STUDY OF THE CONTINUOUSLY VARIABLE MACH NUMBER FLOW FOR A SUPERSONIC WIND TUNNEL BY THE CONTROL OF MASS FLOW RATE

ICAS-94-3.3.4

Yasuhiko AIHARA* Takashi MANDAI**
Etsuo MORISHITA Masafumi YAMANOUCHI
Department of Aeronautics and Astronautics
Faculty of Engineering, the University of Tokyo
7-3-1, Hongo, Bunkyo-ku, Tokyo 113 JAPAN

Susumu NAKANO
Mechanical Engineering Research Laboratory, Hitachi, Ltd.
3-1-1, Saiwai-cho, Hitachi, Ibaraki 317, JAPAN

Abstract

A new version of the concept of a supersonic wind tunnel where the Mach number is variable by the control of the mass flow rate is proposed, and is studied analytically and experimentally. Numerical analyses are performed for the two-dimensional channel flows with given wall pressure distributions and the consequent mass flow reduction in the flow direction, showing the possibility of the wind tunnel with a continuously variable Mach number without changing the configuration of the flow path. Preliminary experiments show the increase in the Mach number with the reduction of the mass flow rate. The more detailed experimental study by using the porous duct with the initial Mach number of 2 also shows promising results and further discussion will be given in relation to its application to the wind tunnel.

* Presently Department of Aeronautics and Astronautics, Tokai University, 1117 Kitakaname, Hiratsuka, Kanagawa 259-12, JAPAN
** Presently Mitsubishi Research Institute, 2-3-6, Ohte-machi, Chiyoda-ku, Tokyo 100, JAPAN

1. Introduction

The recent development of the aeronautical science and technology requires more highly qualified and large scale ground test facilities. The wind tunnels covering a wide range of parameters such as the Mach number, the Reynolds number and so forth are especially important for the development of the next generation of transports.

For the conventional supersonic wind tunnels, the Mach number is fixed by the selection of the nozzles and/or variable in a limited range by adjusting the nozzle walls variably. In order to do away with the existing state of things and to find the possibilities of the new version of the facility, i.e., the continuously variable supersonic Mach number wind tunnel, we need to study the establishment of the supersonic flow from a different point of view.

The purpose of the present paper is to investigate the potential of the continuously variable Mach number flow for the supersonic wind tunnel by the control of the mass flow rate, analytically, numerically and experimentally.

2. Analysis

2.1 One-dimensional Analysis

The basic concept of the compressible flow is given by the following equations(1)-(6);

$$\frac{dM}{M}=-\frac{\phi}{1-M^2}\frac{dA}{A}+(1+\gamma M^2)\frac{\phi}{1-M^2}\frac{d\dot{m}}{\dot{m}} \tag{1}$$

$$\frac{dp}{p}=\frac{\gamma M^2}{1-M^2}\frac{dA}{A}-2\phi\frac{\gamma M^2}{1-M^2}\frac{d\dot{m}}{\dot{m}} \tag{2}$$

$$\frac{d\rho}{\rho}=\frac{M^2}{1-M^2}\frac{dA}{A}-(\gamma+1)\frac{M^2}{1-M^2}\frac{d\dot{m}}{\dot{m}} \tag{3}$$

$$\frac{dT}{T}=\frac{(\gamma-1)M^2}{1-M^2}\frac{dA}{A}-(1+\gamma M^2)\frac{(\gamma-1)M^2}{1-M^2}\frac{d\dot{m}}{\dot{m}} \tag{4}$$

$$\frac{dp_0}{p_0}=-\gamma M^2\frac{d\dot{m}}{\dot{m}} \tag{5}$$

$$\frac{ds}{R}=\gamma M^2\frac{d\dot{m}}{\dot{m}} \tag{6}$$

where p, ρ, T, s, R, γ, M, A and $\dot{m}$ are the static pressure, the density, the static temperature, the entropy, the specific gas constant, the specific heat ratio, the local Mach number, the local cross-sectional area of the flow path, the local mass flow rate, respectively, and $\phi=1+(\gamma-1)M^2/2$. The subscript 0 denotes the stagnation condition[1]. The conventional wind tunnels are operated based on the relationship between the changes of flow quantities (left hand side) and the change of the cross-sectional area (dA/A) for a constant mass flow rate ($d\dot{m}/\dot{m}=0$).

For the uniform flow in the test section of the conventional wind tunnels, the contour nozzles are designed for the specific Mach numbers, which inevitably leads to the construction of numerous wind tunnels with corresponding Mach numbers to cover the necessary Mach number range.

The present idea is to aim for the possibility of applying the change of the mass flow rate ($d\dot{m}/\dot{m}<0$) so that the flow quantities can be controlled continuously in the flow path.

Figure 1 shows the change of the Mach number in a duct with a constant cross-sectional area ($dA/A=0$) from the inlet (suffix 1) to the exit, where the mass flow rate reduces from $\dot{m}_1$ to $\dot{m}$. These curves correspond to the different initial Mach number M_1, i.e., M_1 =1,2 and 3, where γ=1.4. The results show the remarkable increase in Mach number M with the reduction of the mass flow rate $\dot{m}$, especially for a higher M_1. The hypersonic Mach number is seen to be attainable with reasonable mass flow reduction.

From Eqs. (5) and (6), it is noticed that the mass flow rate reduction increases the stagnation pressure and reduces the entropy, which is considered to correspond to the work done from the outside of the system through the mass extraction. Thus the flow field is not isentropic and the static pressure is expected to be higher than the isentropic case at the same Mach number. Actually as shown in Fig. 2, the reduction of the static pressure with an increase in M is less than that for the isentropic expansion. As a favorable effect, the higher pressure results in a higher Reynolds number at the same Mach number.

Another noteworthy point is that the suction stabilizes the boundary layer on the duct[2], which is important for the reduction of the noise in the test section of the wind tunnel.

2.2 Basic Concept of the Wind Tunnel

Figure 3 shows the basic concept of the wind tunnel derived from the above analyses. The conventional supersonic nozzle producing M_1 is followed by the variable mass flow path with the porous wall which controls M at the inlet of the test section. Sucked air will be discharged into the ambient with the blow-down type wind tunnels or returned into the upstream of the settling chamber with the continuous type wind tunnels.

2.3 Two-Dimensional Analysis

In order to proceed with the further design, the numerical analysis has been conducted by using the two-dimensional Euler equations. The second order non-muscle symmetric TVD scheme and the Euler explicit method were adapted as the space difference scheme and the time integral, respectively[3][4].

The two-dimensional flows between two parallel plates can be computed for a given M_1 and various wall pressure distributions, p_w, from the inlet to the exit of the channel. In the following, M_1 is set at 1 and the nine cases shown in Table 1 are investigated. p_w/p_0 is assumed to change in flow direction as the function of the non-dimensional distance x/D, as shown in Eq. (7), where a, b, c and D are non-dimensional channel length 12.5, p_w/p_0 at M_1=1 (0.528 for γ=1.4), p_w/p_0 at the exit of the channel, and the width of the channel.

$$\left(\frac{(x/D)}{a}\right)^n + \left(\frac{(p_w/p_0)-c}{b-c}\right)^n = 1 \qquad (7)$$

Various distributions of p_w/p_0 can be given by changing n.

In Table 1, c is smaller for cases (1)-(3), corresponding to the higher M at the exit, while for the cases (7)-(9), c is larger corresponding to the lower M. For cases (4) and (5), the same p_w/p_0 as obtained from the contour nozzle analyses corresponding to the uniform flow at the exit and to the constant gradient Mach number increases, respectively.

Figures 4(a)-4(c) compare the given distributions of p_w/p_0 with the resultant distributions of the pressure along the center between the channels, p_c/p_0. It can be seen that p_c decreases following p_w/p_0 with relaxation. When the p_w/p_0 is properly designed for the given c, p_c/p_0 can catch up with p_w/p_0 in the upstream of the exit, and thus the uniform pressure distribution is obtained in the cross section at the exit((1), (4), (5), (8) and (9)). When p_w/p_0 changes too slowly ((2), (3) and (6)), p_c/p_0 does not overtake p_w/p_0 at the exit, or when p_w/p_0 changes too rapidly((7)), p_c/p_0 shows the non-uniform reduction in the downstream direction.

Some examples of the Mach number distributions are shown in Figs. 5(a)-5(c). The increment ΔM of the Mach number contours is 0.05. As can be seen from these results, it is generally not difficult to get uniform Mach number distributions at the exit axially as well as cross-sectionally for the lower Mach numbers (Figs. 5(b) and 5(c)). At higher Mach numbers, on the other hand, more careful control of p_w/p_0 is needed to establish uniform flows at the exit (Fig. 5(a)).

The flow field along the center line is seen to be isentropic from the comparison of M and p_c/p_0.

The mass flow rate $\dot{m}/\dot{m}_1$ decreases in the downstream (except for (7)) and the effect of the change in $\dot{m}/\dot{m}_1$ on the increase in M is dominant with the higher M. This tendency coincides with the result of one-dimensional analysis, but the effectiveness of the suction on the increase of the Mach number is less for the two-dimensional flow, probably due to the fact that the entropy in the latter case is highly associated with the flow curvature induced by the suction.

In order to estimate the viscous effects, the Mach number contours obtained from the Navier-Stokes code[5] and the Euler code are compared in Fig. 6 for a given p_w/p_0. The boundary layer starts to develop near the inlet, but does not grow by the suction (Fig. 7), and the effect on Mach number distribution is negligible. An extensive analysis has been performed for the stepwise p_w/p_0 distribution as shown in Fig. 8. The corresponding distributions of p_c/p_0 and the Mach number contour show that this kind of practical approach is, if properly applied, also useful for our purpose.

3. Experiment

3.1 Experiment in the Supersonic Wind Tunnel Model

A preliminary experiment was performed by using a small pipe flow.

Figure 9 shows the schematic view of the preliminary experiment. The throat diameter is 28mm , and the diameter in the test section is 40mm. The original design was that the test section 300 mm in length is located just after the supersonic nozzle of design Mach number 2, considering the boundary layer displacement thickness. A diffuser system is connected in the outlet to decelerate the flow to the subsonic regime.

In the present experiment, the test section length is nearly doubled, and the upstream half is made of porous material. An annular suction chamber is equipped outside the porous tube, and the air is extracted from this chamber by a mechanical 2-stage vane-type vacuum pump of 600 l/min class.

The large storage tank, the pressure of 30 bar and the total temperature nearly equal to the ambient temperature, is used as the air supply. The supersonic flow is created by opening and adjusting the valve to set the upstream total pressure 2.97 bar, which is monitored by the pressure gauge during the experiment. The static pressure is monitored at x/D=7.5, 11.25 and 15, where x is measured from the end of the expansion nozzle and D is the diameter of the test section. The suction from the main stream take place between x/D=0.625 and 5.625. There are several suction ports around the outer surface of the annular chamber, and the air is sucked from one of them.

A Pitot total pressure tube is set on the center of the test section at x/D=15 to monitor the total pressure and the Mach number. It was found that the total pressure tube disturbed the flow field at x/D=7.5 and 11.25, and it was set at x/D=15.

The experimental static pressure distributions are shown in Fig. 10. The mass flow rate is large compared to the capacity of the suction vacuum pump, and the maximum mass extraction rate is about 1%. Even with such a small amount of mass removal, the static pressure decreases about 0.2 bar at x/D=7.5, where the suction ends just upstream. The unexpected effect of the suction appears at x/D=15, where the static pressure decreases noticeably. This is the effect of the boundary layer suction; the blockage is reduced, and the Mach number is increased. The shock location in the diffuser moves downstream. Although this is not the original aim of this suction test, the effect is rather distinctive. The Mach number changes at x/D=15, is shown in Fig.11 as a reference.

3.2 Mach Number Increase

The above experiment, together with the preliminary small pipe trial test, may be summarized in Figs. 12 and 13.

In Fig. 12, the relative static pressure change is shown against the mass removal rate. The prediction by the inviscid flow theory, i.e., Eq.(2) (dA=0) is also included. In the supersonic flow, where the Reynolds number $Re=1.5\times10^6$, the experimental data at x/D=7.5 are close to the theory; while in the lower Reynolds number experiment($Re=0.11\times10^6$), the static pressure drop at x/D=2.5 is smaller than that in the theory. This might be attributed to the viscous effect in the pipe flow, i.e., the Reynolds number effect.

The relative Mach number increase is shown in Fig. 13, estimated from the experimental static pressure decrease shown in Fig. 12 by employing the inviscid flow theory for $Re=1.5\times10^6$ and the viscous flow theory for $Re=0.11\times10^6$, respectively. In the present mass removal rate of up to about 5%, the relative Mach number increase is about 15%. The Mach number increase in these experiments shows a similar trend to that in the inviscid flow theory(Eq.(1), dA=0), although the experiments give slightly lower values than the theory. This is considered to be the viscous effect. This figure experimentally verifies the original intended purpose and further mass removal is sure to be effective in realizing much higher Mach numbers.

3.3 Supersonic Wind Tunnel

A supersonic wind tunnel is now being constructed. The detailed flow field measurements are planned. The uniformity of the physical quantities in the test section may reveal the quality of the supersonic wind tunnel after the control of the suction. Further research efforts might be necessary and useful to provide an ideal supersonic flow field by this new technology.

4. Concluding Remarks

The variable Mach number flow was studied analytically, numerically and experimentally.

It was predicted in theory that a very high Mach number would be possible by the mass extraction from the main flow . The numerical experiments also supported this idea. The longer the suction length, the higher the Mach number.

The preliminary experiments were conducted. The theory was validated by the actual experiment. The static pressure decreased and the Mach number, together with the total pressure, increased with the suction. The present experimental data indicated that about a 15% increase in the Mach number was achieved with about a 5% mass removal at Mach number 1.5 and Reynolds number 1.1×10^5. Although it was smaller than in theory, the experimental result was consistent with the theoretical prediction.

The large amount of mass removal from the wind tunnel test section was necessary, and is being planned in the future experiment. One method is to employ the suction techniques with a large flow capacity, and another one could be to increase the suction area. A full scale supersonic wind tunnel using this suction technique is now also being prepared.

References

[1] Shapiro, A.H., The Gas dynamics and Thermodynamics of Compressible Fluid Flow, Vol1.1 The Ronald Press Co., N.Y., 1953, pp.219-262.

[2] El-Hady, N.M., " Secondary Instability of High Speed Flows and the Influence of Wall Cooling and the Suction ", NASA CR 4427, 1992.

[3] Beam, R.M. and Warming, R.F., " An Implicit Factored Scheme for the Compressible Navier-Stokes Equations ", AIAA J., 4, 1978, pp.393-402.

[4] Anderson, Jr., J.D., Modern Compressible flow with Historical Perspective, McGraw-Hill, 1982.

[5] Yee, H.C., " A Class of High Resolution Explicit and Implicit Shock-Capturing Methods", NASA TM-101088, 1989.

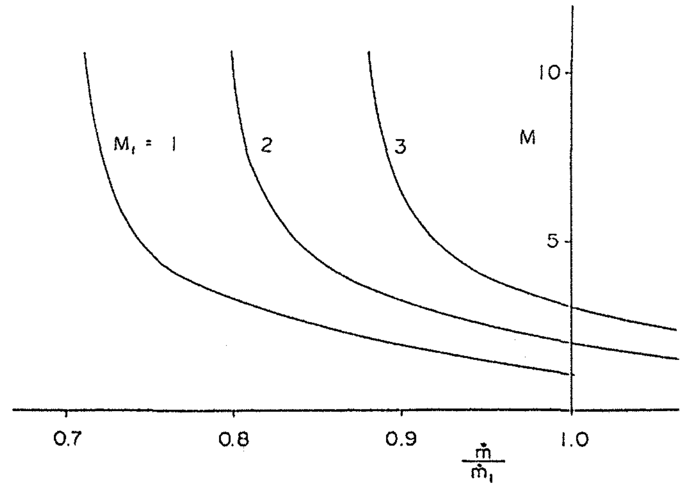


Fig.1 Change in the Mach number due to the change of mass flow rate $\dot{m}$ for a different inlet Mach number M_1

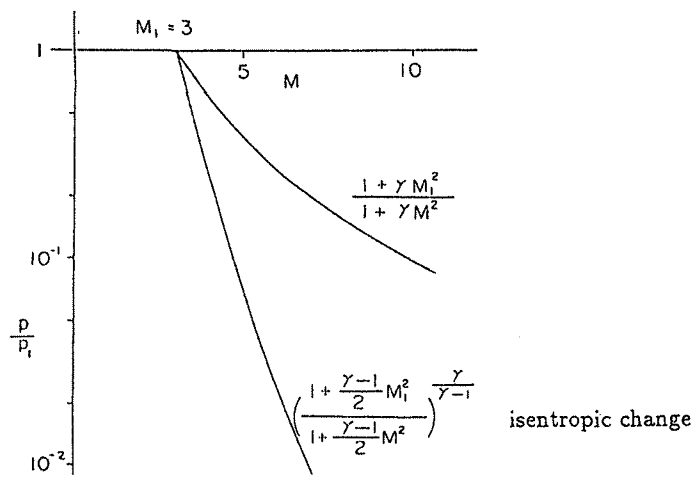


Fig.2 Static pressure change due to the change in the Mach number

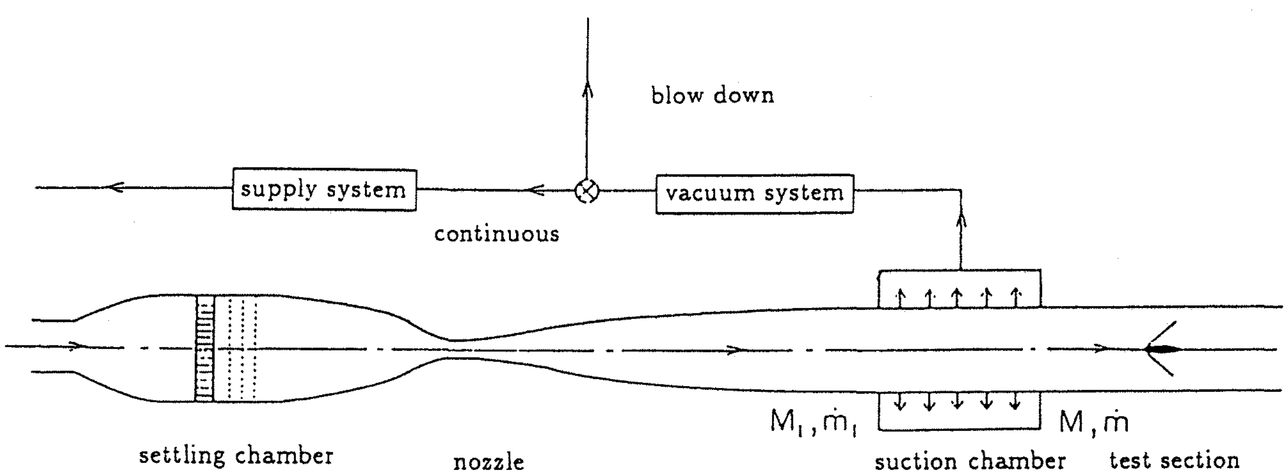
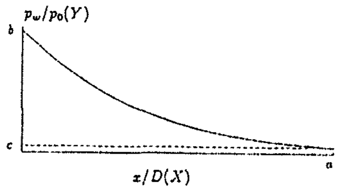


Fig.3 Concept of the wind tunnel



$$\left(\frac{X}{a}\right)^n + \left(\frac{Y-c}{b-c}\right)^n = 1$$

$$\begin{cases} a = 12.5 \\ b = 0.528 \end{cases}$$

	c	n
CASE(1)	0.001	0.3
(2)	0.001	0.5
(3)	0.001	0.8
(4)	0.0167	Distribution to obtain uniform M at the exit.
(5)	0.0167	Distribution to obtain constant dM/dx
(6)	0.0167	0.8
(7)	0.1	0.3
(8)	0.1	0.5
(9)	0.1	0.8

Table 1 Parameters c and n used for the given distributions of p_w/p_0

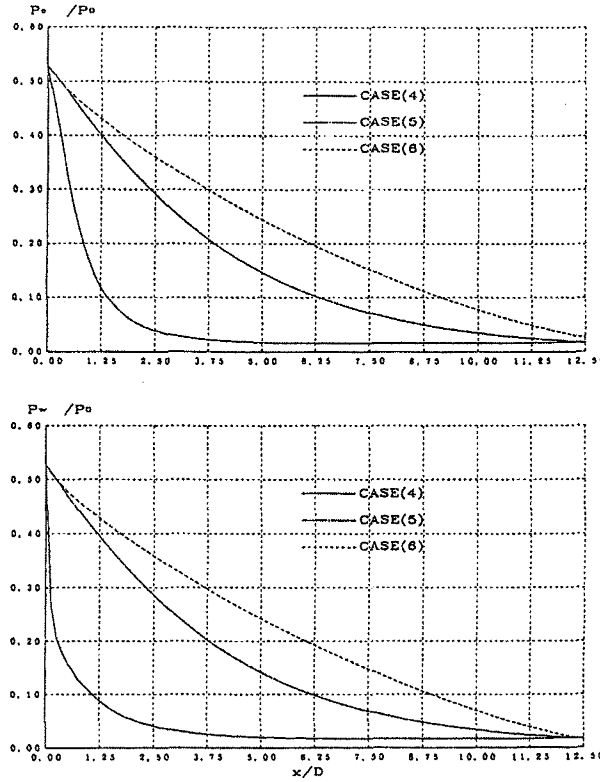


Fig.4(b) p_w/p_0 and p_c/p_0 for cases (4),(5) and (6)

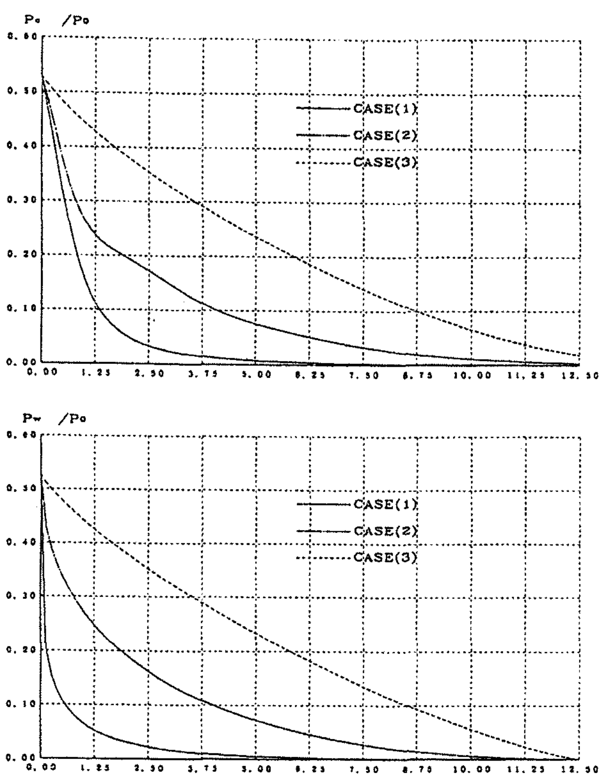


Fig.4(a) p_w/p_0 and p_c/p_0 for cases (1),(2) and (3)

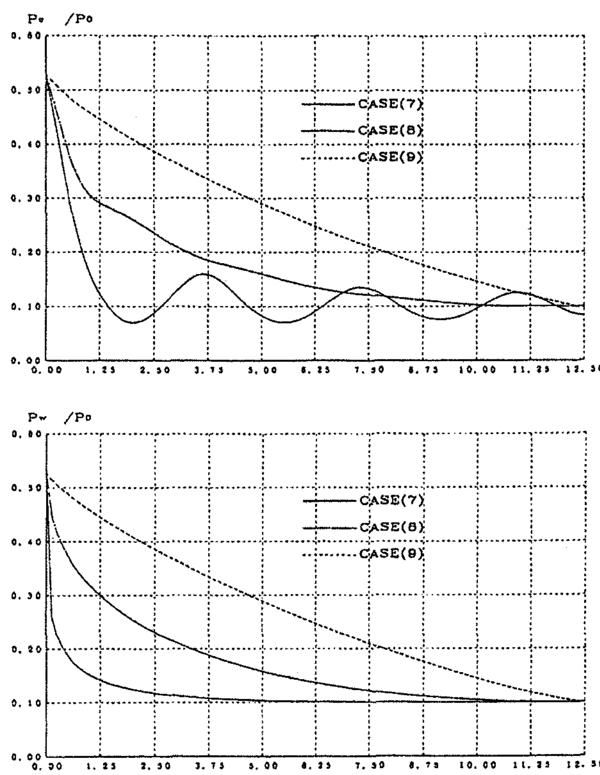


Fig.4(c) p_w/p_0 and p_c/p_0 for cases (7),(8) and (9)

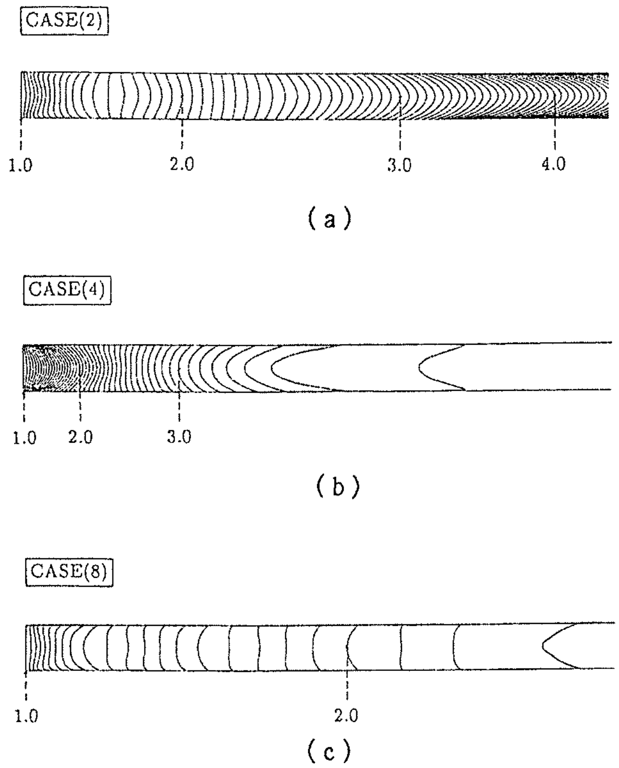


Fig.5 Mach number contours

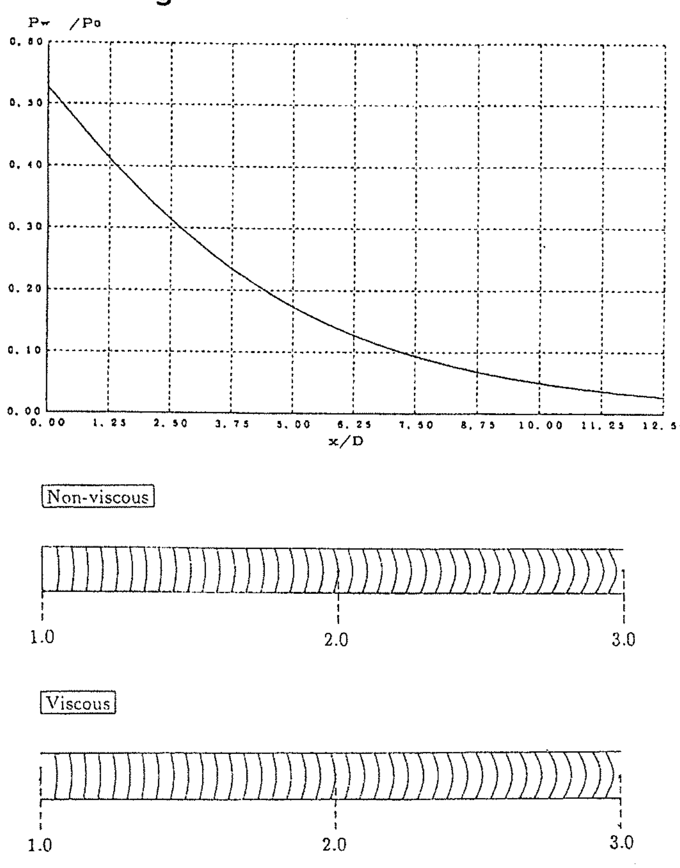


Fig.6 Viscous effect on the Mach number contours for a given distributions of p_w/p_0

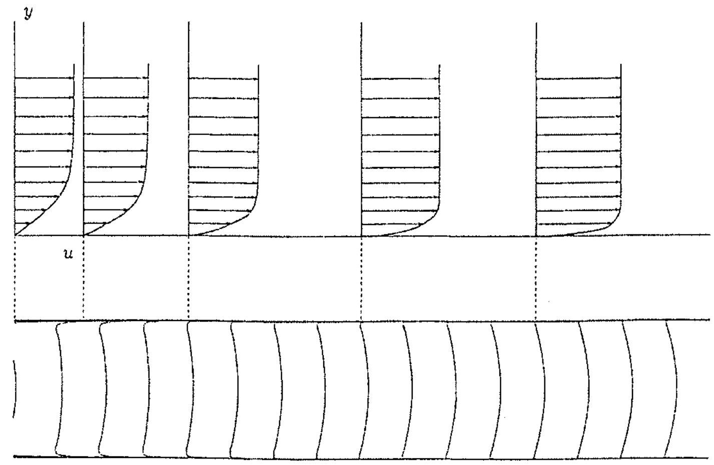


Fig.7 Boundary layer development near the inlet of the channel under the influence of suction for p_w/p_0 shown in Fig.6

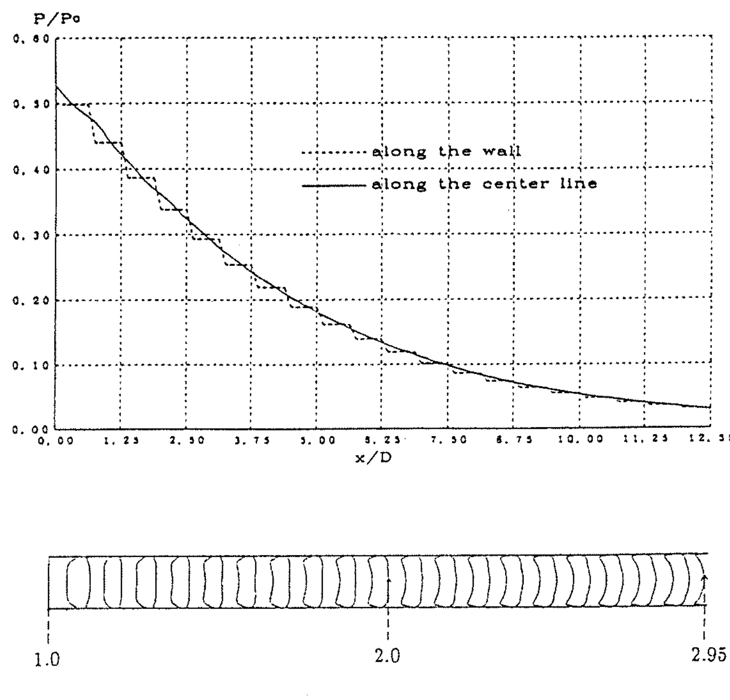


Fig.8 Stepwise p_w/p_0 distribution, the corresponding p_c/p_0 and Mach number contours of the viscous flow

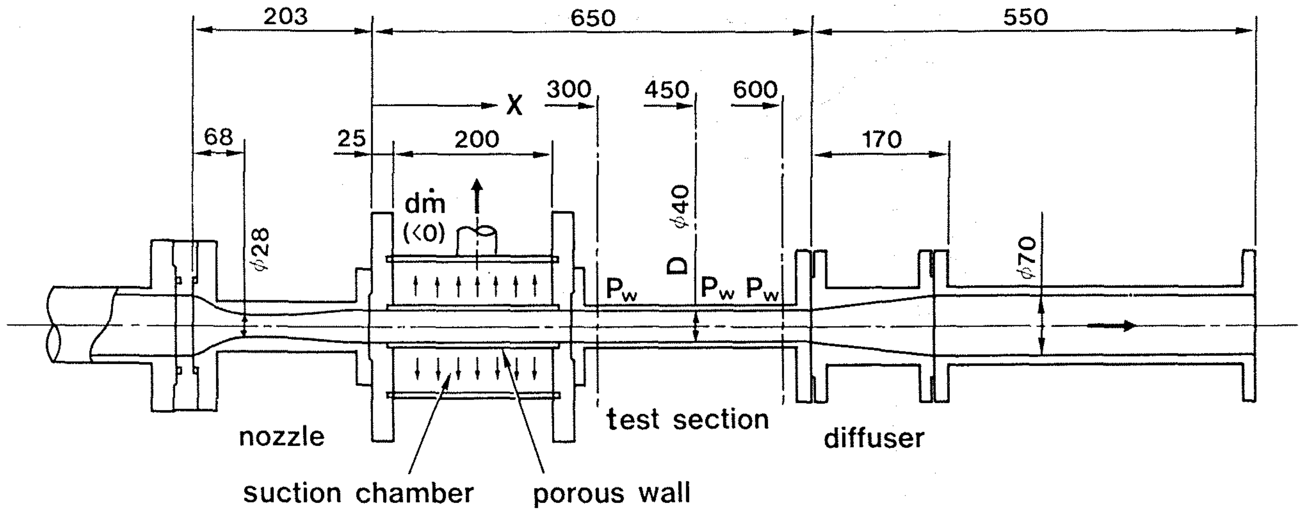


Fig.9 Supersonic flow with suction

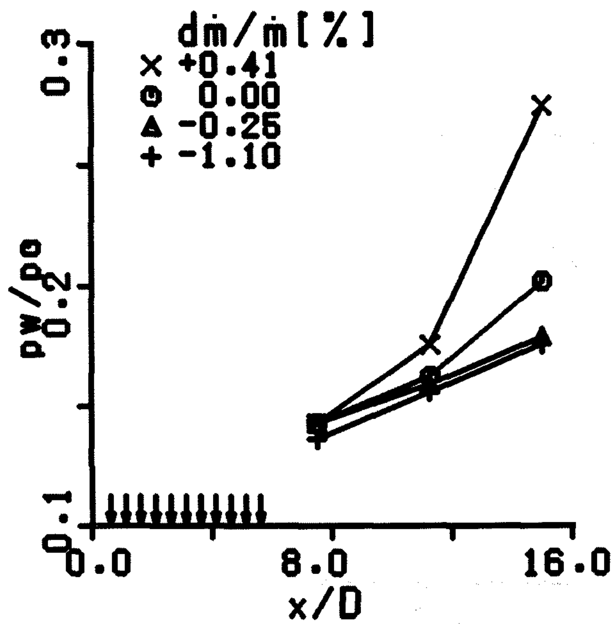


Fig.10 Static pressure distribution

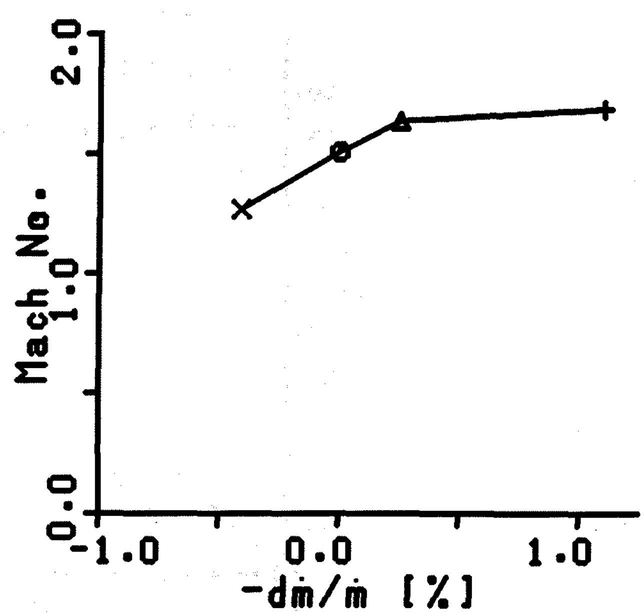


Fig.11 Mach number change at x/D=15

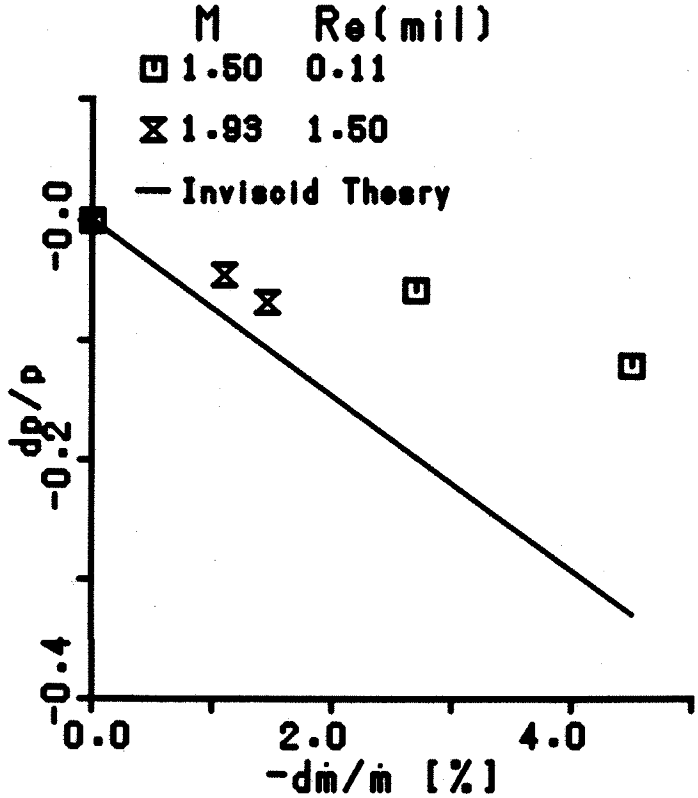


Fig.12 Static pressure decrease due to suction

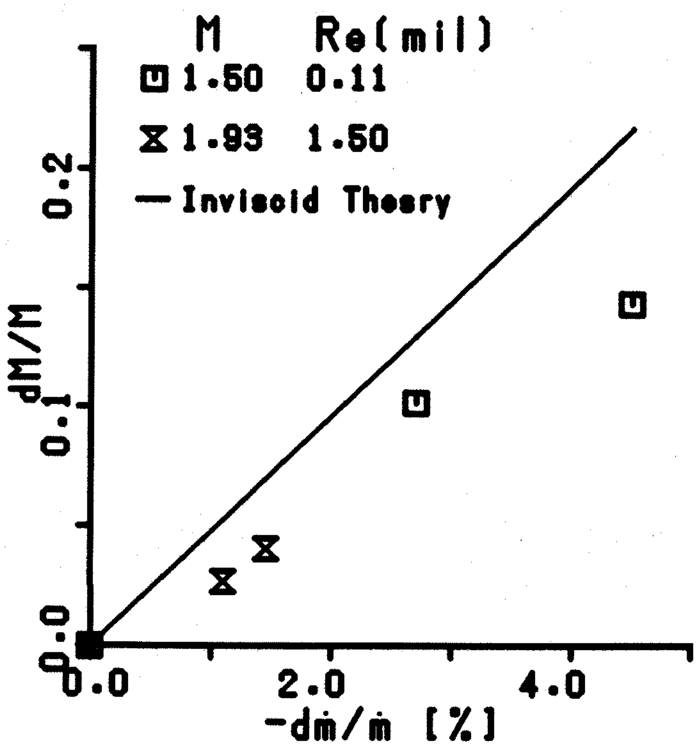


Fig.13 Mach number increase due to suction