturally, transonic base pressures should offer themselves as challenging problems.

A model has been developed to deal with a transonic flow past a backward facing step whether it is in a two-dimensional[7] or axisymmetric configuration[8,9]. The basic idea lies in the establishment of a corresponding inviscid body geometry which relies upon a certain characteristic parameter and the governing viscid-inviscid interaction is manifested from the fact that this characteristic parameter is to be determined from the viscous flow analysis. For a backward facing step geometry, the equivalent body within the separated flow region assumes a functional form of a polynomial. Once this geometry with a selected characteristic value is specified, the corresponding inviscid transonic flow field can be established through numerical calculations. The viscous flow processes such as mixing, recompression, and reattachment can be built up and described with the already established corresponding inviscid flow providing the guiding free stream. It has been observed that the point of reattachment behaves as a saddle point singularity for the system of equations describing the viscous process of recompression which provides the criterion to determine the correct value of the characteristic parameter. Detailed description of these analyses may be found in Refs. 7,8,9.

It should be emphasized that the selection of a polynomial functional form seems to limit the choice for the corresponding body geometry within the separated flow region. It turned out that the solution established thus far only serves as an initial approximation to the problem since the corresponding inviscid body geometry compatible to the established viscous flow is at a distance of the "displacement thickness" of the viscous layer away from the viscous dividing streamline. Additional closer approximation to the problem would require iteration of the corresponding inviscid body geometry[10]. It is believed that few iterations would completely eliminate the arbitrariness in the selection of a polynomial functional form. In addition, this process of iteration should converge quickly since it is well known that the influence of Reynolds number is very small as long as the Reynolds number is very large. Although a higher order of iteration has not been carried out, it is believed that the results of base pressure would be fairly insensitive to these corrections of the corresponding inviscid body geometry. Results of these studies are shown in Figs. 4, 5, and 6. It is obvious that the base pressure decreases quickly as the approaching flow tends toward sonic Mach number.

2.3 Large Scaled Calculation of the Turbulent Navier-Stokes Equation based on the Two-Equation Model

Large scaled calculations of the Navier-Stokes equation seems to be the trend of future method of solving the fluid dynamic problems. One of the major difficulties of calculating the turbulent Navier-Stokes equation lies in the estimation of the transport coefficients. Recent methods of dealing with these problems are based on the turbulence modeling by describing the variation of the turbulent kinetic energy and the length scale based on dissipation. In order to learn what this two-equation model can do for a specific practical situation where considerable experimental data obtained from hot-wire anemometers are available[11], large scaled calculations of the two-dimensional flow past a backstep under low speed flow condition was first carried out. It was found that the wall pressure distribution has a similar trend and level as that obtained from the experimental investigation (see Fig. 7). However, the location of the peak pressure and the point of reattachment occurred one step height upstream when compared with measurements. This point of discrepancy leads to the question whether the experimental data were obtained under the truly two-dimensional condition. Future experimental investigation should clarify this point.

Additional calculations of the flow past a smooth curved configuration (which was obtained from an insert into the backstep) have also been performed for both laminar and turbulent flows. Results are shown in Figs. 8 and 9. Future experimental verification of these results is being planned.

2.4 Numerical Calculation of the Potential Flow based on the Hodograph Transformation

One important activity which has been carried out within the research program was the numerical calculation of potential flow field based on the hodograph transformation. The efficacy of such an approach was first established and verified by reproducing contracting coefficients of jets for incompressible flow and predicating these coefficients for compressible flow[12], where previous results were produced only through tangent gas approximations. Subsequently, it has been shown that previously unsolved problems in the area of open channel flows[13] where the gravitational influences predominate, can easily be solved through this approach. The problem of a free overfall has been solved in this manner[14]. The problems of a sluice gate and the sharp crested weir have also been examined and will be reported in a Ph.D. thesis dissertation[15]. Indeed, this approach seems to be very fruitful and promising. Figures 10 through 14 present some of the results obtained from these calculations. It is also true that this method of approach can be extended to bodies with curved boundaries, to compressible flows, and to flows with axisymmetry.

3. List of Publication formally Acknowledging Support of this Grant

a. Chow, W. L., and T. S. Shih, "Transonic Flow past a Backward Facing Step," AIAA J., Vol. 15, No. 9, pp. 1342-1343, 1977.

b. Liu, S. K., and W. L. Chow, "Base Pressure Problems associated with an Axisymmetric Transonic Flow past a Backward Facing Step," ME-TR-395-5, Dept. of Mech. and Ind. Engr., University of Ill. Tech. Report prepared for U.S. Army Res. Grant DAAG 29-76-G-0199, Nov. 1977, ADA050658.

c. Weng, C. H., and W. L. Chow, "Axisymmetric Supersonic Turbulent Base Pressures," AIAA J., Vol. 16, No. 6, 1978, pp. 553-554.

d. Liu, S. K., and W. L. Chow, "Numerical Solutions of the Compressible Hodograph Equation," AIAA J., Vol. 16, No. 2, pp. 188-189, 1978.

e. Chow, W. L., T. Han, and C. Wu, "Hydrodynamic Solution for Incompressible Flow as Influenced by Gravitation," AIAA J., Vol. 16, No. 10, 1978, pp. 1097-1098.

f. Liu, S. K., and W. L. Chow, "Base Pressures of an Axisymmetric Transonic Flow past a Backward Facing Step," AIAA J., Vol. 17, No. 4, 1979, pp. 330-331.

g. Chow, W. L., and T. Han, "Invisicid Solution for the Problem of Free Overfall," J. of Applied Mech., Vol. 46, No. 1, March 1979, pp. 1-5.

h. Warpinski, N. R., and W. L. Chow, "Base Pressure associated with Incompressible Flow past Wedges at High Reynolds Numbers," paper to be published by J. of Applied Mech..

4. Participating Scientific Personnel

The scientific personnel participating in this research program are listed below:

W. L. Chow, Professor of Mechanical Engineering, Project Director;

D. Sharma, Consultant, part-time basis;

S. K. Liu, Research Assistant, Ph.D. Degree obtained in Oct. 1977;

T. Han, Research Assistant, will receive Ph.D. Degree in Oct. 1979;

A. Nakayama, Research Assistant;

P. Chan, Research Assistant;

C. M. Rhie, Research Assistant.

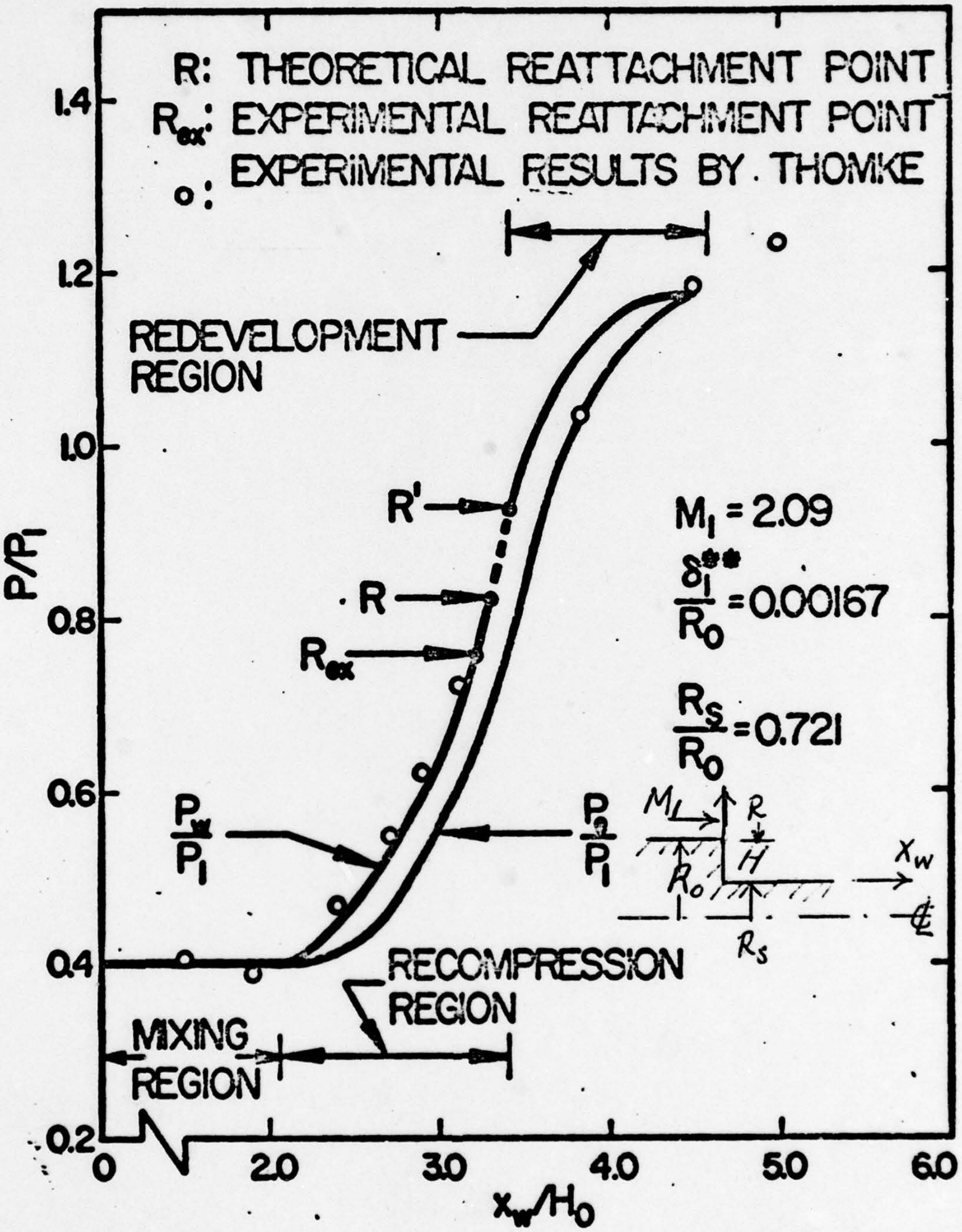

Figure 1 Comparison between Numerical and Experimental Wall Pressure Distribution (adapted from Ref. 3)

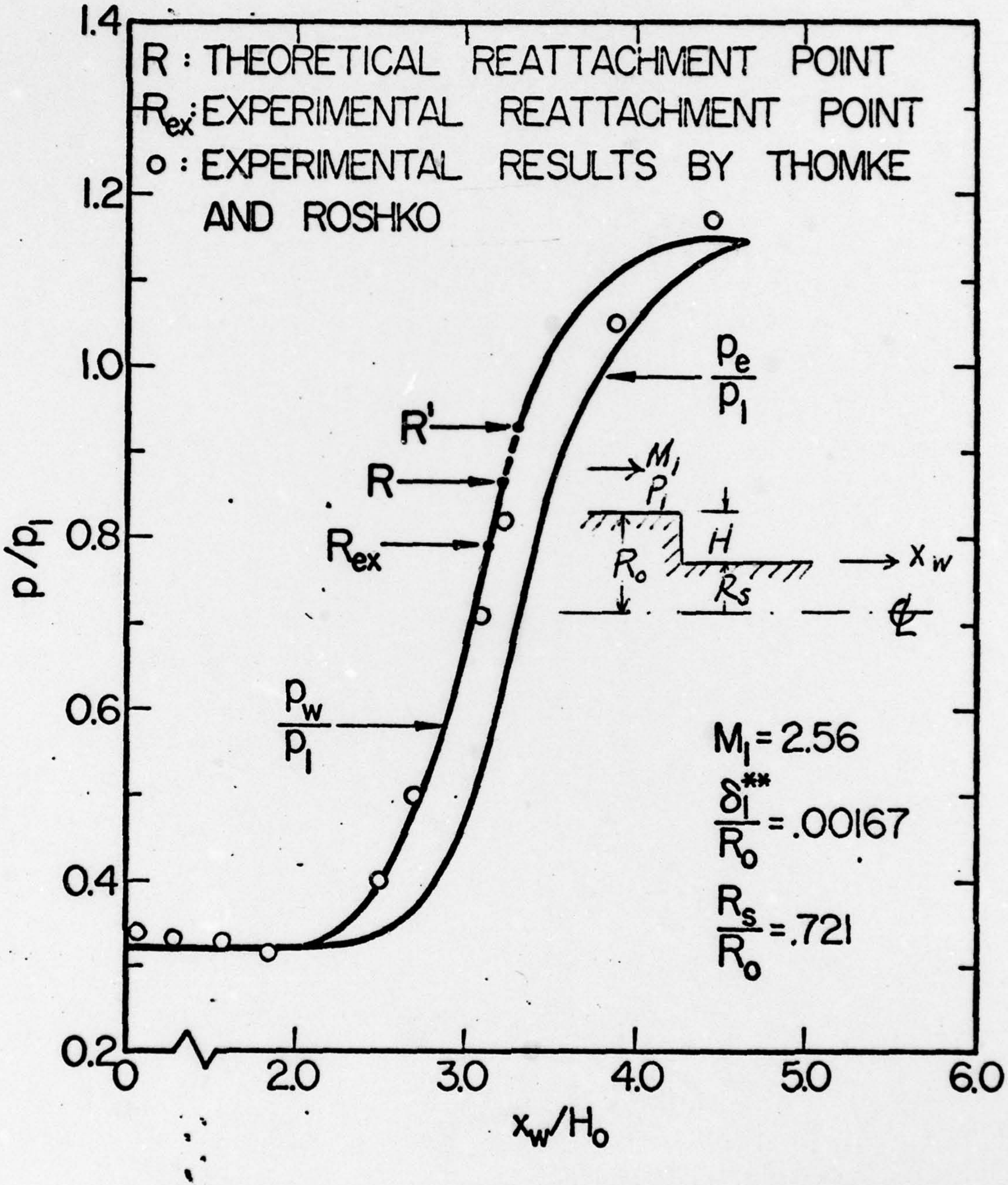

Figure 2 Comparison between Calculated and Experimental Wall Pressure Distribution (adapted from Ref. 3)

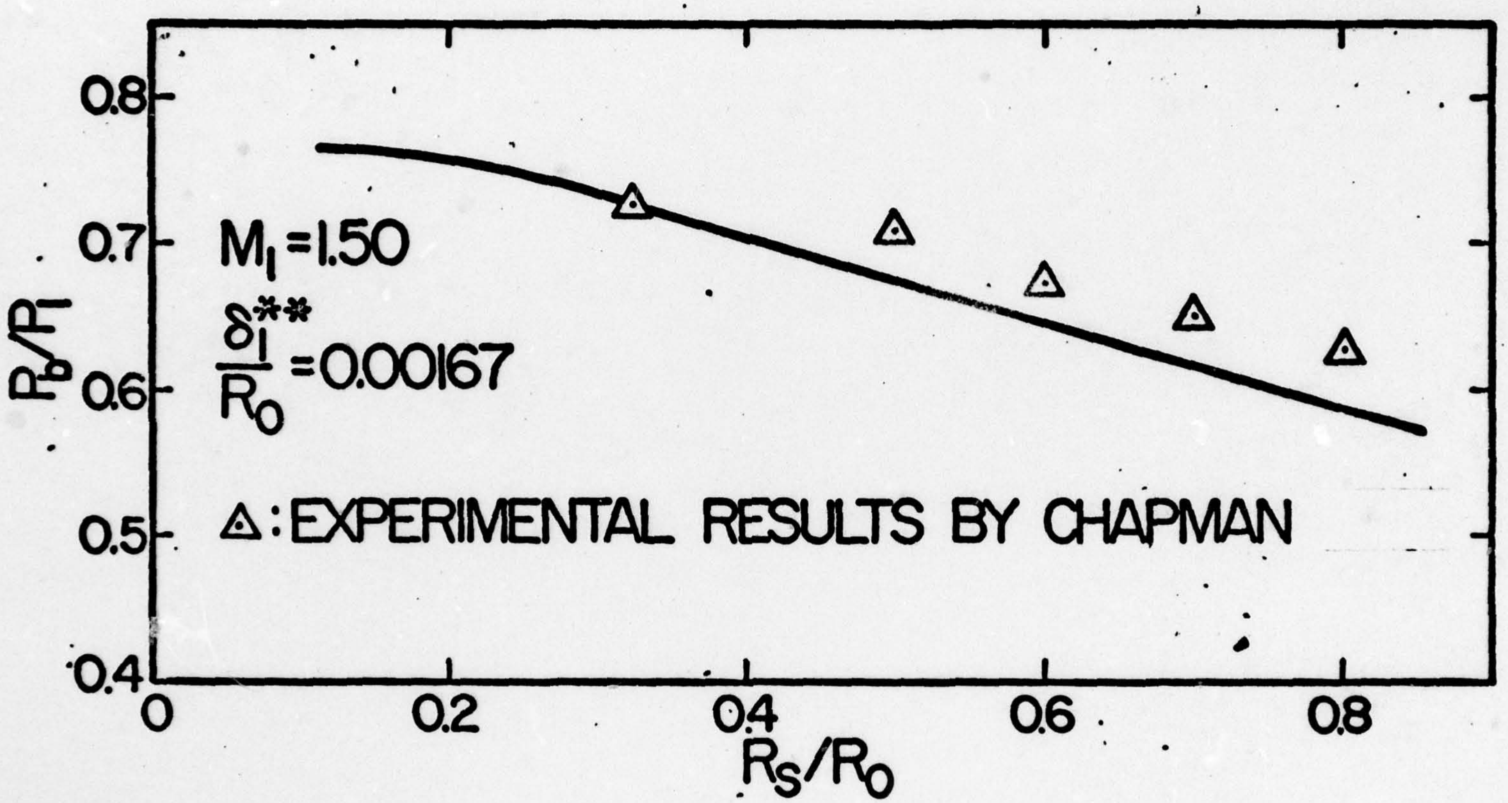

Figure 3 Effect of Sting Radius on Base Pressure Ratio (adapted from Ref. 3)

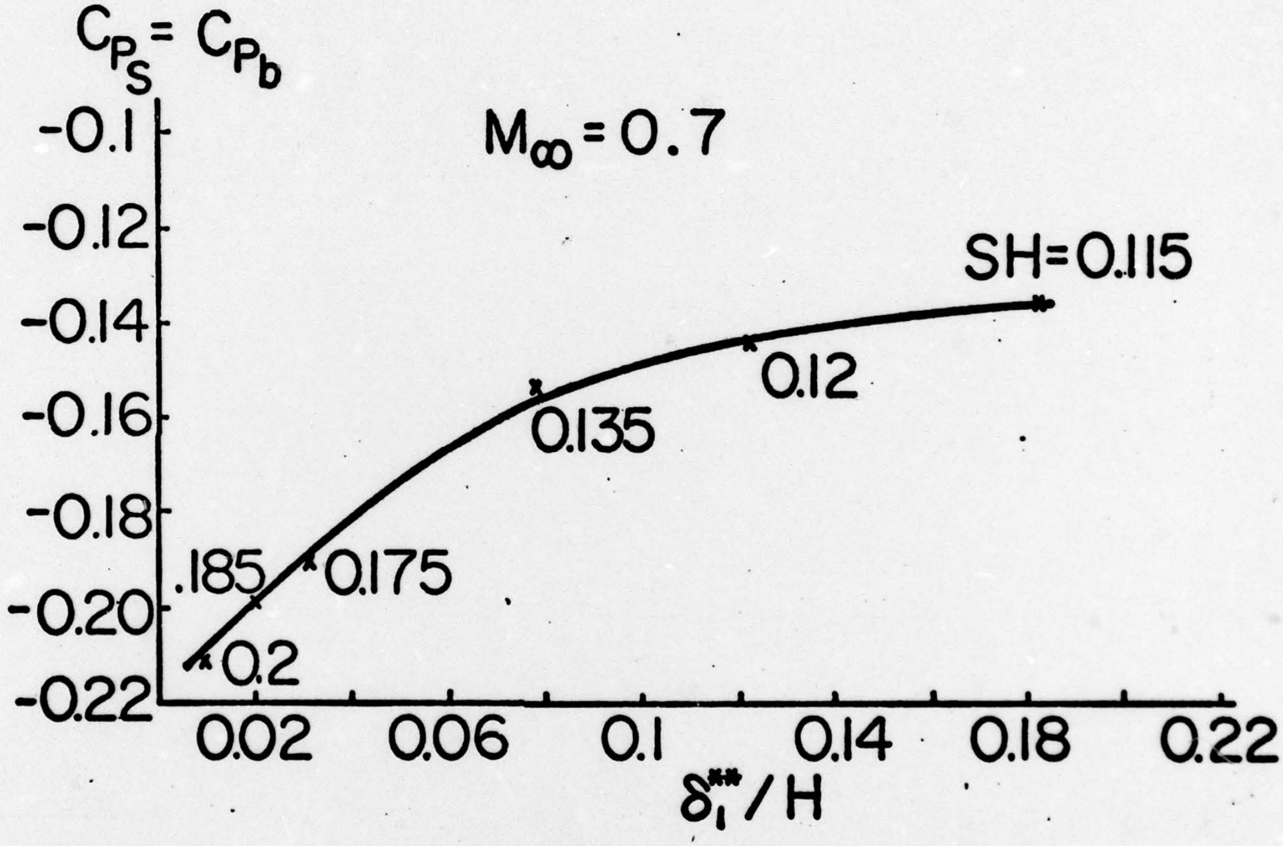

Figure 4 Influence of Reynolds number on Base Pressure for a Transonic Flow past a Backward Facing Step (adapted from Ref. 7)

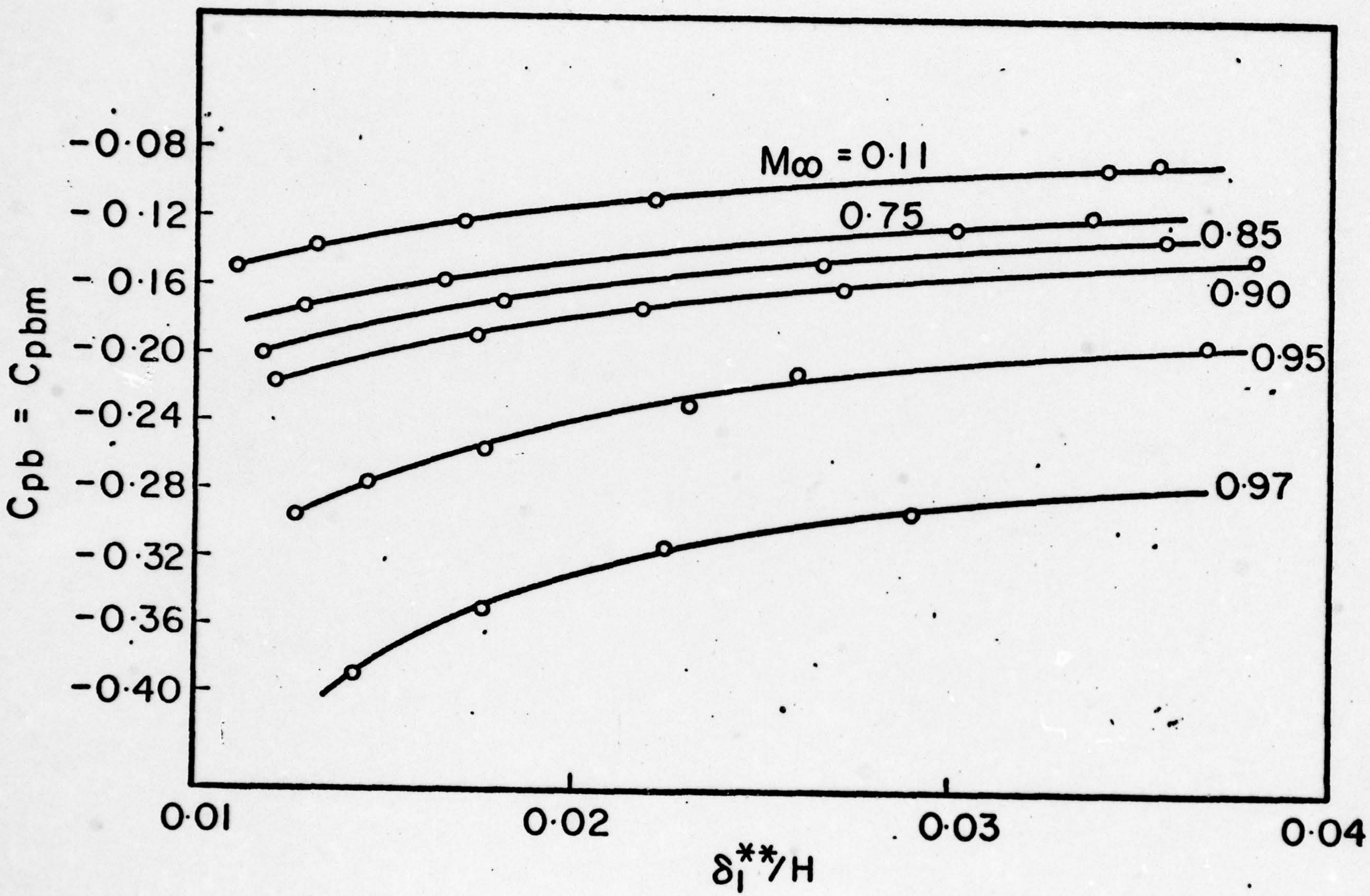

Figure 5 Influence of Mach and Reynolds Numbers on Base Pressure in Axisymmetric Flow (adapted from Ref. 9)

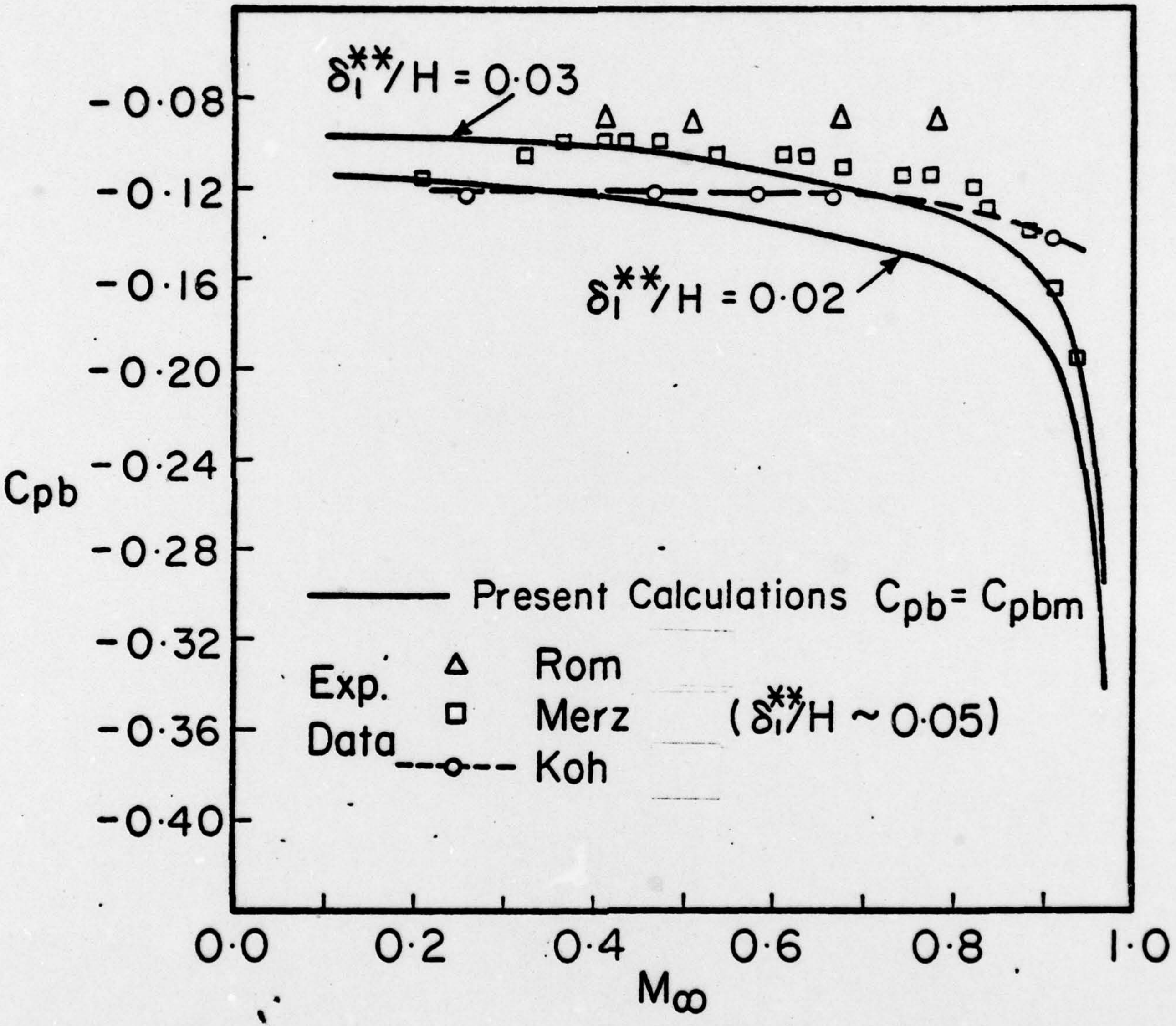

Figure 6 Base Pressures of Axisymmetric Transonic Flow past a Backward Facing Step (adapted from Ref. 9)

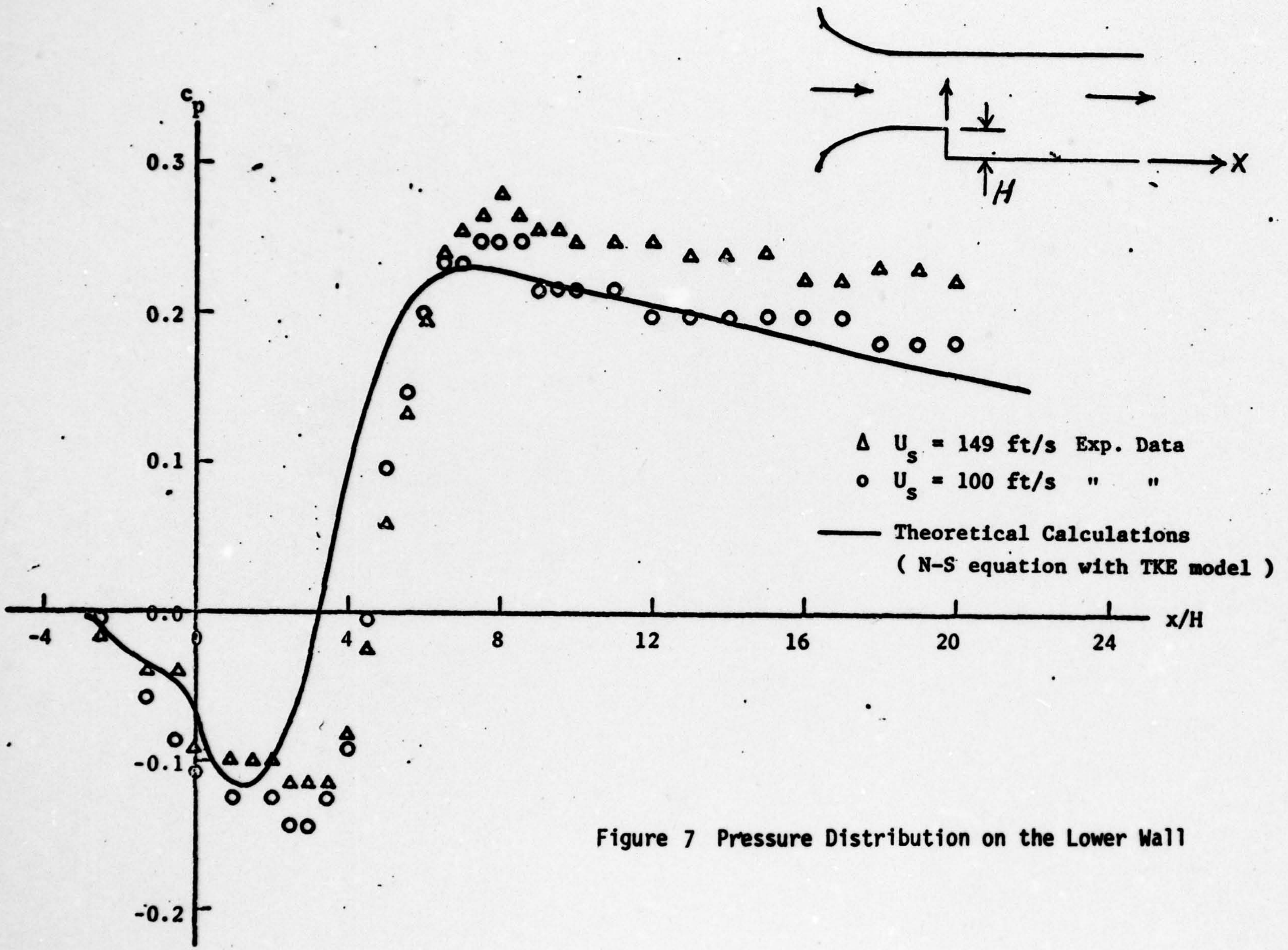

Figure 7 Pressure Distribution on the Lower Wall

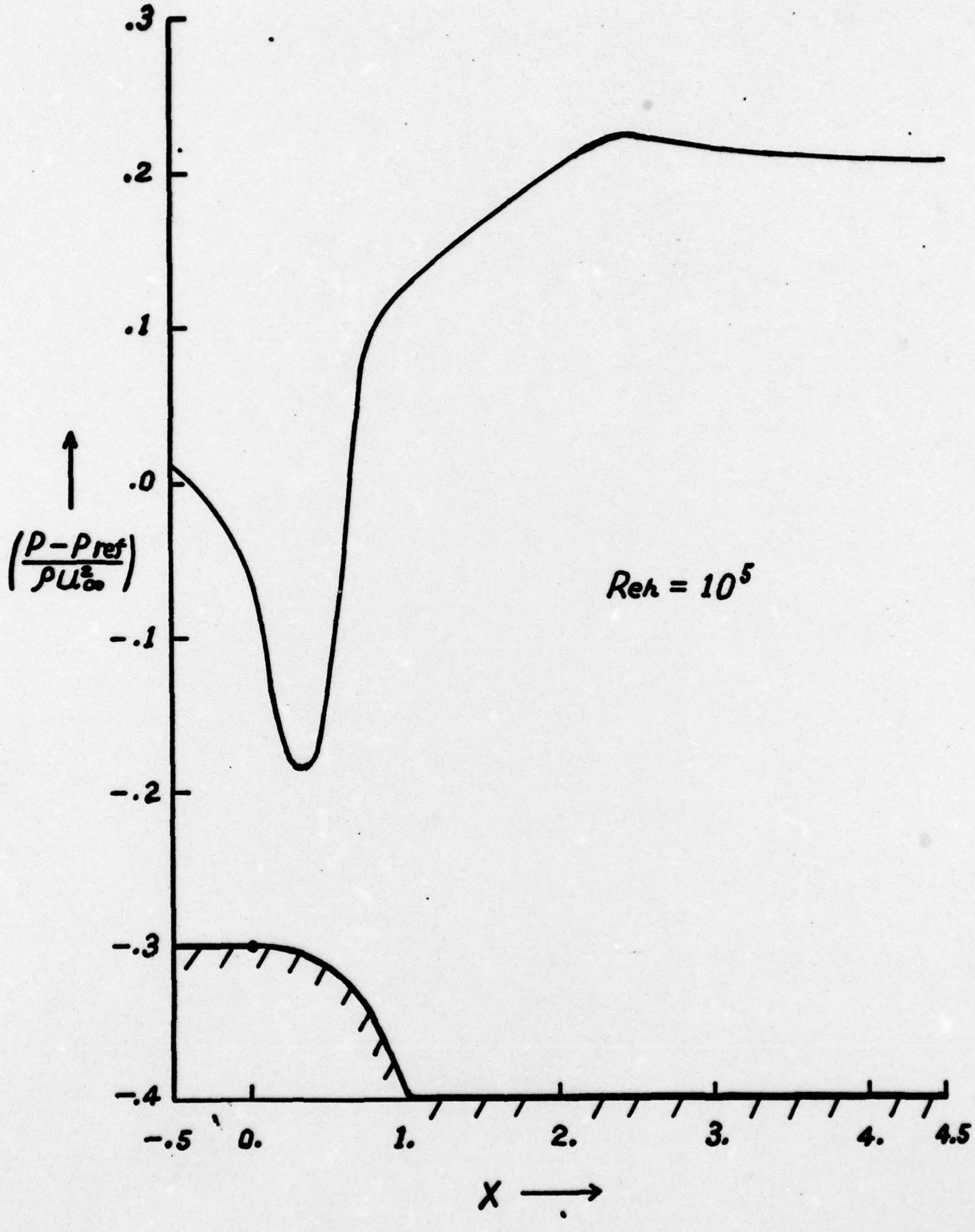

Figure 8 Wall Pressure Distribution obtained from Numerical Calculation of the Turbulent Navier-Stokes Equation

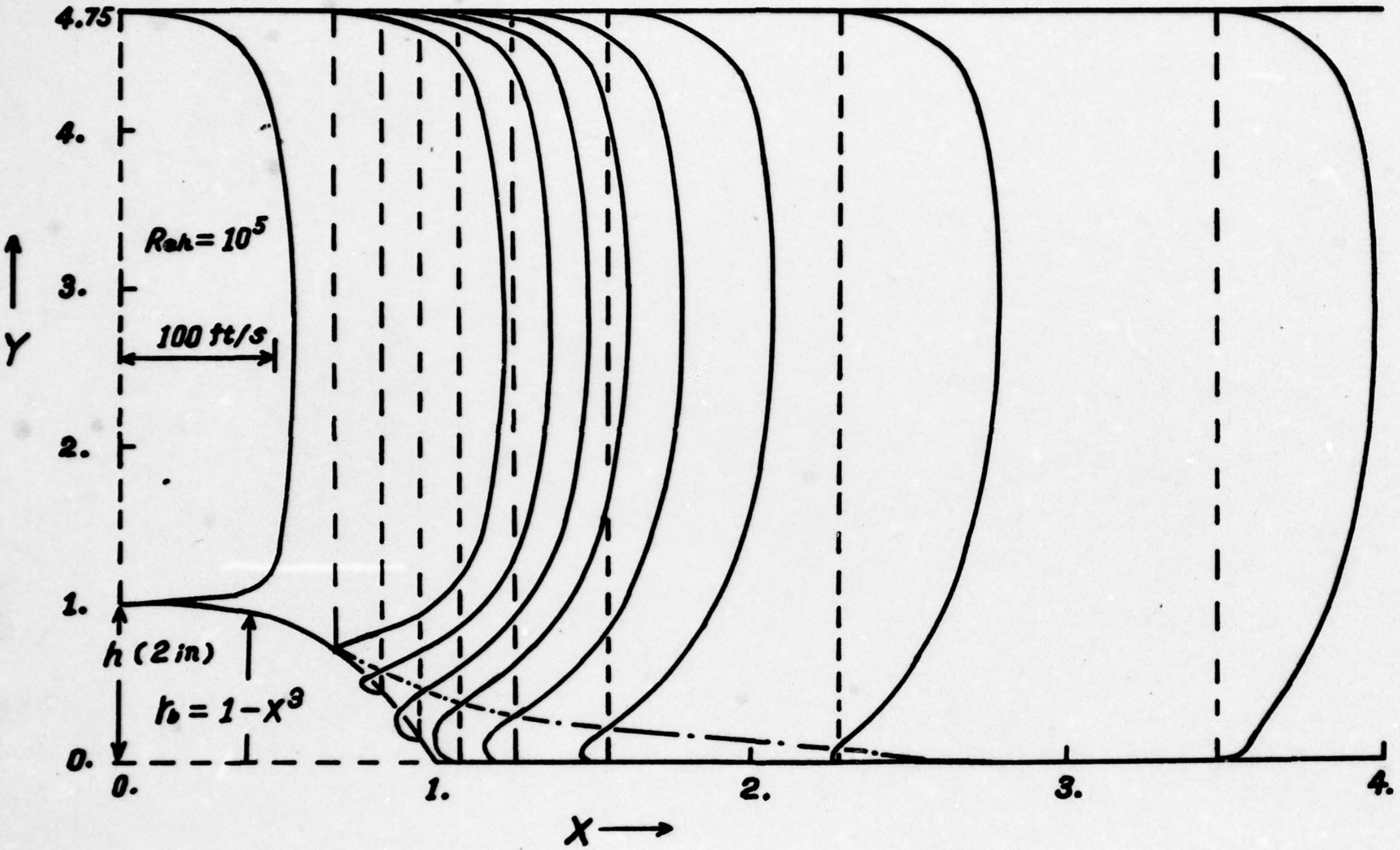

Figure 9 Velocity Distribution within a Channel obtained from Numerical Calculation of the Turbulent Navier-Stokes Equation

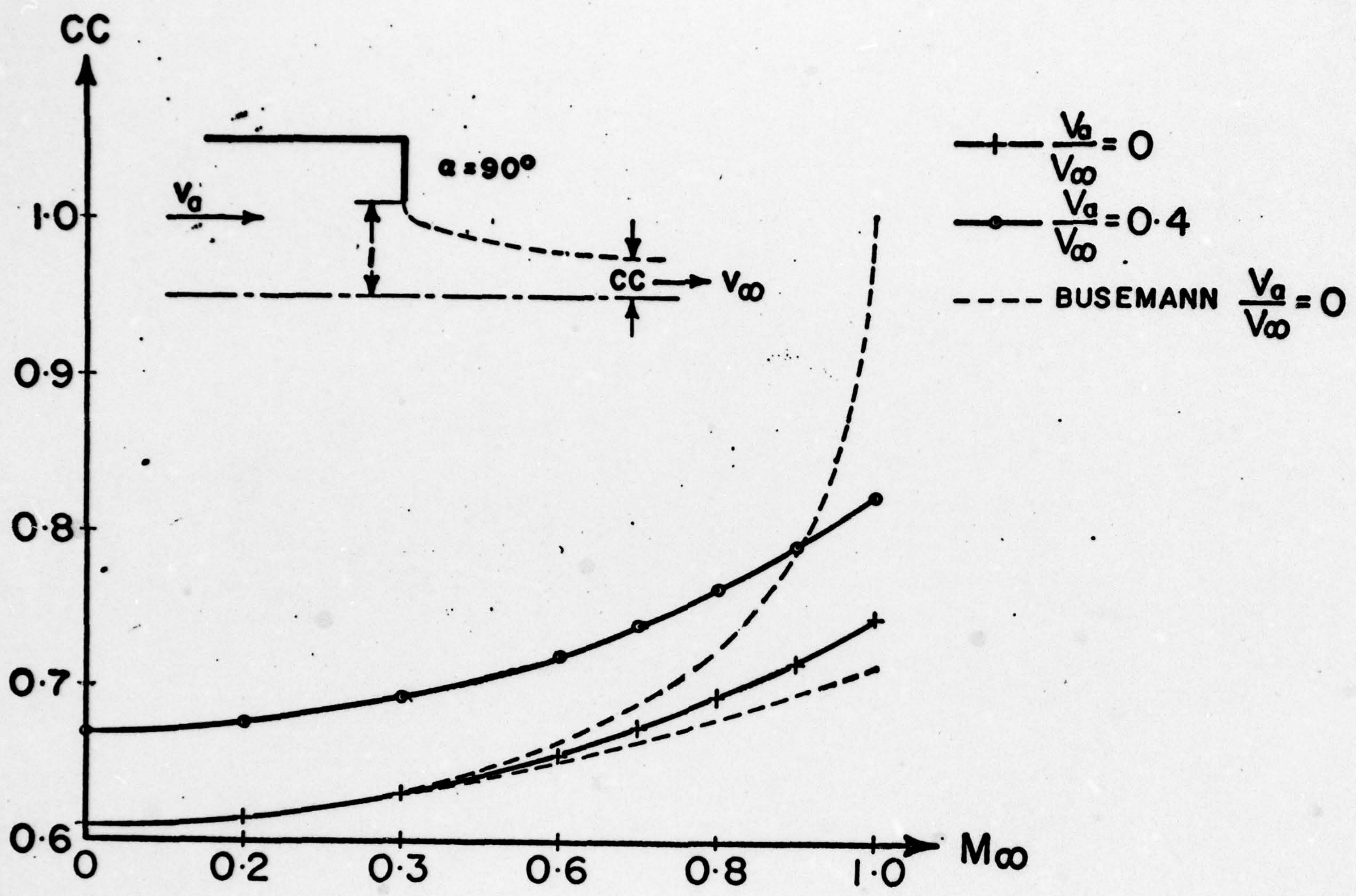

Figure 10 Contracting Coefficient of the Compressible Flow discharging from a Confined Channel

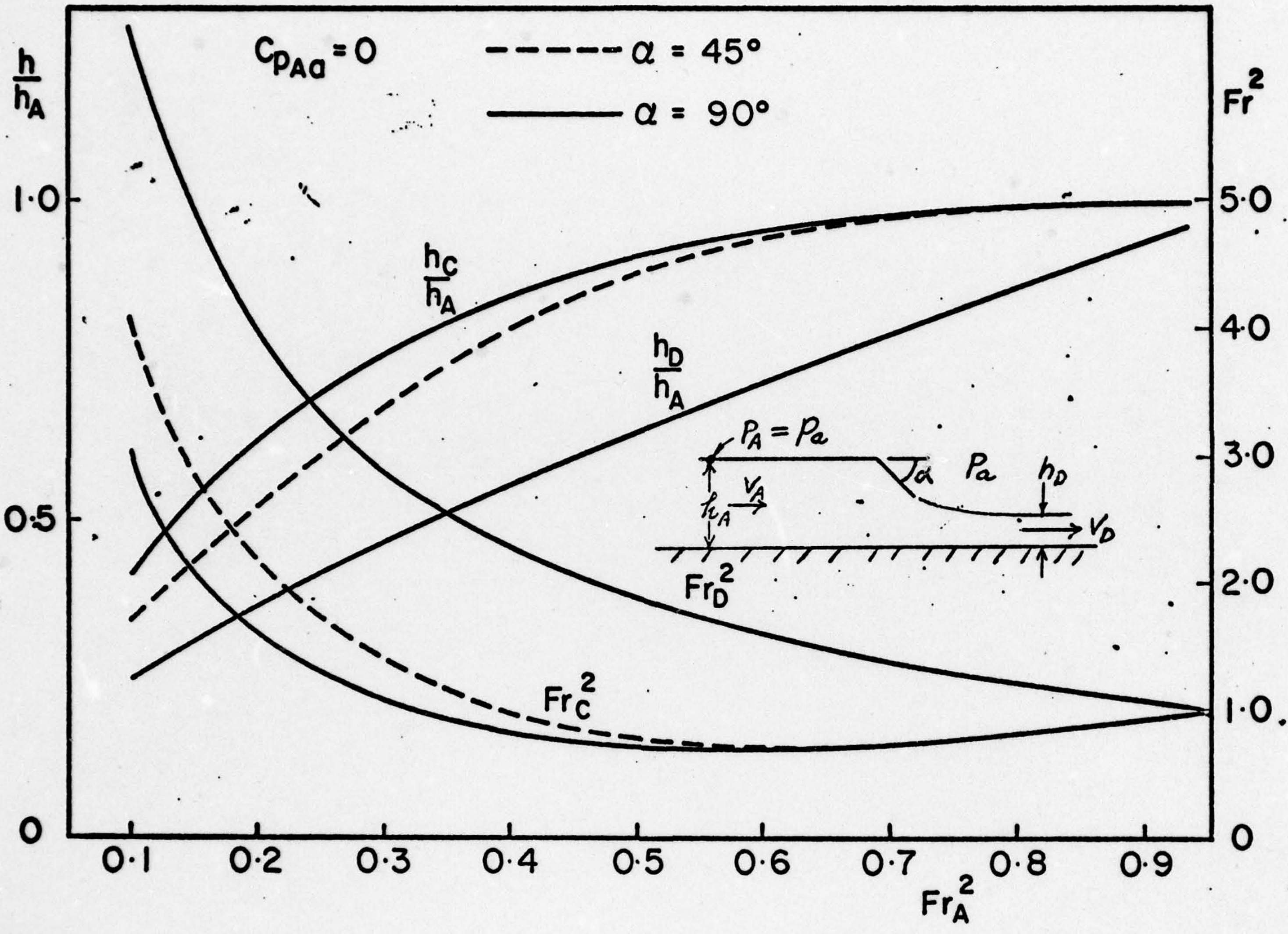

Figure 11 Results of Calculations for an Incompressible Flow discharging from a Channel under the Influence of Gravitation (Ref. 13)

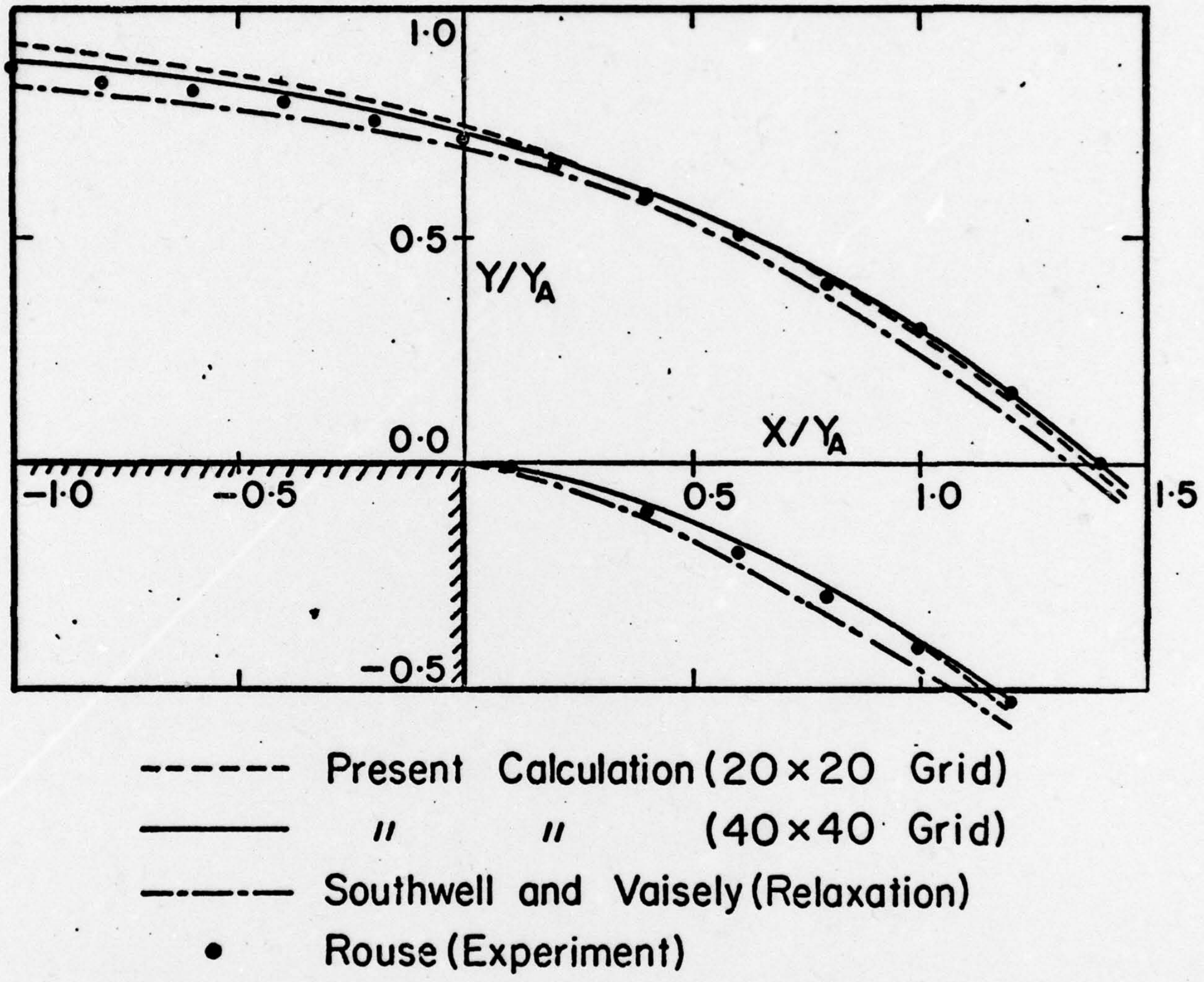

Figure 12 Jet Configuration of a Free Overfall (adapted from Ref. 14)

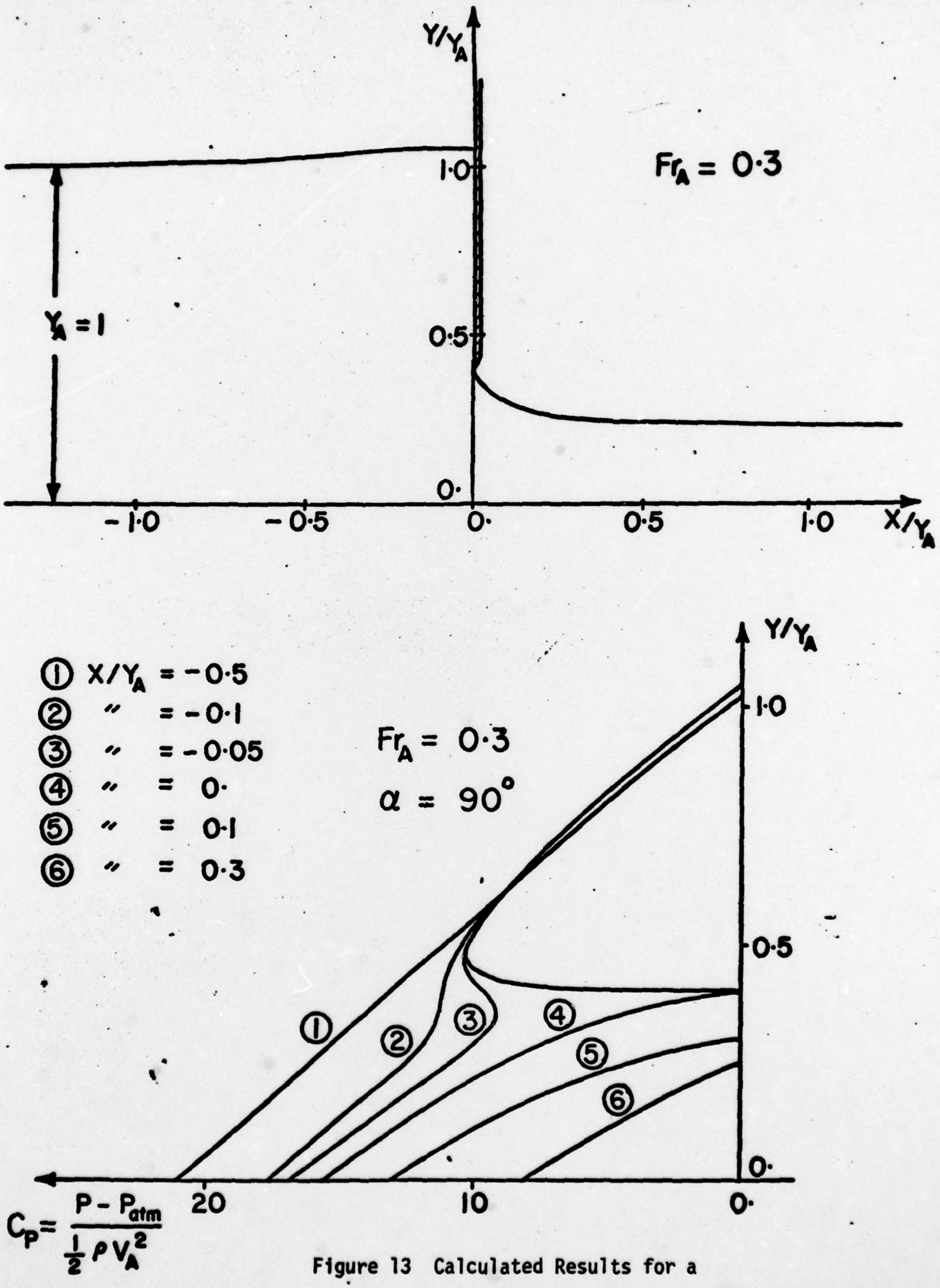

Figure 13 Calculated Results for a Sluice Gate (Ref. 15)

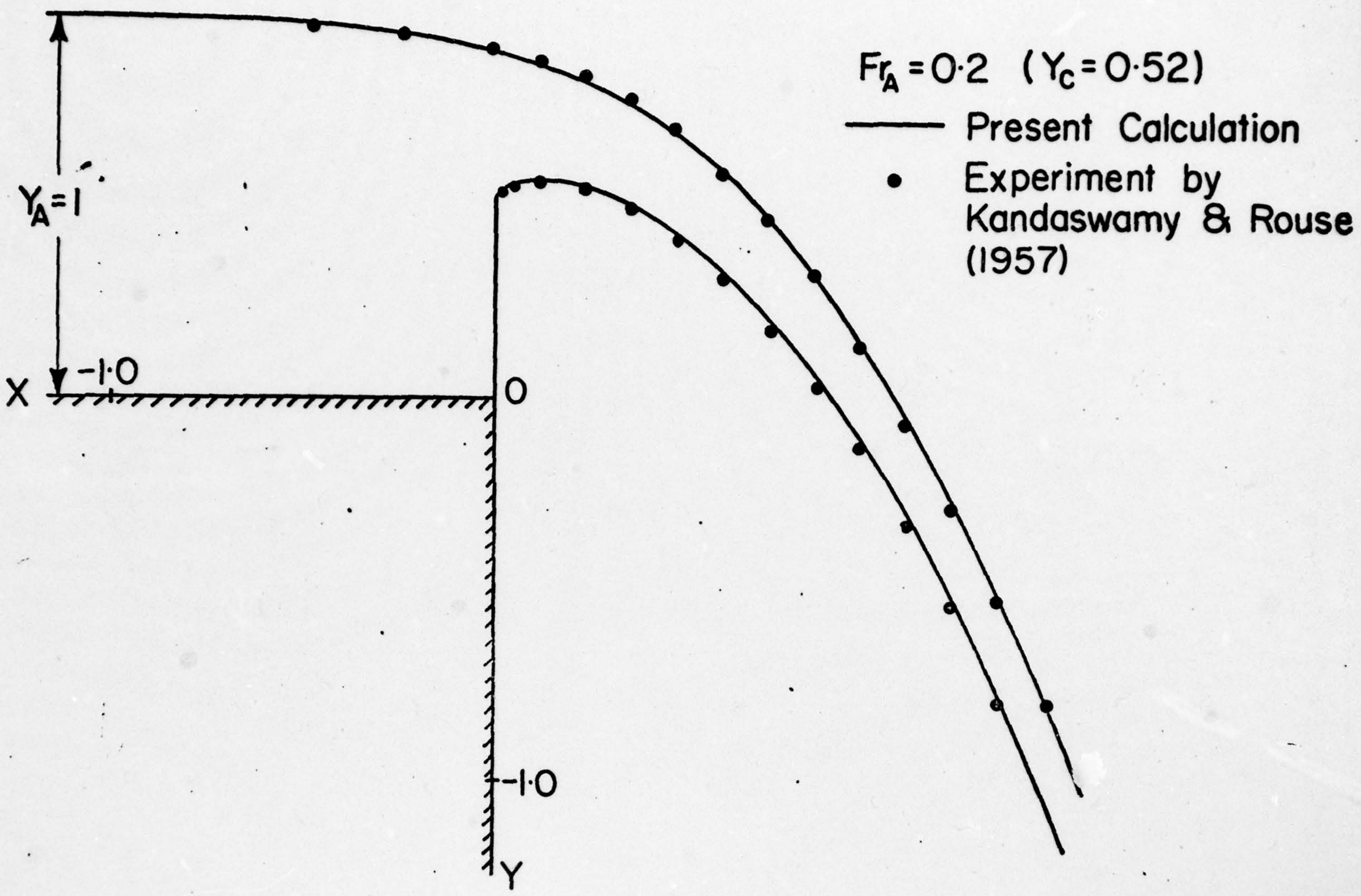

Figure 14 Results of Calculations for a Sharp-Crested Weir (Ref. 15)

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13. Chow, W. L., T. Han, and C. Wu, "Hydrodynamic Solution for Incompressible Flow as Influenced by Gravitation," AIAA J., Vol. 16, No. 10, 1978, pp. 1097-1098.

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