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by

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WALL BOUNDARY LAYERS IN CASCADES

- by -
H. Marsh

SUMMARY

When a boundary layer passes through a cascade, this is an example of the turning of a shear flow. Secondary flow theory predicts that for inviscid flow, there is a change in the velocity profile. This paper examines six theories for the wall boundary layer and compares their predictions for the change of momentum thickness caused by the turning of an inviscid shear flow. It is shown that three theories, refs. (3), (5) and (7), give predictions which are in close agreement with experimental data and this suggests that the inviscid re-adjustment of the flow is the dominant effect in many cascades. The momentum and energy approaches are discussed and the further development of the energy approach is recommended.

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* Replaces A.R.C. 37358

Nomenclature

B	defined in equation (32)
c	chord
F_{eff}	effective blade force
n	exponent in power law profile
q	velocity
Q	velocity at the edge of the boundary layer in the direction of the mainstream flow
u	axial velocity, velocity normal to the cascade
U	velocity at the edge of the boundary layer in the axial direction
V	mainstream velocity, ref. (8)
x	direction normal to the cascade
z	direction normal to the wall
α	flow angle
δ	thickness of the boundary layer
δ^*	displacement thickness
θ	momentum thickness
ρ	density
τ_w	wall shear stress
ψ	stream function

Subscripts

1	upstream, inlet to the cascade
2	downstream, outlet from the cascade

INTRODUCTION

The prediction of the development of the wall boundary layer is one of the major problems in the analysis of turbomachinery flows. Over the past twenty years, much effort has been devoted to methods of boundary layer prediction which might be suitable for turbomachines. The wall boundary layer is an unusual boundary layer in that it contains blades which exert a force on the fluid so as to change its momentum. Furthermore, the rate of change of velocity in the direction of flow can be very high; it is not unusual to have a change of 30 per cent in velocity in a distance which is of the same order as the thickness of the boundary layer. For the turbomachine, the basic assumptions of conventional boundary layer theory must be re-examined and checked by experiments.

Several authors have presented theories for the development of the wall boundary layer and have compared their predictions with experimental results. For lightly loaded blades, there appears to be a reasonable level of agreement between the predictions and the measured values of displacement and momentum thicknesses. However, a lightly loaded blade row is an example where the change in the wall boundary layer is small and the designer may be more interested in highly loaded blading. The level of agreement between the predicted and measured boundary layers for highly loaded blading is not satisfactory. It should be noted that in most of the calculations, the upstream values of momentum and displacement thicknesses are taken from experimental data, so that the theory is being used to calculate the change in the momentum and displacement thicknesses. When viewed in this more critical sense, the level of agreement between the predicted and experimental changes in θ

δ^* can only be regarded as fair; a factor of two in error is not unusual.

The purpose of this paper is to re-examine some of the theories for wall boundary layers and to question the use of the momentum integral equation in a situation where momentum is not conserved for an inviscid flow. For simplicity, the discussion is confined to wall boundary layers in linear cascades and it is assumed that the changes of momentum and displacement thickness are caused by:

a) an inviscid re-adjustment of the flow, and

b) viscous effects.

The wall boundary layer is a shear flow and when this is turned in a cascade, there is a change of the velocity profile. This change in the wall boundary layer is an inviscid effect and can be predicted from Kelvin's circulation theorem or Bernoulli's equation. The inviscid re-adjustment of the wall boundary layer may give a first approximation to the change of the momentum and displacement thicknesses on passing through a cascade and the inclusion of viscous effects would be a further refinement for this model.

It is suggested that useful information about the theories for wall boundary layers can be obtained by examining their prediction for the inviscid re-adjustment of the inlet boundary layer, all viscous effects within the cascade being neglected. If a theory, with the neglect of viscous effects, leads to a model which is consistent with the equations for inviscid flow, and there is reasonable agreement with experimental data for the change of the wall boundary layer, then this may indicate that the method has potential for predicting wall boundary layers in turbomachines.

SOME THEORIES FOR WALL BOUNDARY LAYERS

In the analysis, it will be assumed that a wall boundary layer has formed upstream of the cascade and that within the cascade, there are no viscous effects. The change in the wall boundary layer on passing through the cascade is then an inviscid flow effect. To simplify the problem, it will be assumed that there is no change of axial velocity across the cascade and that at inlet and outlet, the velocity profiles can be represented by power laws,

$$q_1 = Q_1 \left[\frac{z}{\delta_1}\right]^{n_1} \text{ at inlet}$$

and

$$q_2 = Q_2 \left[\frac{z}{\delta_2}\right]^{n_2} \text{ at outlet} . \qquad (1)$$

For a many bladed cascade, the axial velocity profiles will obey the same power law

$$u_1 = U_1 \left[\frac{z}{\delta_1}\right]^{n_1} \text{ at inlet}$$

and

$$u_2 = U_2 \left[\frac{z}{\delta_2}\right]^{n_2} \text{ at outlet} \qquad (2)$$

With no viscous effects, the flow within the boundary layer remains constant and hence the stream function at the edge of the shear layer is constant,

$$\psi_{\delta_1} = \psi_{\delta_2}$$

or

$$\left(\frac{U\delta}{1+n}\right)_1 = \left(\frac{U\delta}{1+n}\right)_2 \qquad (3)$$

so that

$$\frac{\delta_2}{\delta_1} = \frac{U_1}{U_2}\left(\frac{1+n_2}{1+n_1}\right) \qquad (4)$$

Furthermore, for a power law profile, the displacement and momentum thicknesses are given by

$$\left.\begin{aligned} \delta^* &= \frac{\delta n}{1+n} \\ \text{and} \qquad \theta &= \frac{\delta n}{(1+n)(1+2n)} \end{aligned}\right\} \qquad (5)$$

From equations (4) and (5), we have

$$\frac{\delta_2^*}{\delta_1^*} = \frac{\delta_2 n_2}{1+n_2} \cdot \frac{1+n_1}{\delta_1 n_1}$$

$$= \frac{U_1}{U_2} \cdot \frac{n_2}{n_1} \qquad (6)$$

and

$$\frac{\theta_2}{\theta_1} = \frac{\delta_2^*}{1+2n_2} \cdot \frac{1+2n_1}{\delta_1^*}$$

$$= \frac{U_1}{U_2}\left(\frac{n_2}{1+2n_2}\right)\left(\frac{1+2n_1}{n_1}\right) \qquad (7)$$

If there is no change of axial velocity across the cascade, then equations (4), (6) and (7) become

$$\frac{\delta_2}{\delta_1} = \frac{1+n_2}{1+n_1} \qquad (8a)$$

$$\frac{\delta_2^*}{\delta_1^*} = \frac{n_2}{n_1} \qquad (8b)$$

and

$$\frac{\theta_2}{\theta_1} = \frac{n_2}{n_1} \cdot \left(\frac{1+2n_1}{1+2n_2}\right) \qquad (8c)$$

If the exponent n_2 can be calculated for the flow at exit from the cascade, then it is possible to estimate the change in the wall boundary layer from these equations.

Railly and Howard (1)

Railly and Howard defined the displacement and momentum thicknesses for the axial direction as

$$\left.\begin{aligned} U\delta_x^* &= \int_0^\delta (U-u)\,dz \\ U^2\theta_{xx} &= \int_0^\delta u(U-u)\,dz \end{aligned}\right\} \qquad (9)$$

and derived momentum integral equations for the axial and tangential directions. The equation for the axial direction is

$$\frac{d}{dx}\left(U^2\theta_{xx}\right) + \delta_x^* U \frac{dU}{dx} = \frac{\tau_{wx}}{\rho} \qquad (10)$$

so that with constant axial velocity and no viscous effects,

$$\frac{d\theta_{xx}}{dx} = 0 \qquad (11)$$

The theory predicts that there is no change in the momentum thickness,

$$\theta_{xx2} = \theta_{xx1} \qquad (12)$$

and from equation (8a), $n_1 = n_2$. It is clear that this theory does not contain the inviscid readjustment of the flow which takes place when a shear layer is turned by a cascade. The reason may be that Railly and Howard have based their analysis on conventional boundary theory with $\delta \ll s\cos\alpha_2$, whereas for the many bladed cascade, $\delta \gg s\cos\alpha_2$.

Stratford (2)

Stratford considered the change of axial momentum across a blade row and with the same nomenclature as equations (9), he derived a momentum integral equation

$$\frac{d}{dx}\left(U^2\Theta_{xx}\right) + U\delta_x^*\frac{dU}{dx} = \frac{\tau_{wx}}{\rho} \tag{13}$$

This is identical with the axial momentum integral equation of Railly and Howard (1) and for constant axial velocity and no viscous effects, it predicts

$$\begin{aligned} \Theta_{xx2} &= \Theta_{xx1} \\ n_2 &= n_1 \end{aligned} \tag{14}$$

and no change in the wall boundary layer.

Mellor and Wood (3)

Mellor and Wood have developed a theory which includes an effective blade force and they have suggested that the direction of this force remains constant through the boundary layer. They express this condition as

$$U\left[F_{eff}\right]_x + (1-\epsilon)\,V_y\left[F_{eff}\right]_y = 0 \tag{15}$$

For flow in a many bladed cascade, a single momentum integral equation is obtained and for $\epsilon = 0$, corresponding to an effective blade force normal to the mainstream flow, this equation is

$$\frac{d}{dx}\left(U^2\theta_{xx}\right) + U\delta_x^*\frac{dU}{dx} + U^2\operatorname{Tan}\alpha\left(\theta_{xx}+\delta_x^*\right)\frac{d\alpha}{dx} = \frac{\tau_{wx}}{\rho} \tag{16}$$

When the viscous effects are neglected and the axial velocity is constant, then

$$\frac{d\theta_{xx}}{dx} + \operatorname{Tan}\alpha\left(\theta_{xx}+\delta_x^*\right)\frac{d\alpha}{dx} = 0 \tag{17}$$

Now the displacement and momentum thicknesses can be written as

$$\left.\begin{aligned} \delta_x^* &= \frac{\psi_\delta}{U} \cdot n \\ \theta_{xx} &= \frac{\psi_\delta}{U} \cdot \frac{n}{1+2n} \end{aligned}\right\} \qquad (18)$$

where ψ_δ and U are both constant. These expressions for δ_x^* and θ_{xx} can be substituted into equation (17) to obtain

$$\frac{d}{dx}\left(\frac{n}{1+2n}\right) + \frac{2n(1+n)}{1+2n} \tan\alpha \frac{d\alpha}{dx} = 0 \qquad (19)$$

This equation can be integrated to give the variation of n with the flow angle α,

$$\frac{n\,(1+n)}{(1+2n)^2 \cos^2\alpha} = \text{constant} \qquad (20)$$

or for constant axial velocity,

$$\frac{n\,(1+n)\,Q^2}{(1+2n)^2} = \text{constant} \qquad (21)$$

The change in the wall boundary layer can be predicted from equation (20) or (21) and comparison with experimental data will show whether this inviscid effect is of the correct form.

Horlock (4) and Marsh and Horlock (5)

Horlock has used the passage averaged flow equations and has derived momentum integral equations for the streamwise and normal directions. Later, the analysis was extended to include the blade force deficit in the boundary layer, ref. (5), and the momentum integral equation then took the form

$$\frac{d}{dx}(U^2\theta_{xx}) + U\,\delta_x^*\frac{dU}{dx} + U^2 \tan\alpha\,(\theta_{xx}+\delta_x^*)\frac{d\alpha}{dx} = \frac{\tau_{wx}}{\rho} \qquad (22)$$

This equation is identical with that of Mellor and Wood, equation (16), and when the viscous effects are neglected, it leads to equation (21) for the change in the profile of the wall boundary layer.

Horlock and Perkins (6)

Horlock and Perkins have given a very detailed treatment of the blade force deficit and have derived a momentum integral equation for the axial direction,

$$\frac{d}{dx}\left(U^2\theta_{xx}\right) + U\delta_x^*\frac{dU}{dx} = \frac{\tau_{wx}}{\rho} \tag{23}$$

For constant axial velocity and no viscous effects, this equation predicts that there is no change in the wall boundary layer on passing through a cascade.

Glynn, Spurr and Marsh (7)

Glynn, Spurr and Marsh have put forward a simple theory based on secondary flow analysis which attempts to predict the inviscid re-adjustment of a shear flow on passing through a cascade. When a shear layer passes through a cascade, there is a change in the normal component of vorticity and the velccity profile is changed. By applying Kelvin's circulation theorem to the flow on a mean stream surface passing through a cascade, it is found that

$$\left[q\frac{\partial q}{\partial \psi}\right]_{\text{upstream}} = \left[q\frac{\partial q}{\partial \psi}\right]_{\text{downstream}} \tag{24}$$

where ψ is the stream function for the flow on the mean stream surface. This equaticn can also be obtained by assuming that there is no spanwise variation of pressure in the flow upstream and downstream of the cascade, so that from Bernoulli's equation,

$$Q_1^2 - q_1^2 = Q_2^2 - q_2^2$$

and differentiating with respect to ψ,

$$q_1 \frac{\partial q_1}{\partial \psi} = q_2 \frac{\partial q_2}{\partial \psi}$$

Equation (24) assumes that there is no loss of stagnation pressure along any streamline and this may be a reasonable first approximation for the outer part of the boundary layer.

If any viscous effects are confined to the inner boundary layer, say $\psi = 0$ to $\psi = 0.1\ \psi_\delta$, then integrating over the outer part,

$$\int_{0.1\psi_{\delta_1}}^{\psi_{\delta_1}} (Q_1^2 - q_1^2)\, d\psi = \int_{0.1\psi_{\delta_2}}^{\psi_{\delta_2}} (Q_2^2 - q_2^2)\, d\psi \tag{25}$$

For inlet and exit profiles which can be represented by power laws, equation (25) becomes

$$Q_1^2 \cdot \psi_{\delta_1} \cdot f(n_1) = Q_2^2 \cdot \psi_{\delta_2} \cdot f(n_2) \tag{26}$$

where $$f(n) = 0.9 - \frac{1+n}{1+3n}\left[1 - \left(\frac{1}{10}\right)^{\frac{1+3n}{1+n}}\right]$$

But the flow within the boundary layer remains constant, so that $\psi_{\delta 1} = \psi_{\delta 2}$ and equation (25) is then

$$Q_1^2 f(n_1) = Q_2^2 f(n_2) \tag{27}$$

If the inlet profile and Q_2 are known, then equation (27) can be used to determine the exponent n_2 for the outlet boundary layer. Calculations indicate that the solution for n_2 is not sensitive to the extent of the boundary layer over which the integration is taken in equation (25).

It might be argued that in the comparison with the other theories for wall boundary layers, where all viscous effects are neglected, the integration of equation (25) should extend across the entire boundary layer

$$\int_0^{\psi_\delta} (Q_1^2 - q_1^2)\, d\psi = \int_0^{\psi_\delta} (Q_2^2 - q_2^2)\, d\psi \tag{28}$$

For inlet and exit profiles which can be represented by power laws, equation (28) becomes

$$Q_1^2 \cdot \psi_\delta \cdot \left(\frac{2 n_1}{1+3n_1}\right) = Q_2^2 \cdot \psi_\delta \cdot \left(\frac{2 n_2}{1+3n_2}\right) \tag{29}$$

or

$$\frac{Q_1^2 n_1}{1+3n_1} = \frac{Q_2^2 n_2}{1+3n_2} \tag{30}$$

The calculation of the change of momentum thickness now consists of solving equation (30) for n_2 and then substituting this value into equation (8c),

$$\frac{\theta_2}{\theta_1} = \frac{\left(2+\frac{1}{n_1}\right)}{\left(2+\frac{1}{n_2}\right)} \frac{U_1}{U_2} = \left[\frac{2+\frac{1}{n_1}}{\frac{Q_2^2}{Q_1^2}\left(3+\frac{1}{n_1}\right) - 1}\right] \frac{U_1}{U_2} \tag{31}$$

The ratio of momentum thicknesses is then a simple function of the exponent n_1, the velocity ratio Q_2/Q_1 and the axial velocity ratio U_2/U_1.

A COMPARISON WITH EXPERIMENTAL DATA

Papailiou, Flot and Mathieu (8) have presented a correlation of data on wall boundary layers which has been obtained from 85 tests with compressor blades, turbine blades and inlet guide vanes. Following earlier work by Papailiou, they present their correlation as

$$\frac{\theta_2}{\theta_1} = \left(\frac{V_1}{V_2}\right)^3 (1+B)^{5/6} \quad \frac{V_{x1}}{V_{x2}} \tag{32}$$

where

$$B = \left[\frac{C_f}{2\theta_1/c}\right]^{6/5} \frac{\left(\frac{V_1}{V_2}\right)^{4.4} - 1}{4.4\left(\frac{V_1}{V_2}\right)^{3.4}\left[\frac{V_1}{V_2} - 1\right]}$$

The experimental data is shown in fig. 1 as a broad band which follows the general trend of equation (32), the scatter being about $\pm$ 20 per cent.

The analysis given in this paper can be compared with the experimental data in fig. 1 to determine the extent to which the experimental results can be predicted as a re-adjustment of an inviscid shear flow. Fig. 2 shows the predictions for θ_2/θ_1 which are obtained from the various theories for $n_1 = 1/7$ when the viscous effects are neglected and the axial velocity ratio remains constant. On comparing figs. 1 and 2, it is seen that those theories which predict no change of momentum thickness, refs. (1) (2) and (6), do not give the general trends of the experimental results. On the other hand, the theories of Mellor and Wood (3) and Marsh and Horlock (5) both lead to a predicted variation of θ_2/θ_1 which shows the trend of the experimental data. The new approach of Glynn, Spurr and Marsh (7) is based on Bernoulli's equation and this gives a predicted variation for θ_2/θ_1 which lies slightly below that of Mellor and Wood.

Fig. 3 shows a direct comparison between the three theories of refs. (3), (5) and (7) and the experimental data of Papailiou, Flot and Mathieu (8). The experimental results for θ_2/θ_1 have been plotted as a function of a parameter which includes the axial velocity ratio and a viscous effect, whereas the theories are based on inviscid flow with constant axial velocity. The level of agreement between the experimental data and the inviscid theories is very good; the general form of the data is well represented, although the predictions for θ_2/θ_1, tend to lie near the lower boundary. This comparison suggests that in the flow through a cascade, the inviscid re-adjustment of the flow in the boundary layer may be a major effect in determining the change of momentum thickness. Further calculations for each cascade in the correlation would show whether the inclusion of viscous effects improves the level of agreement.

The theory of Glynn, Spurr and Marsh (8) is an extension of their work on secondary flow and it is therefore based on applying the equations of inviscid fluid dynamics to the turning of a shear layer in a cascade. In terms of boundary layer theory, equation (28) states that the energy deficit within the boundary layer remains unchanged as the flow passes through a cascade and this theory can be considered as an energy approach. The other theories are all based on momentum considerations, with various assumptions about pressure, or pressure gradients, being transmitted through the boundary layer and with a variation of the blade force through the boundary layer. The comparisons of figs. 2 and 3 suggest that the mathematical models of Mellor and Wood (3) and Marsh and Horlock (5) may be a good approximation for the turning of a shear layer in a cascade, even though these theories do not give exact agreement with inviscid secondary flow theory.

In the further development of theories for wall boundary layers, there is a choice between continuing with the momentum integral approach, with the difficulties associated with estimating the blade force deficit, or alternatively, modifying the inviscid energy approach to include viscous effects. The comparisons given in this paper indicate that a more detailed investigation of the energy approach would be justified and that it might provide a better basis for the analysis of wall boundary layers in turbomachines.

The inviscid theory of ref. (7) appears to give good agreement with the cascade data and this is achieved with a remarkably simple calculation which could be a short subroutine in a through-flow programme. The theory appears to give the lower boundary to the experimental results and a better approximation to the data is

$$\frac{\theta_2}{\theta_1} = 1.3 \left(\frac{\theta_2}{\theta_1}\right)_{\text{theory}}$$

This simple empirical rule provides a good estimate for the change in momentum thickness and it indicates that in many cascades, viscous effects may not be large.

CONCLUSIONS

When a wall boundary layer passes through a cascade, this is an example of the turning of a shear flow. Secondary flow theory predicts that there is a change in the shape of the velocity profile, an inviscid re-adjustment of the flow in the wall boundary layer. A theory for wall boundary layers in turbomachines should be capable of predicting this change of profile for the inviscid flow. This paper has therefore concentrated on examining several theories for wall boundary layers and it has shown that these theories may give very different predictions for the turning of an inviscid shear flow. Three theories predict a significant change in the momentum thickness as the flow passes through a cascade, while three other theories predict no change in momentum thickness.

Papailiou, Flot and Mathieu (8) have provided a correlation of data on momentum thickness which is taken from tests on 85 cascades. This data can be used to test the theories for wall boundary layers. The comparisons show that the theories of Mellor and Wood (3), Marsh and Horlock (5) and Glynn Spurr and Marsh (7) predict a change of momentum thickness which is in close agreement with the experimental results. The predictions based on inviscid flow lie close to the lower boundary for the experimental data and the better agreement may be obtained when viscous effects are included. The comparisons given in this paper suggest that the inviscid re-adjustment of the flow in the wall boundary layer may be the dominant effect in many cascades.

In the development of the theory for wall boundary layers in cascades or turbomachines, there is a choice between continuing with the momentum integral approach of refs. (1), (2), (3), (5) and (6), or attempting to include viscous effects into the energy approach of ref. (7). A major difficulty in the momentum approach is that for flow through a cascade, momentum is not conserved and assumptions must be made for the variation of the blade force in the boundary layer. In the energy approach, the energy deficit is conserved for an inviscid flow and it may be possible to develop this theory by adding the viscous effects, without the need to specify the variation of the blade force in the boundary layer. The inviscid energy approach of ref. (7) leads to good agreement with the experimental data of Papailiou, Flot and Mathieu (8). This suggests that with the inclusion of viscous effects, the energy approach might provide a better basis for the prediction of wall boundary layers in turbomachines.

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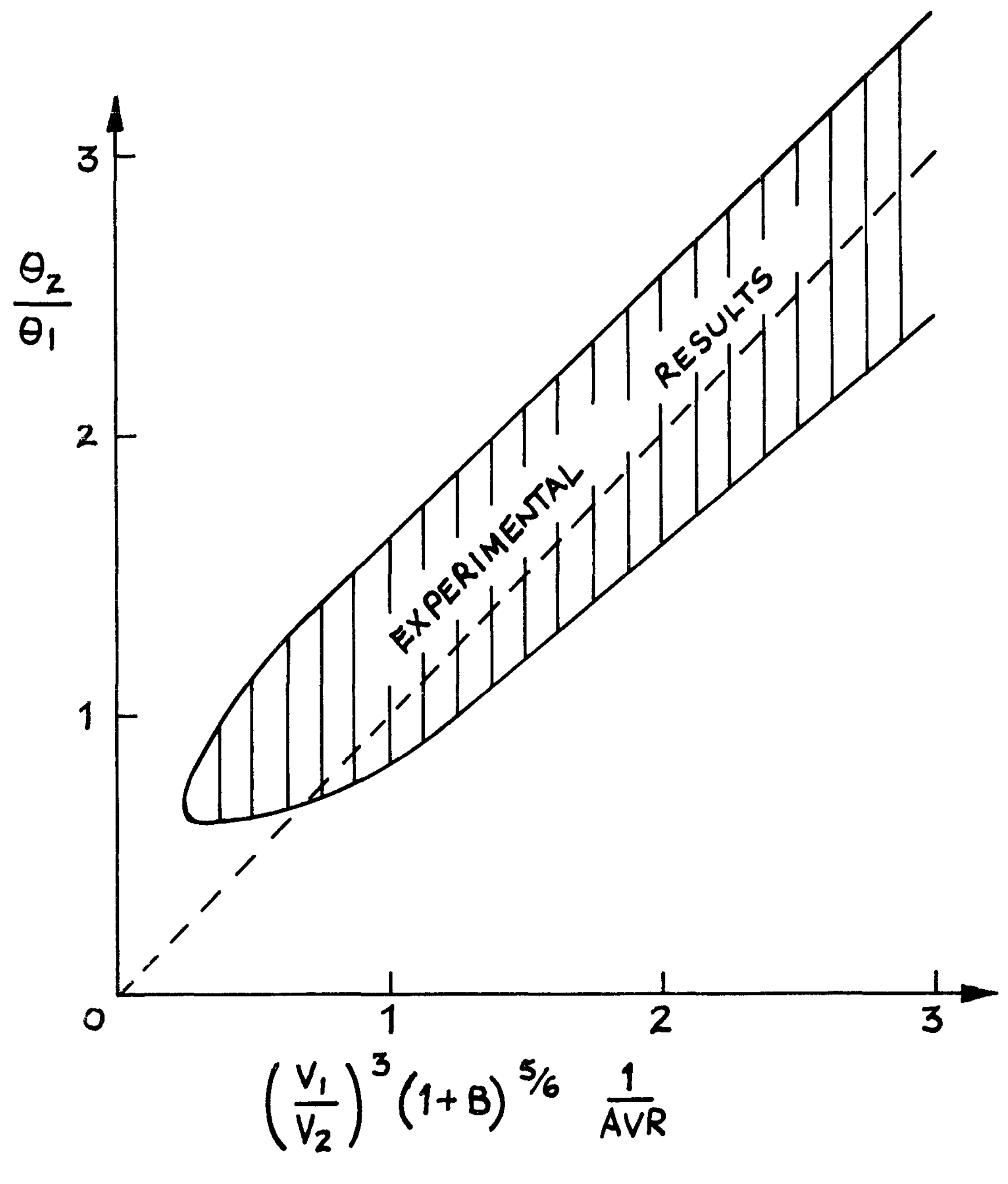
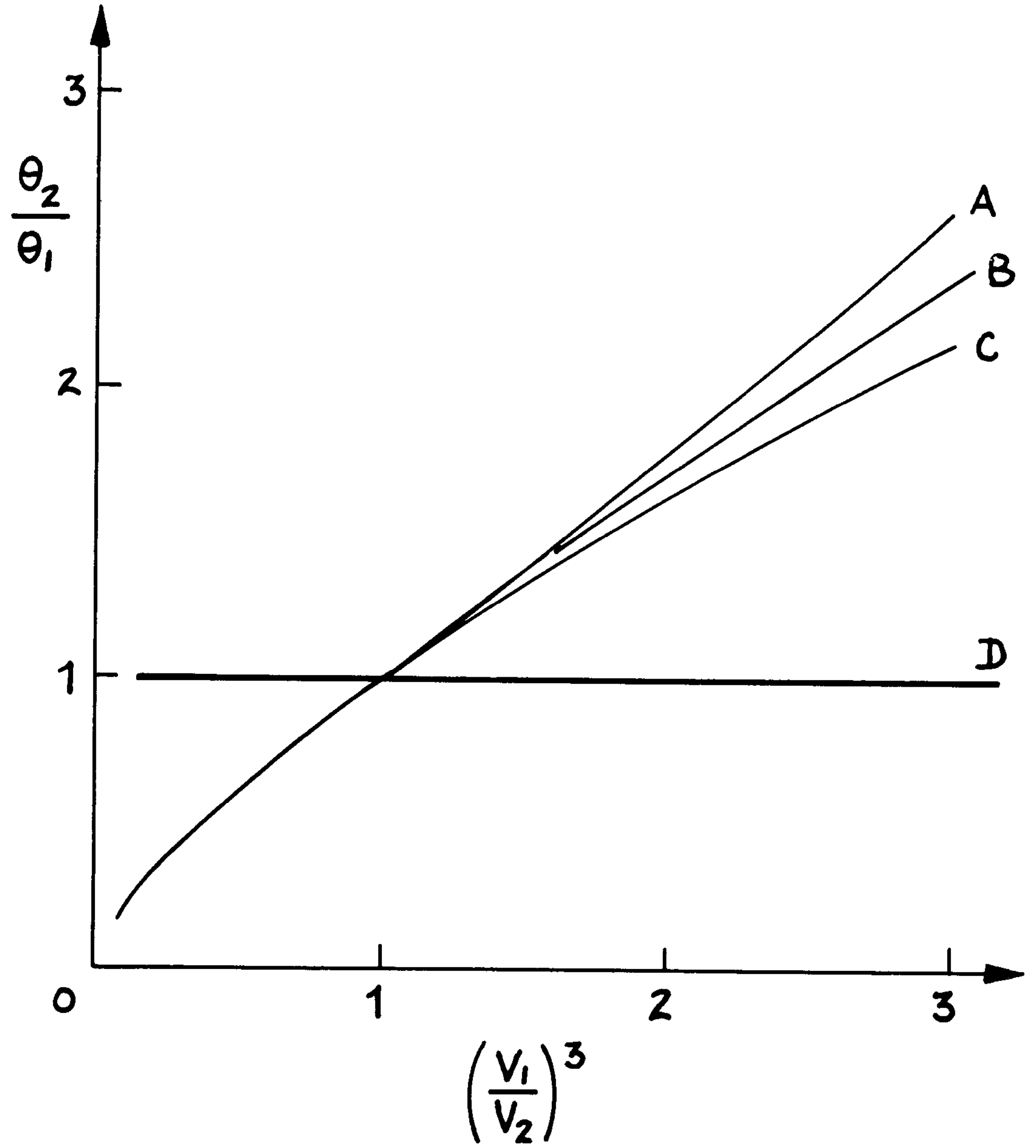


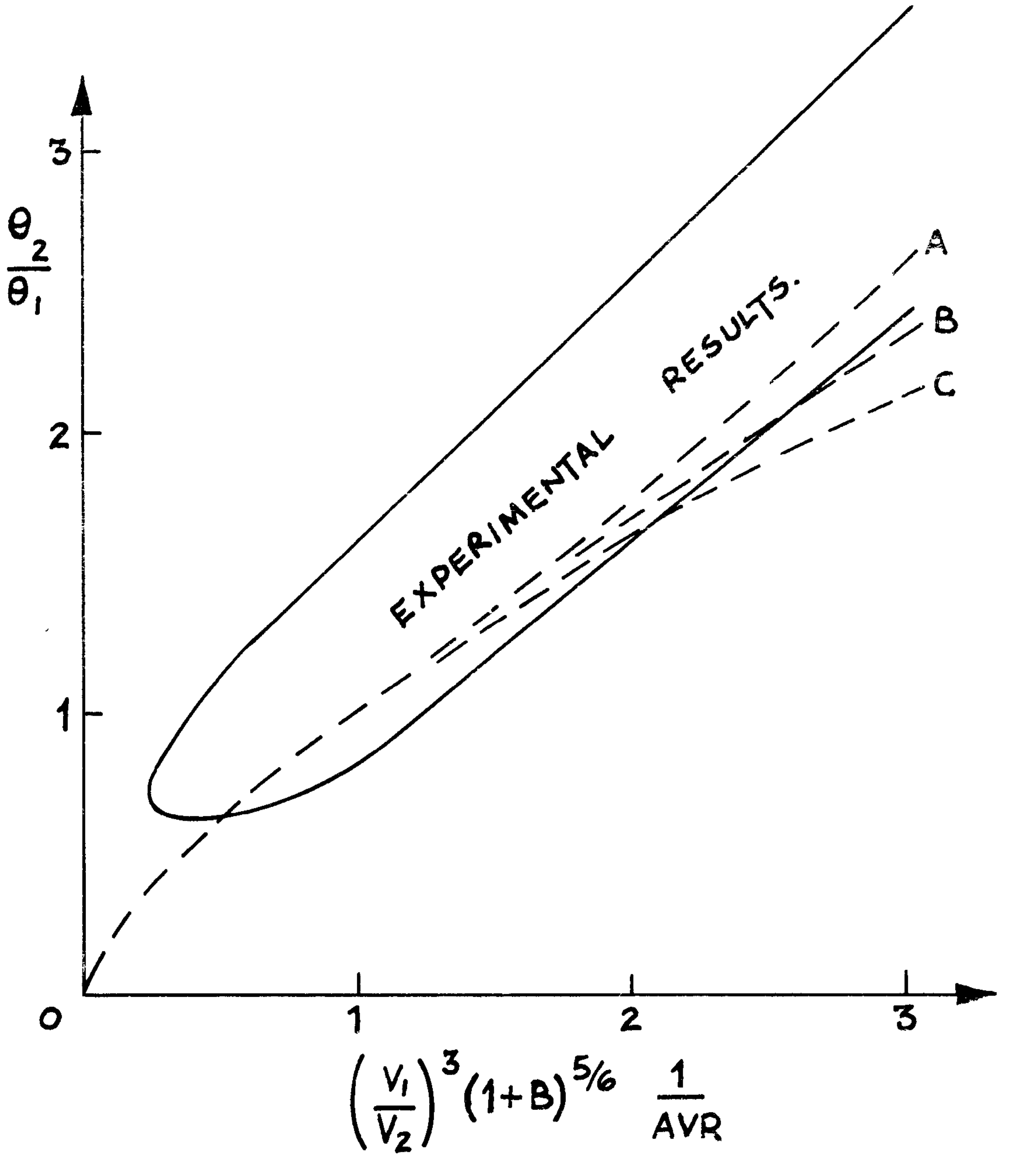
Fig.1. CORRELATION FOR CASCADE FLOWS. (8)



$n_1 = \frac{1}{7}$

- A REFS. 3 & 5.
- B " 7 FULL BOUNDARY LAYER.
- C " 7 OUTER 90% OF BOUNDARY LAYER.
- D " 1, 2 & 6.

Fig. 2. THEORIES FOR WALL BOUNDARY LAYERS.



A REFS. 3 & 5
B " 7 FULL BOUNDARY LAYER.
C " 7 OUTER 90% OF BOUNDARY LAYER.

Fig. 3. COMPARISON WITH EXPERIMENTAL RESULTS.

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