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Theoretical Velocity Distribution in a High-Speed Tunnel Contraction

By

M. Jones, B.Sc. and P. Bright

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Theoretical Velocity Distribution in a High-Speed Tunnel Contraction

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M. Jones, B.Sc. and P. Bright

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October, 1945

Summary.—By an arithmetical method, contours of constant Mach number have been determined in the contraction cone of a circular tunnel whose axial distribution of area was assumed to be the same as that in the Royal Aircraft Establishment High Speed Tunnel. The results show a definite tendency for the velocity to be lower on the centre line than on the wall, the difference becoming smaller as the working section is entered.

Sufficient work has been done to show that the method described can be used to obtain solutions for the flow of a compressible fluid in a pipe of varying cross section, provided that there are no discontinuities in the boundaries.

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1. *Introduction.*—During measurements of wall pressures made in the Royal Aircraft Establishment High Speed Tunnel[1], the velocity recorded at the wall of the working section was considerably higher than the mean value over the cross section. To investigate whether this should be expected on theoretical grounds, the calculations detailed here were undertaken. As the actual shape of the tunnel could not be dealt with, a circular section was assumed throughout, each section having the same area as the corresponding section in the tunnel. Throughout the working section the radius was assumed constant since the very small expansion there had little effect on the solution in the contraction cone. Thus at some distance down this parallel portion, conditions became uniform across a section.

* R.A.E. Tech. Note Aero. 1698—received 29th October, 1947.

In order to overcome certain difficulties encountered on the curved boundaries during the solution of the differential equation describing the flow, Laplace's equation

$$\frac{\partial^2\psi}{\partial z^2} + \frac{\partial^2\psi}{\partial r^2} = 0$$

was first solved in a plane having the given boundaries, and the conformal network of stream and equipotential lines so obtained was used as a grid for solving the differential equation for compressible flow in the case of axial symmetry.

2. *Derivation of the Differential Equation of the Motion.*—In using Stokes' stream function ψ, where

$$2\pi\psi = \text{total flow through a circle of radius } r,$$

we have the following expressions for the axial and radial components of velocity:—

$$\left.\begin{aligned} u &= \frac{1}{\rho r}\,\frac{\partial\psi}{\partial r} \\ v &= -\frac{1}{\rho r}\,\frac{\partial\psi}{\partial z} \end{aligned}\right\}, \qquad (1)$$

where ρ is the density, and z, r are measured along the axis and radius respectively.

It is assumed that there is no vorticity, whence

$$\frac{\partial v}{\partial z} = \frac{\partial u}{\partial r}$$

which leads to

$$\frac{\partial^2\psi}{\partial z^2} + \frac{\partial^2\psi}{\partial r^2} = \frac{1}{\rho}\,\frac{\partial\rho}{\partial z}\cdot\frac{\partial\psi}{\partial z} + \frac{1}{\rho}\,\frac{\partial\rho}{\partial r}\cdot\frac{\partial\psi}{\partial r} + \frac{1}{r}\,\frac{\partial\psi}{\partial r}. \qquad (2)$$

From Bernouilli's equation, we get

$$\left.\begin{aligned} \tfrac{1}{2}\frac{\partial q^2}{\partial z} &= -\frac{1}{\rho}\,\frac{\partial\rho}{\partial z}\cdot\frac{dp}{d\rho} \\ \tfrac{1}{2}\frac{\partial q^2}{\partial r} &= -\frac{1}{\rho}\,\frac{\partial\rho}{\partial r}\cdot\frac{dp}{d\rho} \end{aligned}\right\}, \qquad (3)$$

where q is the local velocity.

We also have $\quad \dfrac{dp}{d\rho} = a^2,$

where a is the local velocity of sound.

Using these relations, equation (2) becomes

$$\nabla^2\psi = -\frac{1}{2a^2}\left[\frac{\partial\psi}{\partial z}\cdot\frac{\partial q^2}{\partial z} + \frac{\partial\psi}{\partial r}\cdot\frac{\partial q^2}{\partial r}\right] + \frac{1}{r}\,\frac{\partial\psi}{\partial r}. \qquad (4)$$

If U is the speed in the downstream parallel portion, and a_0 is the velocity of sound associated with the flow when moving at speed U, then Bernouilli's equation leads to the relation

$$a^2 = a_0^{\,2} - \tfrac{1}{2}(\gamma - 1)\,(q^2 - U^2) \qquad (5)$$

and $a_0 = U/M_0$,

where M_0 is the Mach Number in the downstream parallel portion.

If $\gamma = 1 \cdot 4$, we get

$$\frac{1}{2a^2} = \frac{M_0^2}{2\left[1 - \frac{M_0^2}{5}\left(\frac{q^2}{U^2} - 1\right)\right]},$$

so that finally equation (4) becomes

$$\nabla^2 \psi = \frac{1}{r}\frac{\partial \psi}{\partial r} - \frac{M_0^2}{2\left[1 - \frac{M_0^2}{5}\left(\frac{q^2}{U^2} - 1\right)\right]} \left\{\frac{\partial \psi}{\partial z} \cdot \frac{\partial q^2}{\partial z} + \frac{\partial \psi}{\partial r}\,\frac{\partial q^2}{\partial r}\right\}. \quad \ldots \quad \ldots \quad (6)$$

Equation (6) determines the flow in the tunnel.

2.1. *Expressions for the Velocity q.*—Bernouilli's equation may be expressed in the form

$$\tfrac{1}{2} q^2 + \frac{\gamma}{\gamma - 1}\frac{p}{\rho} = \text{constant} = \tfrac{1}{2} U^2 + \frac{\gamma}{\gamma - 1}\frac{p_0}{\rho_0} \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad (7)$$

and $$\frac{\gamma p_0}{\rho^0} = a_0^2 = \frac{U^2}{M_0^2},$$

where suffix $_0$ refers to conditions in the downstream parallel portion.

With $\gamma = 1 \cdot 4$ as before, we obtain

$$\frac{\rho^2 q^2}{\rho_0^2 U^2} = \frac{q^2}{U^2}\left[1 + \frac{M_0^2}{5}\left(1 - \frac{q^2}{U^2}\right)\right]^5. \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad (8)$$

But equations (1) give

$$\begin{aligned} \rho^2 q^2 &= \rho^2 (u^2 + v^2) \\ &= \frac{1}{r^2}\left\{\left(\frac{\partial \psi}{\partial r}\right)^2 + \left(\frac{\partial \psi}{\partial z}\right)^2\right\}. \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad (9) \end{aligned}$$

For a given value of M_0, when the derivatives $\partial\psi/\partial r$ and $\partial\psi/\partial z$ are known, equations (8) and (9) can be solved for q^2/U^2.

3. *Solution of Equation* (6).—A numerical solution of equation (6) was obtained by the squares method given by Thom in R. & M. No. 1194[2].

In using the interpolation method of solution of the equation $\nabla^2\psi = f(z,r)$, the value of ψ at the centre of a square of side $2n$ is

$$\psi_c = \psi_M - \frac{n^2}{2}\nabla^2\psi, \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad (10)$$

which is correct up to and including all third order derivatives, where $\psi_M = \frac{1}{4}(A + B + C + D)$, A, B, C, and D being the values of ψ at the corners of the square.

Difficulties encountered on the curved boundaries were dealt with by the method given in Ref. 3. The equation $\nabla^2\psi = 0$ was solved in a plane having the given boundaries, and thus a network of stream and equipotential lines was obtained as shown in Fig. 1.

Let the grid co-ordinates be α, β *i.e.* the lines forming the network have, in the (z, r) field, the equations $\alpha =$ constant, $\beta =$ constant. Then

$$\left.\begin{aligned} \frac{\partial \alpha}{\partial r} &= -\frac{\partial \beta}{\partial z} \\ \frac{\partial \alpha}{\partial z} &= \frac{\partial \beta}{\partial r} \end{aligned}\right\} \qquad \text{(11)}$$

and
$$\frac{\partial^2 \psi}{\partial z^2} + \frac{\partial^2 \psi}{\partial r^2} = q_1^2 \left(\frac{\partial^2 \psi}{\partial \alpha^2} + \frac{\partial^2 \psi}{\partial \beta^2}\right)$$

or
$$\underset{z,r}{\nabla^2 \psi} = q_1^2 \underset{\alpha,\beta}{\nabla^2 \psi} \qquad \text{(12)}$$

where
$$q_1^2 = \left(\frac{\partial \alpha}{\partial z}\right)^2 + \left(\frac{\partial \beta}{\partial z}\right)^2 = \left(\frac{\partial \alpha}{\partial r}\right)^2 + \left(\frac{\partial \beta}{\partial r}\right)^2 = \frac{1}{\left(\frac{\partial r}{\partial \alpha}\right)^2 + \left(\frac{\partial r}{\partial \beta}\right)^2} \qquad \text{(13)}$$

q_1 is the velocity of transformation.

Equations (6) and (9) may now be transformed into the (α,β) field, when they become

$$\underset{\alpha,\beta}{\nabla^2 \psi} = \frac{1}{r q_1^2}\left(\frac{\partial \psi}{\partial \alpha}\frac{\partial \alpha}{\partial r} + \frac{\partial \psi}{\partial \beta}\frac{\partial \beta}{\partial r}\right) - \frac{M^2}{2\left[1 - \frac{M_0^2}{5}\left(\frac{q^2}{U^2} - 1\right)\right]}\left\{\frac{\partial \psi}{\partial \alpha}\frac{\partial q^2}{\partial \alpha} + \frac{\partial \psi}{\partial \beta}\frac{\partial q^2}{\partial \beta}\right\} \qquad \text{(14)}$$

$$\rho^2 q^2 = \frac{1}{r^2 q_1^2}\left\{\left(\frac{\partial \psi}{\partial \alpha}\right)^2 + \left(\frac{\partial \psi}{\partial \beta}\right)^2\right\}. \qquad \text{(15)}$$

Values of the gradients $\partial r/\partial \alpha$, $\partial r/\partial \beta$ were obtained by numerical differentiation at all points of the grid and the corresponding values of $q_1^2 = 1/\ (\partial r/\partial \alpha)^2 + (\partial r/\partial \beta)^2$, $\partial \alpha/\partial r = q_1^2\, \partial r/\partial \alpha$, $\partial \beta/\partial r = q_1^2\, \partial r/\partial \beta$, were calculated. Substitutions were made in equation (11) to check the accuracy of the solution, and no error greater than one or two per cent was found.

Central and sloping difference formulae (*see* Ref. 4) were used for the numerical differentiation.

3.1. *Incompressible Flow.*—In order to have some idea of the values of the velocity at the corner points of the grid, a solution of equation (6) was obtained first for incompressible flow, *i.e.* $M_0 = 0$.

With $M_0 = 0$, and $\rho = \rho_0$, equations (14) and (15) become respectively

$$\underset{\alpha,\beta}{\nabla^2 \psi} = \frac{1}{r q_1^2}\left\{\frac{\partial \psi}{\partial \alpha}\cdot\frac{\partial \alpha}{\partial r} + \frac{\partial \psi}{\partial \beta}\cdot\frac{\partial \beta}{\partial r}\right\}, \qquad \text{(16)}$$

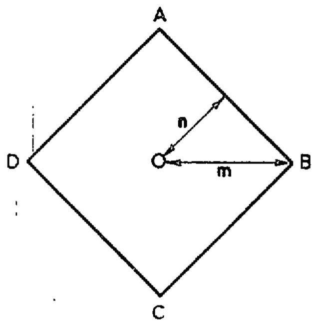
$$q^2 = \frac{1}{r^2 q_1^2}\left\{\left(\frac{\partial \psi}{\partial \alpha}\right)^2 + \left(\frac{\partial \psi}{\partial \beta}\right)^2\right\}. \qquad \text{(17)}$$

Take the centre-line of the tunnel to be the line $\psi = 0$. Then on the wall, ψ is given by

$$2\pi\psi = \rho_0\, U.\pi \times (\text{radius of downstream parallel portion})^2.$$

Values of ψ, assumed at the remaining points of the grid, were corrected by repeated applications of equation (10) until they settled.

In practice, it was found more convenient to work with diagonal squares, A, B, C, D being the values of ψ at the points shown. In this case equation (10) becomes



$$\psi_0 = \psi_M - \tfrac{1}{4} m^2 \nabla^2\psi \qquad \ldots \qquad (18)$$

where $2m$ is the diagonal, so that the working formula is

$$\psi_0 = \tfrac{1}{4}(A + B + C + D) - \tfrac{1}{4}\frac{m^2}{rq_1^2}\left[\frac{(B-D)}{2m}\frac{\partial\alpha}{\partial r} + \frac{(A-C)}{2m}\frac{\partial\beta}{\partial r}\right] \qquad \ldots \qquad (19)$$

where q_1, $\partial\alpha/\partial r$, $\partial\beta/\partial r$ and r assume their values at 0.

The value of m depends on the size of square used. To reduce the amount of computation, a large square, $m = 2$, was used initially until the field was settled, then the intervening values were filled in by interpolation and were resettled by equation (19).

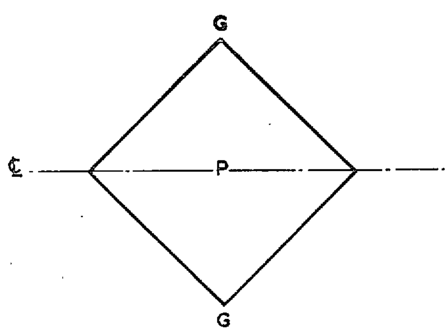
The values of q^2 were calculated by equation (17), except on the centre line where r, $\partial\psi/\partial\alpha$ and $\partial\psi/\partial\beta$ are all zero. It is easily proved that $1/r\ \partial\psi/\partial z \rightarrow 0$ on the centre-line, and hence from equation (9),

$$q^2 = \frac{1}{r^2}\left(\frac{\partial\psi}{\partial r}\right)^2$$

$$= \frac{1}{r^2}\left\{\frac{\partial\psi}{\partial\alpha}\frac{\partial\alpha}{\partial r} + \frac{\partial\psi}{\partial\beta}\frac{\partial\beta}{\partial r}\right\}^2 .$$

$$= q_1^4 [\nabla^2\psi]^2 \quad \text{from equation (16)}. \qquad \ldots \qquad (20)$$

Since the flow is symmetrical about the centre-line, ψ has the same value G at corresponding points on opposite sides of the line. Hence at any point P on the line, equation (18) gives



$$0 = \psi_P = \frac{G}{2} - \tfrac{1}{4} m^2 \nabla^2\psi ,$$

$$i.e.\ [\nabla^2\psi]_P = \frac{2G}{m^2} . \qquad \ldots \qquad (21)$$

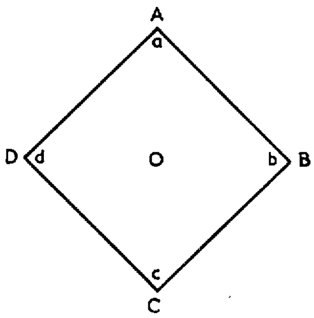
Combining equations (20) and (21) we get finally

$$q^2 = q_1^4 \frac{4G^2}{m^4} . \qquad \ldots \qquad (22)$$

The velocity ratio q/U rose to a maximum value of $0{\cdot}995$ at a point on the wall $4{\cdot}5$ feet ahead of the beginning of the working section. It then fell and increased again to unity after entering the working section. Curves of constant q/U are plotted in Fig. 2. The dotted lines show the values obtained by one-dimensional theory, *i.e.*, assuming uniform conditions across each cross-section.

(96125) A*

3.2. *Solution for Compressible Flow.* $M = 0 \cdot 7$.—Starting with the values of ψ and q_1^2/U^2 in the incompressible solution, the solution for $M = 0 \cdot 7$ proceeds as follows.



For the diagonal square shown, if capital letters denote values of ψ, and small letters values of q^2/U^2 at the given points, then the working formulae are:—

$$4\psi_0 = A + B + C + D - \frac{m}{2rq_1^2}\left[(B-D)\frac{\partial\alpha}{\partial r} + (A-C)\frac{\partial\beta}{\partial r}\right]$$

$$+ \frac{0 \cdot 06125\,[(B-D)\;(b-d) + (A-C)\;(a-c)]}{1 - 0 \cdot 098\,(q^2-1)}$$

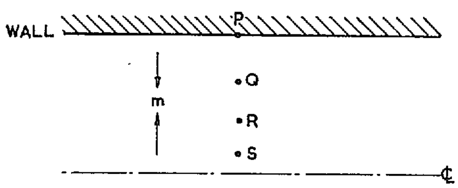
$$= A + B + C + D - \triangle \,. \qquad \ldots \quad (23)$$

At interior points, $\rho^2 q^2 = \dfrac{1}{r^2 q_1^2}\left[\dfrac{(B-D)^2 + (A-C)^2}{4m^2}\right]. \qquad \ldots \quad (24)$

On the centre-line, with the notation of equation (22)

$$\rho^2 q^2 = q_1^4 \frac{4G^2}{m^2} \,. \qquad \ldots \quad (25)$$

On the wall, $\rho^2 q^2 = \dfrac{1}{r^2 q_1^2}\left[\dfrac{11P - 18Q + 9R - 2S}{6m}\right]^2, \qquad \ldots \quad (26)$



where P, Q, R, S are the values of ψ at the points shown.

The ψ field was settled before calculations of $\rho^2 q^2$ were made. It was found unnecessary to use equation (23) in the second and successive rounds, since the correction term $\triangle$ was not affected by the changes obtained. The formula then became

$$4\,\delta\psi_0 = \delta A + \delta B + \delta C + \delta D$$

where $\delta\psi_0$, etc. were the differences obtained between the corrected values of ψ and the values obtained in the previous round.

When the values of ψ no longer moved, the new values of $\rho^2 q^2$ were calculated, and the corresponding values of q^2/U^2 were obtained from equation (8). With these new values of q^2/U^2 and the values of ψ obtained in the last calculation, equation (23) was again applied and the differencing process was repeated. This gave a further set of values of $\rho^2 q^2$ and hence of q^2/U^2. It was found necessary to repeat this process four or five times before there was no longer any variation in the values of ψ or of $\rho^2 q^2$.

The final ψ values showed an increase from the incompressible values over the whole field, the increment being much greater near the wall than near the centre line, *i.e.* the streamlines moved away from the wall, and the values of $\rho^2 q^2$ there decreased by such an amount that q^2 also decreased. There was still a patch of high velocity on the wall, but this was not so pronounced as in the incompressible solution. Curves of constant local Mach Number are plotted in Fig. 3.

4. *Use of Potential Function.*—An attempt was made to obtain algebraic solutions for ϕ and q^2 as power series in M^2 by means of the potential function. This method was attractive, since differentiation of ϕ gives q^2 directly, and equation (8) is eliminated.

A solution was obtained for incompressible flow, $M_0 = 0$. In the compressible case, however, the rate of convergence was extremely slow since the value of ϕ could be fixed at one point only and the compressibility effect had to be allowed to spread indefinitely both up and downstream. As there was no means at that time of estimating the final result, the method was abandoned.*

5. *Conclusions.*—Sufficient work has been done to show that the method described can be used to obtain solutions for the flow of a compressible fluid in a pipe of varying cross section, provided there are no discontinuities in the boundaries.

In this particular application, it will be seen that there is a definite tendency for the velocity to be lower on the centre line than on the wall, but the difference seems to become smaller as the working section is entered. In the incompressible case, there is a region of local high velocity close to the wall near the entrance to the working section, but this has no counterpart in the compressible case at high Mach Numbers.

---

* Since the calculations described in this paper were completed, a method has been developed by Thom[5] whereby the values of ϕ at infinity may be estimated by the use of influence factors. Thus the difficulties arising from the slow rate of convergence would be overcome and a solution in terms of the potential function obtained fairly quickly.

LIST OF SYMBOLS

ψ	stream function
ϕ	potential function
U	velocity in the downstream parallel portion
q	local velocity
u	axial component of velocity
v	radial component of velocity
a	local velocity of sound
M	Mach Number
ρ	density
p	pressure
γ	ratio of specific heats $= 1 \cdot 4$
z, r	distance measured along axis and radius respectively
$2n$	side of square
$2m$	diagonal of square
α, β	grid co-ordinates
q_1	velocity of transformation $= 1 \Big/ \left[\left(\frac{\partial r}{\partial \alpha}\right)^2 + \left(\frac{\partial r}{\partial \beta}\right)^2\right]^{1/2}$
∇	vector operator

$$\nabla^2_{z,r} = \frac{\partial^2}{\partial z^2} + \frac{\partial^2}{\partial r^2}.$$

Suffix 0 denotes conditions in the downstream parallel portion *A*, *B*, *C*, *D*, *P*, *Q*, *R*, *S*, *G*, *a*, *b*, *c*, *d*, $\triangle$—*see* sections 3.1 and 3.2.

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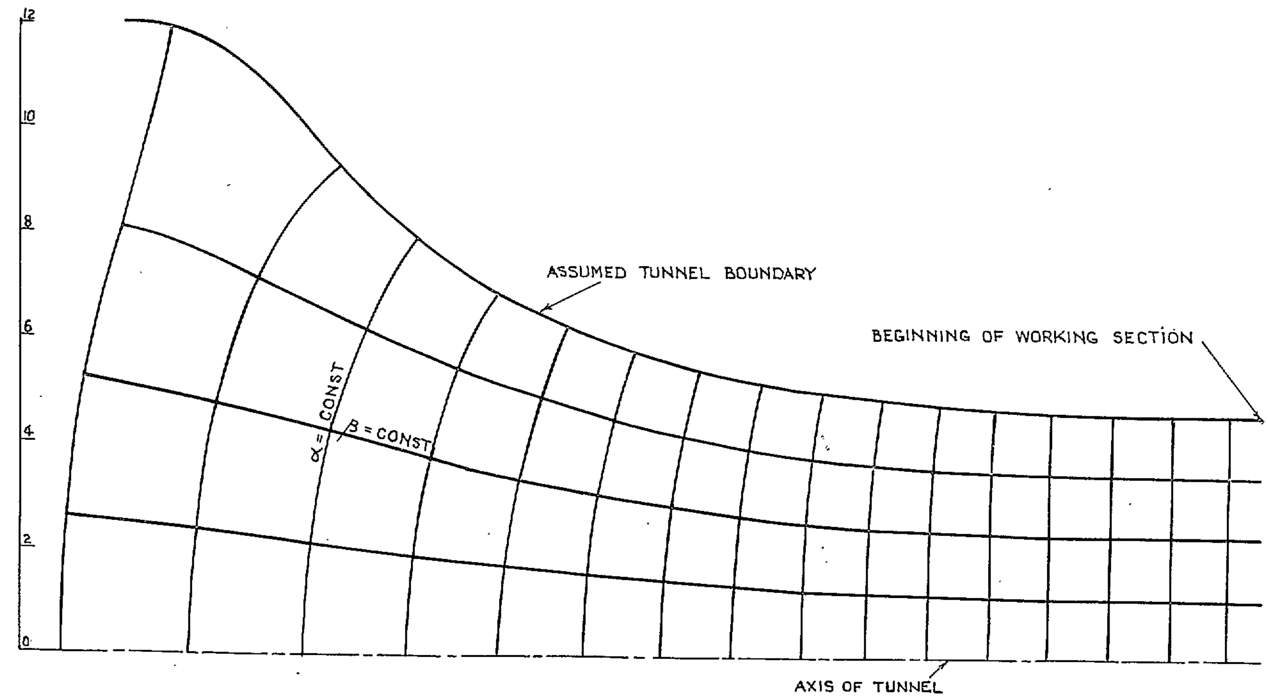

FIG. 1. Two dimensional network of stream and equipotential lines used as grid for the case of axial symmetry.

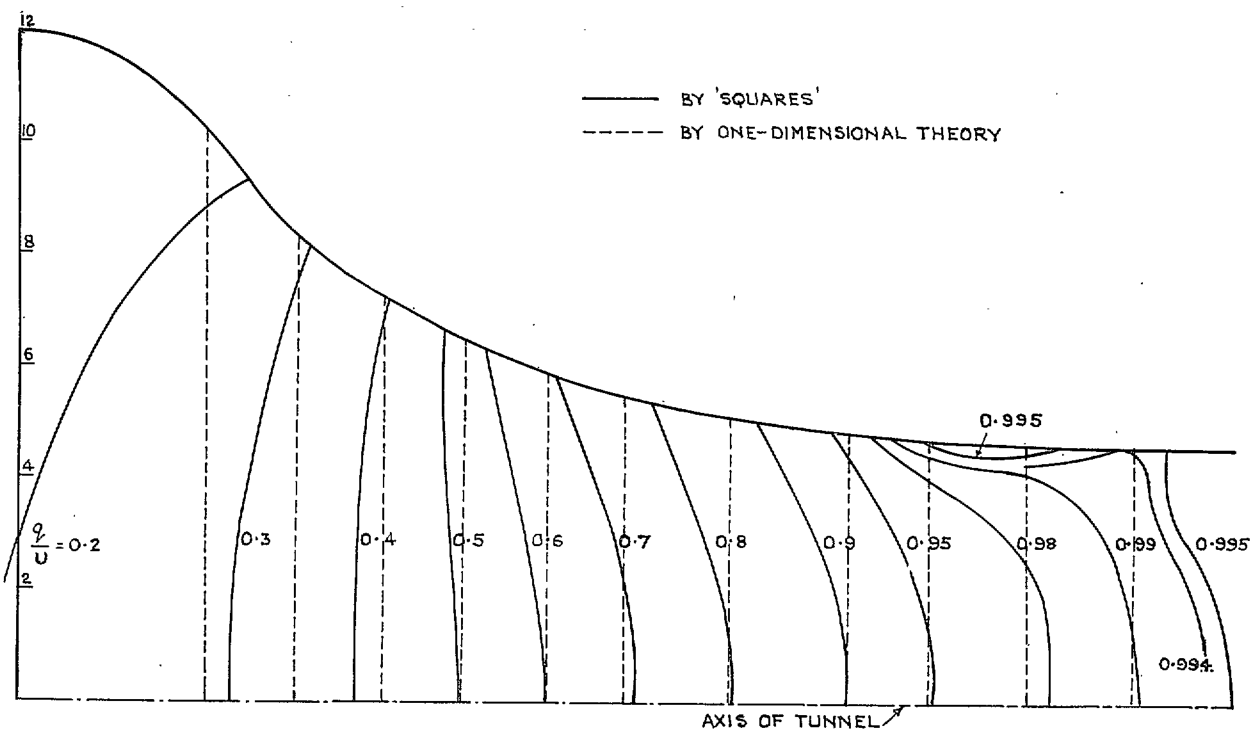

FIG. 2. Flow through a contraction in a circular tunnel—incompressible case.
Mach number = 0 velocity distribution.

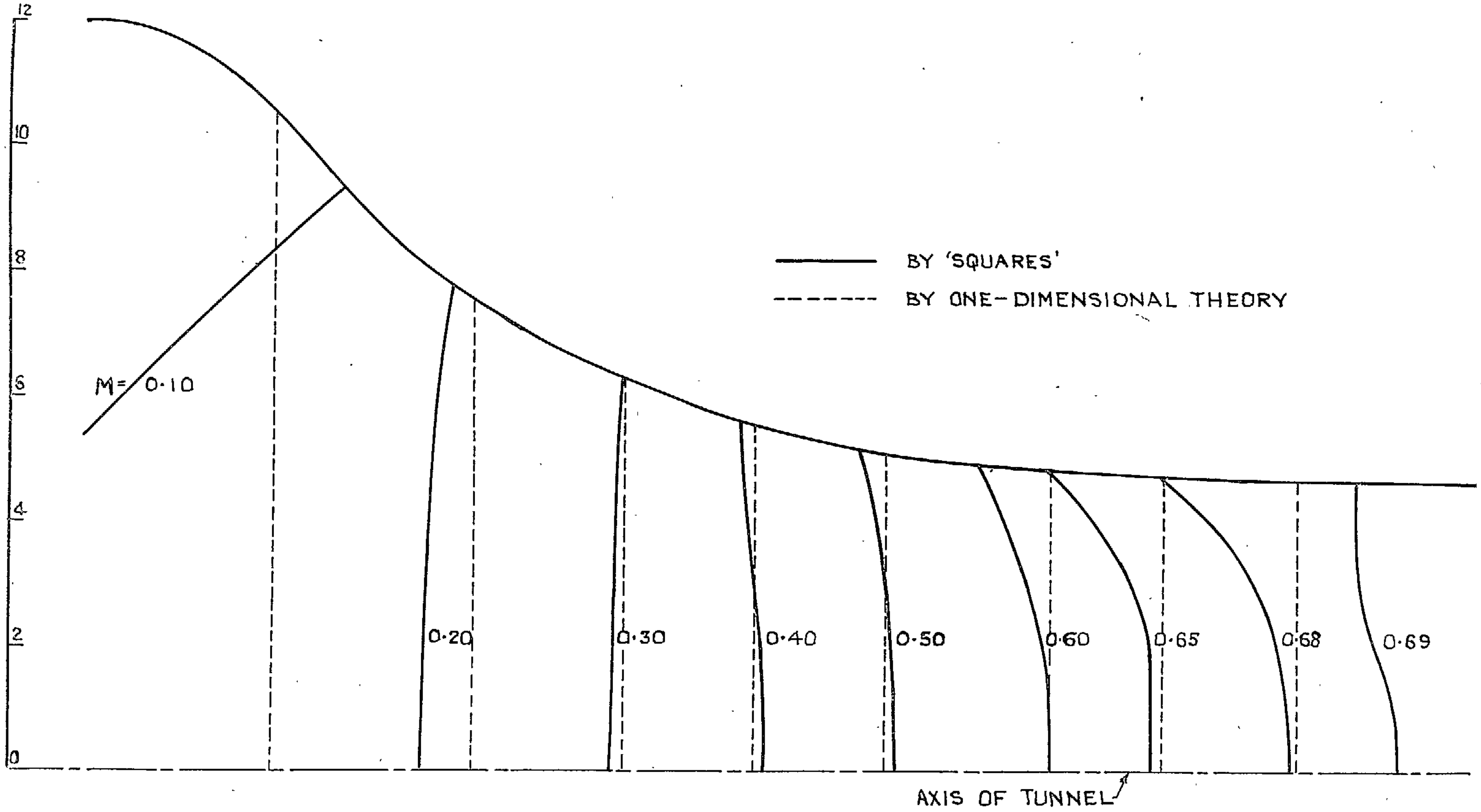

FIG. 3. Flow through a contraction in a circular tunnel—compressible case.
Mach number in downstream parallel portion = 0·7 Mach number distribution.

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