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Some Notes on Turbulent Boundary Layers with Fluid Injection at High Supersonic Speeds

by

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SOME NOTES ON TURBULENT BOUNDARY LAYERS WITH FLUID INJECTION AT HIGH SUPERSONIC SPEEDS

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L. C. Squire, Ph.D.

SUMMARY

Transpiration cooling has been suggested as a research topic for the High Supersonic Speed wind tunnel (M = 2·5 to 5·0) at R.A.E. Bedford. In these notes a brief review of existing work on this subject is given and regions where more experimental work is needed are pointed out.

Using existing data an attempt is made to assess the importance of transpiration cooling for a long range aircraft flying at high supersonic speeds.

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CONTENTS

ILLUSTRATIONS

1 INTRODUCTION

The research programme of the H.S.S. tunnel at R.A.E. Bedford includes both aimed research, particularly in the fields of lifting surfaces and engine aerodynamics, and basic research mainly connected with boundary layer flows. One suggested item in the boundary layer research programme is that of fluid injection into turbulent boundary layers to reduce skin-friction and heat transfer. It was decided that any experimental work should be preceded by (a) a review* of existing work in this field in order to establish worthwhile research topics for the tunnel; and (b) calculations, insofar as they could be made from existing data, to assess the order of possible advantages from the practical application of fluid injection at flight speeds within the tunnel speed range ($2\cdot5 \leqslant M \leqslant 5\cdot0$). Results of both studies are given in the present note.

A comprehensive review of the topic has been made by Craven[1]. In the following notes (Section 2) an attempt is made rather to highlight gaps in the existing knowledge.

2 REVIEW OF EXISTING WORK

2.1 Analytic methods

A variety of methods, ranging from simple film theory to complex mixing-length analysis, has been used to predict the heat transfer and skin friction in a turbulent flat-plate boundary layer with fluid injection. The most complete methods appear to be those of Turcotte[2], who uses a sub-layer theory in incompressible flow with air as the injected fluid, and of Rubesin[3,4], who uses mixing length for both air and foreign-gas injection. Both theories refer essentially to the case of zero pressure gradient.

Turcotte assumes that the main effect of fluid injection is produced in the laminar sub-layer. Using Rannie's formulation[5] for the eddy viscosity near the wall, he derives a formula for the ratio of skin-friction with injection to that without injection. This formula contains a single free parameter, b, the value of which lies in the range $1 \leqslant b \leqslant \sqrt{\tau_{w_o}/\tau_w}$. Using a mean of these two extreme values, Turcotte's formula becomes:-

$$\frac{\tau_w}{\tau_{w_o}} = e^{-6\cdot94(v_w/u_{\tau_o})\left(1 + \sqrt{\tau_{w_o}/\tau_w}\right)} \tag{1}$$

or

$$= e^{-6\cdot94\left(\frac{v_w}{u_1}\sqrt{\frac{2}{C_{f_o}}}\right)\left(1 + \sqrt{\tau_{w_o}/\tau_w}\right)} \tag{2}$$

This result is found to be in good agreement with the measurements of Mickley and Davies[6].

*This paper was written primarily as an internal R.A.E. document to help in the planning of the H.S.S. Tunnel programme; as a result it did not aim to provide a really comprehensive review of the subject.

Nash[7] has pointed out that since Turcotte's ·ory stresses the importance of conditions near the wall it might be expected to apply reasonably well in the case of compressible flow. He found no good agreement when he plotted existing experimental results at various Mach numbers against v_w/u_{τ_o}, but he did get a reasonable collapse against the parameter $\rho_w v_w/\rho_1 u_{\tau_o}$; see Fig.1, which is reproduced from Nash's report. The experimental results lie close to Turcotte's prediction, this being obtained by replacing v_w/u_{τ_o} in equation (1) above by $\rho_w v_w/\rho_1 u_{\tau_o}$. With $u_{\tau_o} = \sqrt{\tau_{w_o}/\rho_w}$, the equation becomes:-

$$\frac{\tau_w}{\tau_{w_o}} = e^{-6\cdot 94\left(\frac{\rho_w v_w}{\rho_1 u_1}\sqrt{\frac{2\rho_w}{\rho_1 C_{f_o}}}\right)\left(1 + \sqrt{\tau_{w_o}/\tau_w}\right)} \quad . \qquad (3)$$

No reasoned argument for this particular form of extension to compressible flow has been given. It should be noted that if a more usual correlation between incompressible and compressible boundary layers is adopted (see for example Mager[8]) there is obtained from Turcotte's formula:-

$$\frac{\tau_w}{\tau_{w_o}} = e^{-6\cdot 94\left(\frac{\rho_w v_w}{\rho_1 \mu_1}\sqrt{\frac{2}{C_{f_o}}\frac{\mu_o}{\mu_1}}\right)\left(1 - \sqrt{\frac{\tau_{w_o}}{\tau_w}}\right)} \quad . \qquad (4)$$

At a given injection rate $\left(\frac{\rho_w v_w}{\rho_1 u_1} = F\right)$ and Mach number, equation (4) predicts a considerably greater skin-friction reduction from the injection than that given by equation (3).

Rubesin[3] has proposed a mixing length theory for both air and foreign-gas injection. His results for air injection are presented in Fig.2 in the form of ratios of skin-friction and heat transfer with and without injection. As can be seen, the results for $\frac{C_f}{C_{f_o}}$ appear to be largely independent of Reynolds number, Mach number (explicitly) and wall temperature but depend mainly on the parameter $\frac{2\rho_w v_w}{\rho_1 u_1}\frac{1}{C_{f_o}}$ $\left(= \frac{2F}{C_{f_o}}\right)$. For the heat transfer, $\frac{S_t}{S_{t_o}}$ is almost the same function of $\frac{\rho_w u_w}{\rho_1 u_1}\frac{1}{S_{t_o}}$. Early measurements[9] at about $M = 2\cdot 5$

for both skin-friction and heat transfer appeared to be in good agreement with the theoretical results. However, further skin-friction measurements[10] over a Mach number range gave results which were not independent of Mach number. Some of these results, at a Reynolds number of approximately 4×10^6, are plotted in Fig.3. It will be seen that the reduction in skin-friction caused by fluid injection decreases with increase in Mach number, although the results at $M = 2{\cdot}5$ are themselves in reasonable agreement with Rubesin's results.

It should be noted that the lack of agreement between measurements and Rubesin's theory in its present form does not necessarily imply that mixing length theory cannot be used to predict the effect of fluid injection. As formulated by Rubesin the theory contains three free parameters: the thickness of the laminar sub-layer, the velocity at the edge of the sub-layer and the mixing length parameter K. The velocity in the laminar sub-layer is given by

$$y^* = \frac{\sqrt{\frac{C_f}{2}\left(\frac{T_w}{T_1}\right)^{\omega}}}{F}\,\ell n\left(1 + F\,\frac{u^*}{\sqrt{\frac{C_f}{2}}}\right) \tag{5}$$

where $$y^* = \frac{\rho_1 u_1}{\mu_1}\sqrt{\frac{C_{f_o}}{2}}\,y\,, \quad u^* = \frac{u}{u_1\sqrt{\frac{C_f}{2}}}\,, \quad F = \frac{\rho_w v_w}{\rho_1 u_1}\,.$$

Thus the thickness of the sub-layer is directly related to the velocity at the edge of the sub-layer. Rubesin then assumes that the mixing length parameter, K, is unaffected by fluid injection and that u_a^* is given by $13{\cdot}1\sqrt{\frac{T_w}{T_1}}$. It would appear that the main reason for the lack of agreement between theory and experiment is in the inadequacy of these assumptions. For example, Mickley and Davies analysed their velocity profiles at one Reynolds number for various injection rates and found that in incompressible flow,

$$u_a^*\,y_a^* = 195 + 2{\cdot}5 \times 10^4\,\frac{v_w}{u_1}\,. \tag{6}$$

Using this relation, together with $K = 0{\cdot}392$ and equation (5), they obtained excellent agreement between measured and calculated skin-friction for the full range of their tests (see Fig.4 which also includes Rubesin's results with $u_a^* = 13{\cdot}1$). A repeat of Mickley's experiment at supersonic speeds might enable the empirical relationship (6) to be extended to supersonic speeds and hence enable Rubesin's results to be recalculated giving more realistic answers for a wide range of flight conditions.

Some measurements of velocity and temperature profiles at supersonic speeds near M = 5·0 with various injection rates and wall temperature ratios have recently been made by Danberg[11]. Unfortunately these measurements do not include accurate values of skin-friction and hence it is difficult to find u_a^*, y_a^* (Mickley and Davies measured velocity profiles at a large number of stations along a flat plate and obtained the skin-friction coefficient by means of the momentum equation; whereas Danberg measured profiles at two stations only, and then attempted to find skin-friction by extrapolation of his measured profiles back to the wall).

Rubesin has also used a type of mixing length theory to study the case of foreign gas injection. This work is subject to the same sources of error as mentioned above; however, it certainly does predict an increasing reduction in skin-friction with decrease in density of the injected gas, a trend which is in agreement with experimental results.

It should be noted that all the theoretical studies for turbulent boundary layers have considered only the case of flat plate (constant pressure) boundary layers with continuous injection.

2.2 Experimental data

Most of the experimental results have already been discussed in conjunction with the theoretical results. As shown in the last section the experimental results on skin friction do not in fact correlate generally with the parameter $\frac{\rho_w v_w}{\rho_1 u_1} \frac{2}{C_{f_o}}$ as suggested by Rubesin's prediction methods. However, a fair degree of correlation is obtained by using the parameter $\frac{(\rho_w v_w)}{(\rho_1 u_{\tau_o})}$ suggested by Nash (Fig.1). It is of interest to note also the degree of correlation provided by the straightforward injection parameter $\frac{\rho_w v_w}{\rho_1 u_1}$ (Fig.5). In both Fig.1 and Fig.5 there is a tendency for the results obtained from overall drag measurements on cones to lie slightly above those obtained from measurements on flat plates.

As with the theoretical treatments of this problem, all the experiments reviewed have been concentrated on the case of zero pressure gradient with continuous injection.

3 APPLICATIONS OF FLUID INJECTION

In this section some observations are made on the practical applications of fluid injection to an aircraft flying at supersonic speeds.

We may first consider the effect of fluid injection on skin-friction alone and thence on overall performance. In order to find the order of magnitude of the effect we may use the theoretical results of Rubesin (Fig.2). These show that, in order to reduce the skin-friction by half with air injection, the injection rate per unit area $(\rho_w v_w)$ at a point on the surface must be at least equal to $\rho_1 u_1 C_{f_o}$ (i.e. $\frac{\rho_w v_w}{\rho_1 u_1} \frac{2}{C_{f_o}} \geq 2$, C_{f_o} being the skin-friction coefficient at the point in the absence of fluid injection). The injected air can either be taken from the free stream or carried in the aircraft. In the former case, since the air is ultimately ejected with zero velocity parallel to the aircraft surface, the momentum drag per unit area of ejection surface is $\rho_w v_w u_1$. To meet the required injection rate, this is at least equal to $\rho_1 u_1^2 C_{f_o}$. Thus the momentum drag is equivalent to a local drag coefficient of at least $2C_{f_o}$; so that, although the local skin-friction coefficient is reduced by half, the total effective drag is increased locally by a factor of at least 2·5. Edwards[12] has pointed out that it might be possible to convert some of the momentum loss in the ejected air into a thrust. However, at the most efficient, only half the loss could be saved, so that even in this case there is still an increase in effective drag.

To examine the effect of fluid carried in the aircraft, we may consider an aircraft flying at M = 4·0 at 80,000 ft (EAS = 400 knots). At a particular position on this aircraft, C_{f_o} will be about 0·0015, and at this flight condition $\rho_1 u_1 = 10{\cdot}8$ lb/ft^2 sec. Thus, to halve the local skin-friction, the required mass flow of air is approximately

$$\rho_1 u_1 C_{f_o} = 0{\cdot}0015 \times 10{\cdot}8 \text{ lb/ft}^2 \text{ sec} .$$

For a flight of 1 hour (approximately 2,500 miles) the amount of ejected air is 59 lb per sq ft. Thus for upper and lower surfaces the weight of air carried is equivalent to a wing loading of approximately 120 lb/sq ft. Experiment and theory both show that if helium is used as the ejected fluid, then for the same reduction in skin-friction the mass flow rate is about 1/6 of the value for air. Thus to halve the skin-friction by helium would, for this particular flight condition, require a wing loading of about 20 lb/sq ft. Even when it is considered that the skin-friction coefficient may be lower than 0·0015 on some parts of the aircraft, it can be seen that to transport fluid for the sole purpose of reducing skin-friction is unlikely to prove an economic procedure.

However, this does not necessarily imply that fluid injection will have no application in practice. At flight speeds in excess of about M = 3·0 some cooling of the aircraft structure will be necessary, this cooling probably implying the carrying of some coolant in addition to fuel. In this case fluid injection may be a satisfactory method of cooling the outer structure. Thus we are led to a study of the relative efficiency of fluid injection cooling and of internal cooling. In both cases it will be assumed that the coolant is water, that the amount of heat absorbed by the water is the same for both internal and transpiration cooling, and that the aircraft surface is to be maintained at 150°C. Calculations have been made for two points on an aircraft, 10 ft and 100 ft respectively, from the leading edge, with the aircraft flying at 400 knots E.A.S. at Mach numbers between M = 4·0 and M = 10.

In order to calculate the amount of coolant required with water ejection it is necessary to make some assumptions regarding the effects of this water on heat transfer coefficient and on recovery temperature. For the purpose of this study it is assumed that the ejection of water, in the form of steam, has the same effect as that of an equal mass of air. In order to find the effect of air injection in the required Mach number range it is necessary to extrapolate the existing results to higher Mach numbers. This extrapolation can be made in at least three different ways, and calculations have been made for all three extrapolations. They are

(1) Extrapolation based on Rubesin's theoretical results: these can be represented by the simple formulae (see Fig.2)

$$\frac{S_t}{S_{t_o}} = 1 - \frac{1}{3}\frac{F}{S_{t_o}} \; ; \; \frac{C_f}{C_{f_o}} = 1 - \frac{2}{3}\frac{F}{C_{f_o}} \quad \left(\frac{F}{S_{t_o}} , \; \frac{2F}{C_{f_o}} < 1\right) . \qquad (7)$$

(2) Extrapolation based on the experimental results for skin-friction reduction by fluid injection at M = 3·2 and 4·3 (Fig.3), and the relationship between Stanton number and skin-friction coefficient given by equation (7) with $S_{t_o}/C_{f_o} = 0{\cdot}6$.

For F small, Fig.3 shows that

$$\frac{C_f}{C_{f_o}} \doteqdot 1 - \frac{1}{2}\frac{F}{C_{f_o}} , \qquad (8)$$

hence from equation (7)

$$\frac{S_t}{S_{t_o}} \doteqdot 1 - \frac{1{\cdot}4}{6}\frac{F}{S_{t_o}} . \qquad (9)$$

(3) Extrapolation based on the experimental correlation for skin-friction reduction on cones shown in Fig.5, assuming that S_t/C_f is independent of fluid injection. Fig.5 shows that

$$\frac{C_f}{C_{f_o}} \doteqdot 1 - 200F \qquad (10)$$

so

$$\frac{S_t}{S_{t_o}} \doteqdot 1 - 200F. \qquad (11)$$

The skin-friction and heat-transfer coefficients without fluid ejection have been found by the intermediate enthalpy method at the appropriate Reynolds number and at the surface temperature of 150°C. In the case of internal cooling, the amount of coolant required was obtained directly from the excess of heat gained by aerodynamic heating over that lost by radiation. With transpiration cooling, an initial value of F was found using the amount of water required for internal cooling. Using this value, the reduced heat transfer rate could be found from equations (7), (9) or (11). This gave a second approximation to the amount of coolant required, and the process was continued until a heat balance was found. In all the calculations it was assumed that fluid injection had no effect on recovery temperature.

The results of these calculations are shown in Fig.6, where the ratio of the weight of water required for cooling by fluid injection to the weight of water required for internal cooling is plotted against Mach number for various flight conditions. It will be seen that, although the calculations based on the various extrapolations show the same trends, that is an increasing advantage of fluid injection with increasing Mach number, the magnitude of this effect depends strongly on the particular extrapolation. Thus, until more reliable data are available it is difficult to draw firm conclusions on the advantages of fluid injection. It should be noted that, in the calculations, the parameter $F \left(= \frac{\rho_w v_w}{\rho_1 u_1}\right)$ is almost proportional to heat transfer coefficient and thus depends on Reynolds number and Mach number. This dependence on flight conditions is removed by the form of extrapolations (1) and (2) but not (3). Tunnel tests which could find Reynolds number effects on fluid injection would be extremely useful.

The advantages of fluid injection shown in Fig.6 are almost certainly underestimated, since they are based on results for air injection. Steam has a lower molecular weight than air and so probably has a greater effect on heat transfer; however, the magnitude of this effect is unknown. Interpolation on a molecular weight basis between the results for air, helium and hydrogen suggests that the advantages of water injection could possibly be twice as big as shown in Fig.6.

Further it must be recalled that in addition to reducing the aerodynamic heating, and hence the amount of coolant required, fluid injection also gives a reduction in skin-friction: the percentage reduction is approximately the same as the percentage reduction in coolant shown in Fig.6. It will be seen from Fig.6 that the advantage of transpiration cooling at Mach numbers below 5·0 is still marginal, especially when the small reductions in coolant carried and in skin-friction are balanced against a possible weight increase caused by the ejection equipment.

4 POSSIBLE EXPERIMENTAL PROGRAMME

The results of the last section suggest that fluid injection is likely to be of most importance at Mach numbers in excess of 5·0. At the same time it is clear that the range of marginal benefits ($M = 4 - 6$, say) requires further investigation. The main reason for the increasing advantage of fluid injection with increase in Mach number is the increasing aerodynamic heating rate and hence the larger mass flows required to counteract this heating. An investigation of the effects of various mass-flow rates over a range of Reynolds numbers at Mach numbers around $M = 5{\cdot}0$ would be valuable. In particular, as mentioned in section 2.1, a detailed investigation of velocity and temperature profiles on a flat plate with injection at two Mach numbers might provide enough data for a reliable estimate of the free parameters in Rubesin's theory and hence make it possible to extend the calculations to higher speeds and also to make more reliable performance estimates in the marginal range. These tests could be made for both air and light gas injection.

In addition to such tests, which are essentially a continuation of investigations by other workers, there are a number of problems which appear to have received little attention to date; for example:-

(i) a comparison of injection through a porous surface and through discrete slots;

(ii) shock-wave/boundary layer interaction in the presence of injection;

(iii) fluid injection in junctions (where heating rates may be particularly high);

(iv) intake problems with fluid injection upstream of the intake.

An understanding of any of these effects at Mach numbers near $M = 5{\cdot}0$ would be of great value in assessing the use of fluid injection for a full scale aircraft.

5 CONCLUSIONS

(1) The review made here highlights the deficiencies in existing theories for calculating the reduction of skin-friction produced by injecting fluid from the surface into the boundary layer. No theory exists which describes adequately the effects either of compressibility or of pressure gradient.

(2) Using orders of magnitude which are supported by a fair amount of experimental evidence, calculations show it to be unlikely that injection of air or light gas for the sole purpose of reducing skin-friction can be performed economically, whether this be coupled with a system for taking air on board during the flight or with the use of a bottled supply.

(3) Fluid injection may however be used for the dual purpose of reducing skin friction and at the same time cooling the skin under conditions of high kinetic heating. Such calculations as it has been possible to make suggest that, using water as the working fluid, injection has an advantage over internal cooling. This advantage is marginal at Mach numbers below 5 but increases with increasing Mach number.

(4) More experimental evidence is required in order to properly assess the practical possibilities. Suggestions for basic work at high supersonic speeds (M around 5) are made. The need to explore an ample range of Reynolds number is stressed. Additional suggestions are made for experiments on injection in particular environmental conditions which have not been studied up to the present.

REFERENCES

No.	Author	Title, etc.
1	Craven, A.H.	Boundary layers with suction and injection. College of Aeronautics Report No.136. ARC 22,332. September 1960.
2	Turcotte, D.L.	A sub-layer theory for fluid injection into the incompressible turbulent boundary layer. Jnl. Aerospace Sci. Vol.27 p.675. 1960.
3	Rubesin, M.W.	An analytical estimation of the effect of transpiration cooling on heat-transfer and skin-friction characteristics of a compressible turbulent boundary layer. NACA Tech. Note 3341. December 1954.
4	Rubesin, M.W. Pappas, C.C.	An analysis of the turbulent boundary layer characteristics on a flat plate with distributed light-gas injection. NACA Tech. Note 4149. February 1958.
5	Rannie, W.D.	Heat transfer in turbulent shear flow. Jnl. Aero. Sci. Vol.23 pp.485-489. May 1956.
6	Mickley, H.S. Davies, R.S.	Momentum transfer for flow over a flat plate with blowing. NACA Tech. Note 4017. November 1957.

REFERENCES (CONTD)

No.	Author	Title, etc.
7	Nash, J.F.	A correlation of skin-friction measurements in compressible turbulent boundary layers with injection. ARC 22,386. November 1960.
8	Mager, A.	Transformation of the compressible turbulent boundary layer. Jnl. Aero. Sci. Vol.25 pp.305-311. May 1958.
9	Tendeland, T. Okuno, A.F.	The effect of fluid injection on the compressible turbulent boundary layer - the effect on skin-friction of air injected into the boundary layer of a cone at M = 2·7. NACA RM A56D05. NACA/TIL 5126. 1956.
10	Pappas, C.C. Okuno, A.F.	Measurements of skin-friction of the compressible turbulent boundary layer on a cone with foreign gas injection. Jnl. Aerospace Sci. Vol.27 p.321. 1960.
11	Danberg, J.E.	Measurement of the characteristics of the compressible turbulent boundary layer with air injection. NAVORD Report 6683. September 1959.
12	Edwards, J.B.	The equivalent drag of surfaces with suction or injection. ARC 23,211. 1961.

SYMBOLS

C_f	skin-friction coefficient
C_{f_o}	" " " in absence of injection
F	injection parameter $\rho_w v_w/\rho_1 U_1$
K	mixing length parameter
M	Mach number
R	Reynolds number
S_t	heat transfer coefficient
S_{t_o}	" " " in absence of injection
T_1	temperature at edge of boundary layer
T_w	temperature at wall
T_o	free stream stagnation temperature
T_s	free stream static temperature
u	velocity in boundary layer
u^*	transformed velocity - equation (5)
u_1	velocity at edge of boundary layer
u_{τ_o}	frictional velocity in absence of injection
v_w	injection velocity; normal to wall
y	distance from wall
y*	transformed distance from wall, equation (5)
ρ_1	density at edge of boundary layer
ρ_w	density of injected fluid
μ_1	viscosity at edge of boundary layer
μ_o	viscosity at stagnation conditions
τ_w	skin friction
τ_{w_o}	" " in absence of injection
ω	exponent in viscosity-temperature law

Suffix a denotes conditions at the edge of the sub-layer

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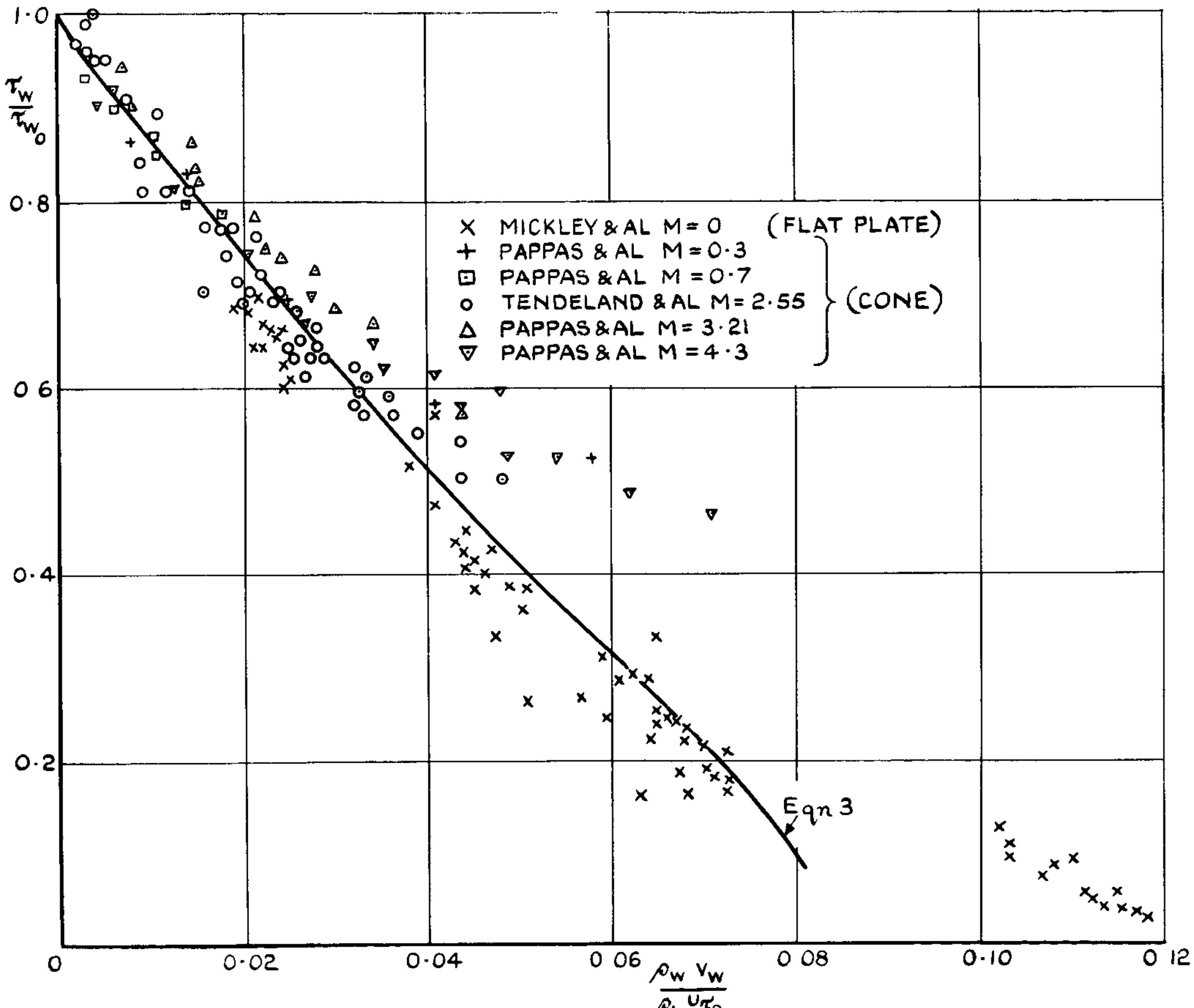


FIG. 1. CORRELATION OF SKIN-FRICTION (NASH; REF. 7)

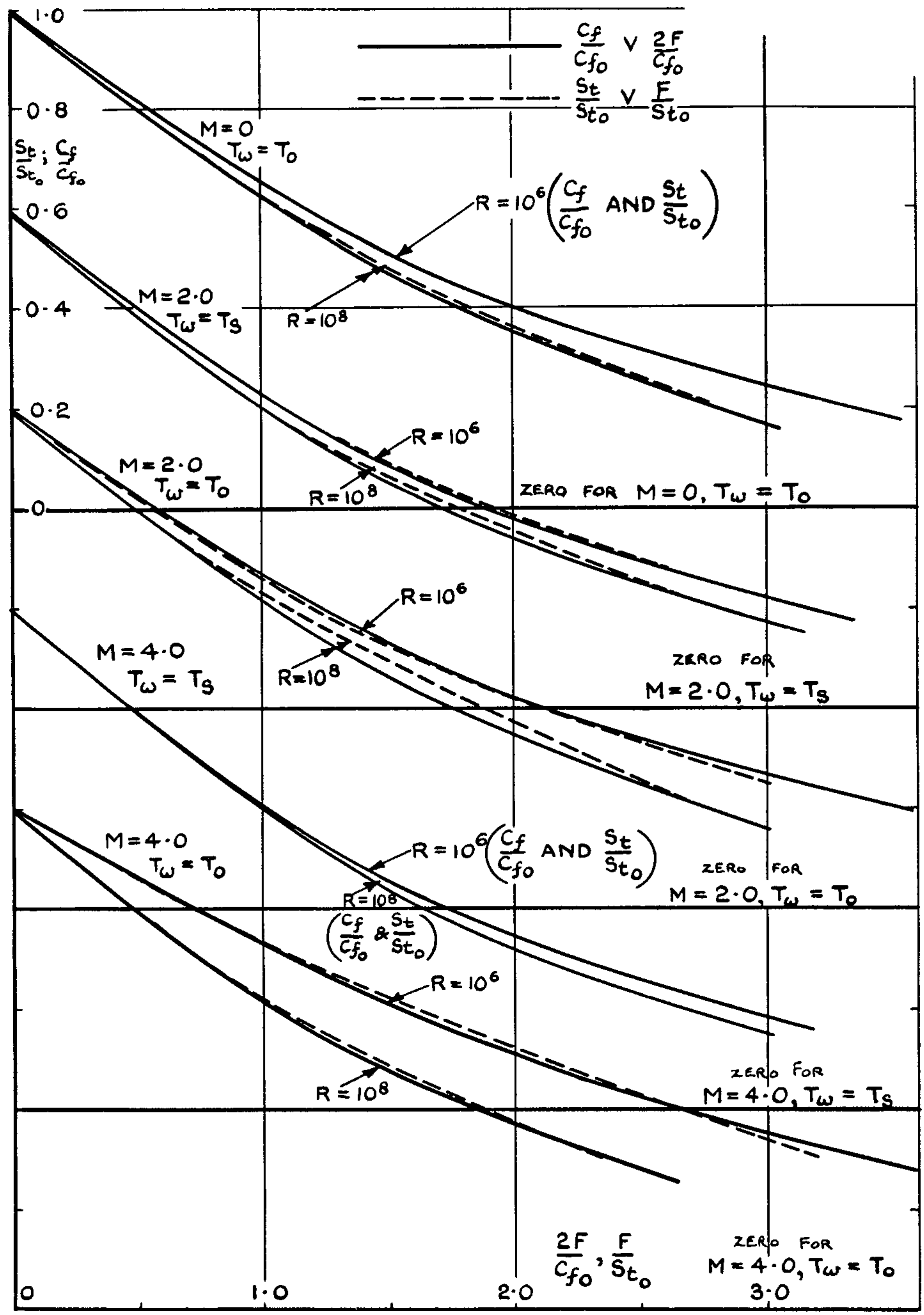


FIG. 2. THEORETICAL EFFECT OF AIR INJECTION FROM RUBESIN, REF. 3.

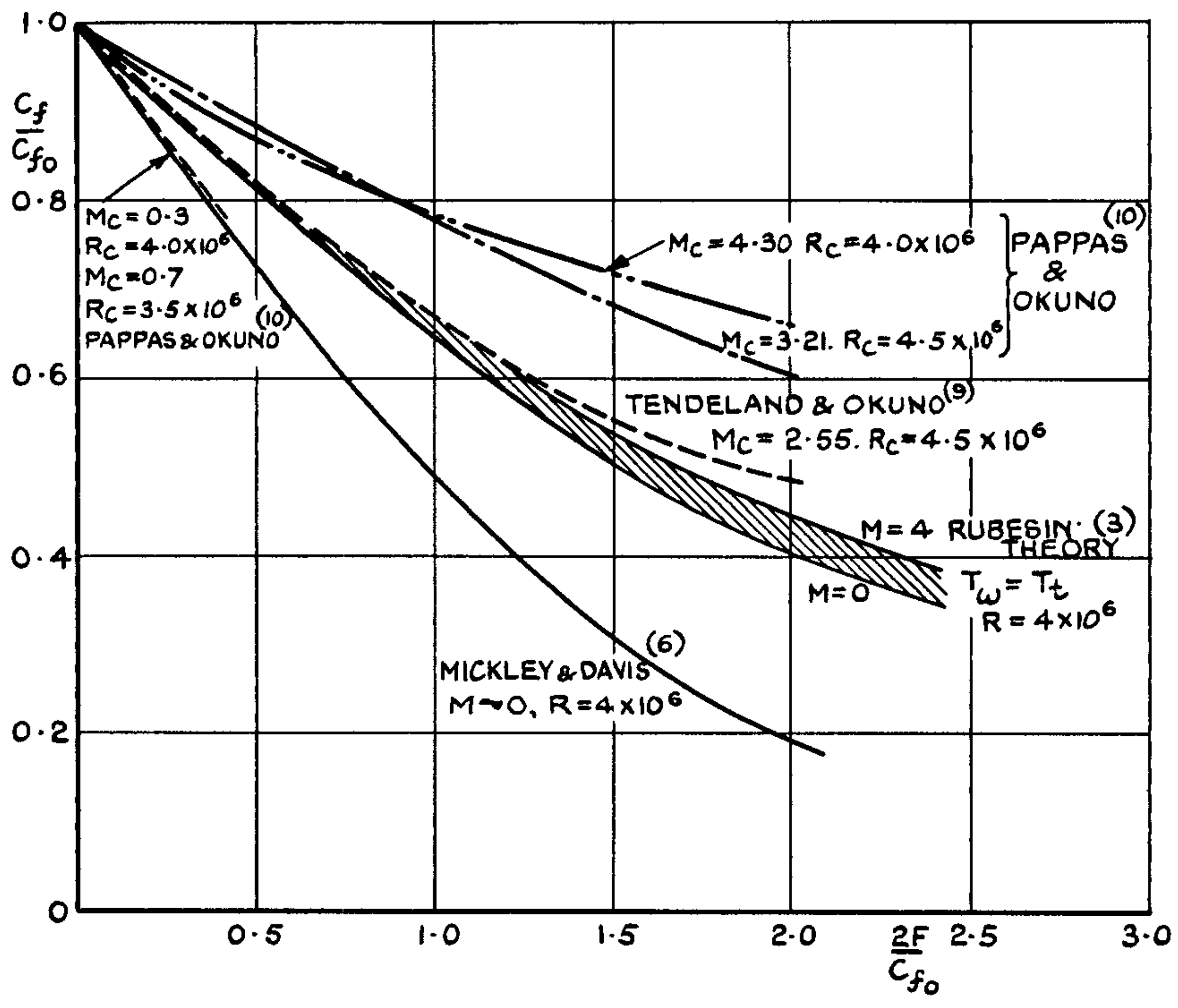


FIG. 3. COMPARISON OF THEORETICAL AND EXPERIMENTAL EFFECTS OF AIR INJECTION.

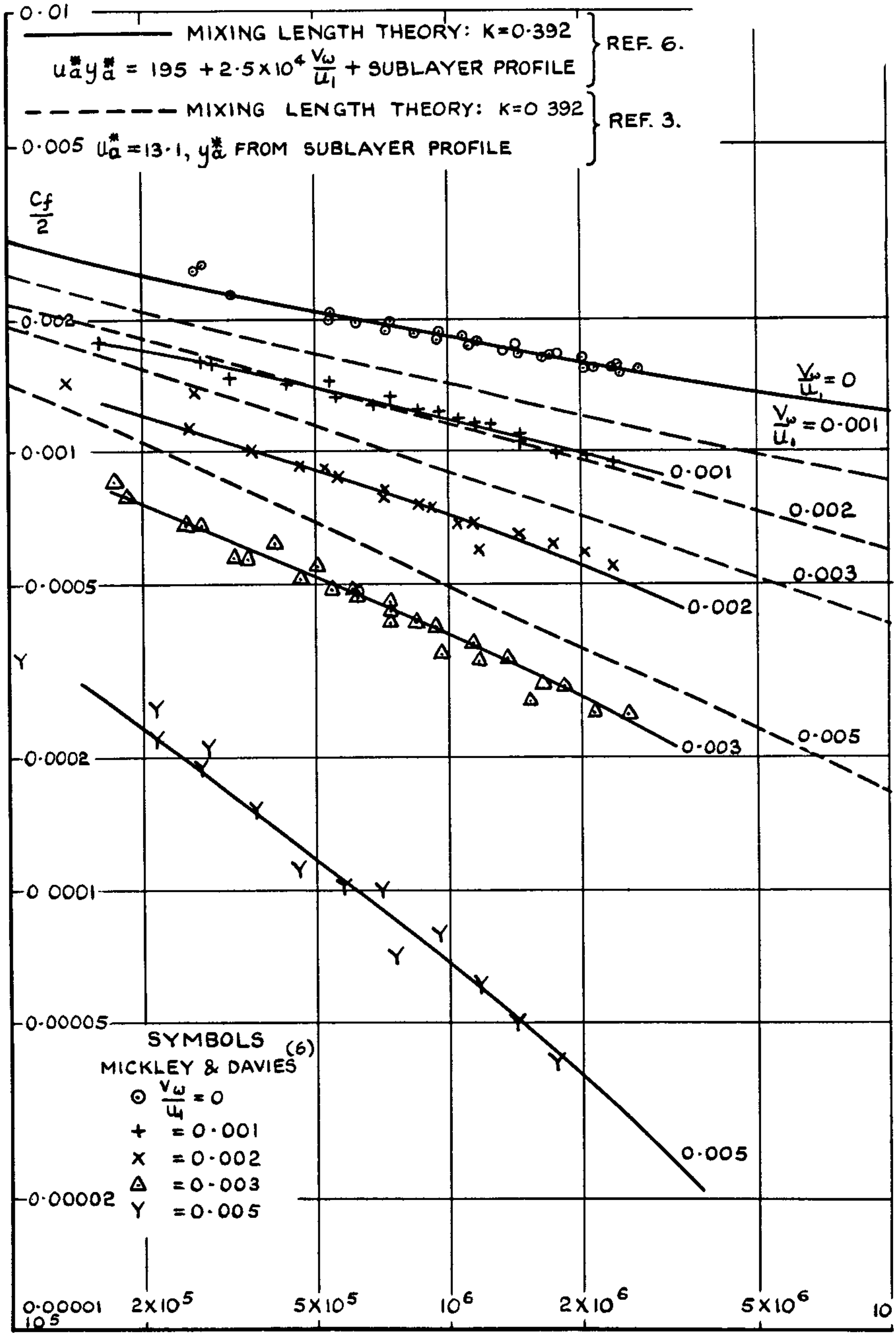
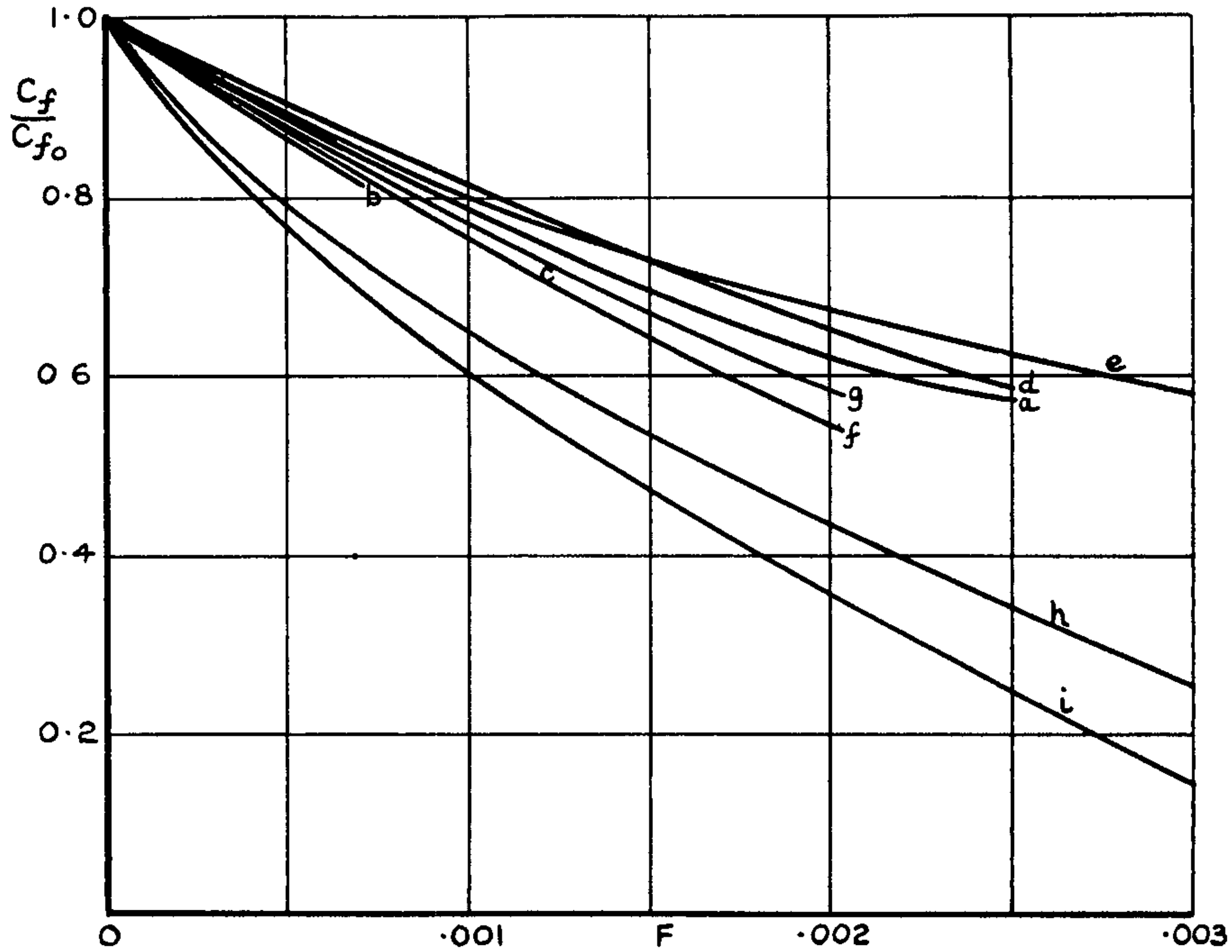


FIG. 4. COMPARISON OF LOW-SPEED RESULTS WITH MODIFIED THEORY.



(a)	PAPPAS & OKUNO[10]	$M_c = 0\cdot3$	$R_c = 0\cdot87 \times 10^6$	CONES (OVERALL SKIN-FRICTION)
(b)	PAPPAS & OKUNO[10]	$M_c = 0\cdot3$	$R_c = 4\cdot03 \times 10^6$	
(c)	PAPPAS & OKUNO[10]	$M_c = 0\cdot7$	$R_c = 3\cdot50 \times 10^6$	
(d)	PAPPAS & OKUNO[10]	$M_c = 3\cdot21$	$R_c = 5\cdot86, 4\cdot42$ & $2\cdot95 \times 10^6$	
(e)	PAPPAS & OKUNO[10]	$M_c = 4\cdot35$	$R_c = 4\cdot68, 3\ 25 \times 10^6$	
(f)	TENDELAND & OKUNO[9]	$M_c = 2\cdot55$	$R_c = 6\cdot25 \times 10^6$	
(g)	TENDELAND & OKUNO[9]	$M_c = 2\cdot55$	$R_c = 8\cdot56 \times 10^6$	
(h)	MICKLEY AND DAVIS[6]	$M = 0$	$R = 5 \times 10^6$	FLAT-PLATE (LOCAL SKIN-FRICTION)
(i)	MICKLEY AND DAVIS[6]	$M = 0$	$R = 3 \times 10^6$	

FIG. 5. CORRELATION OF SKIN-FRICTION MEASUREMENTS WITH INJECTION PARAMETER.

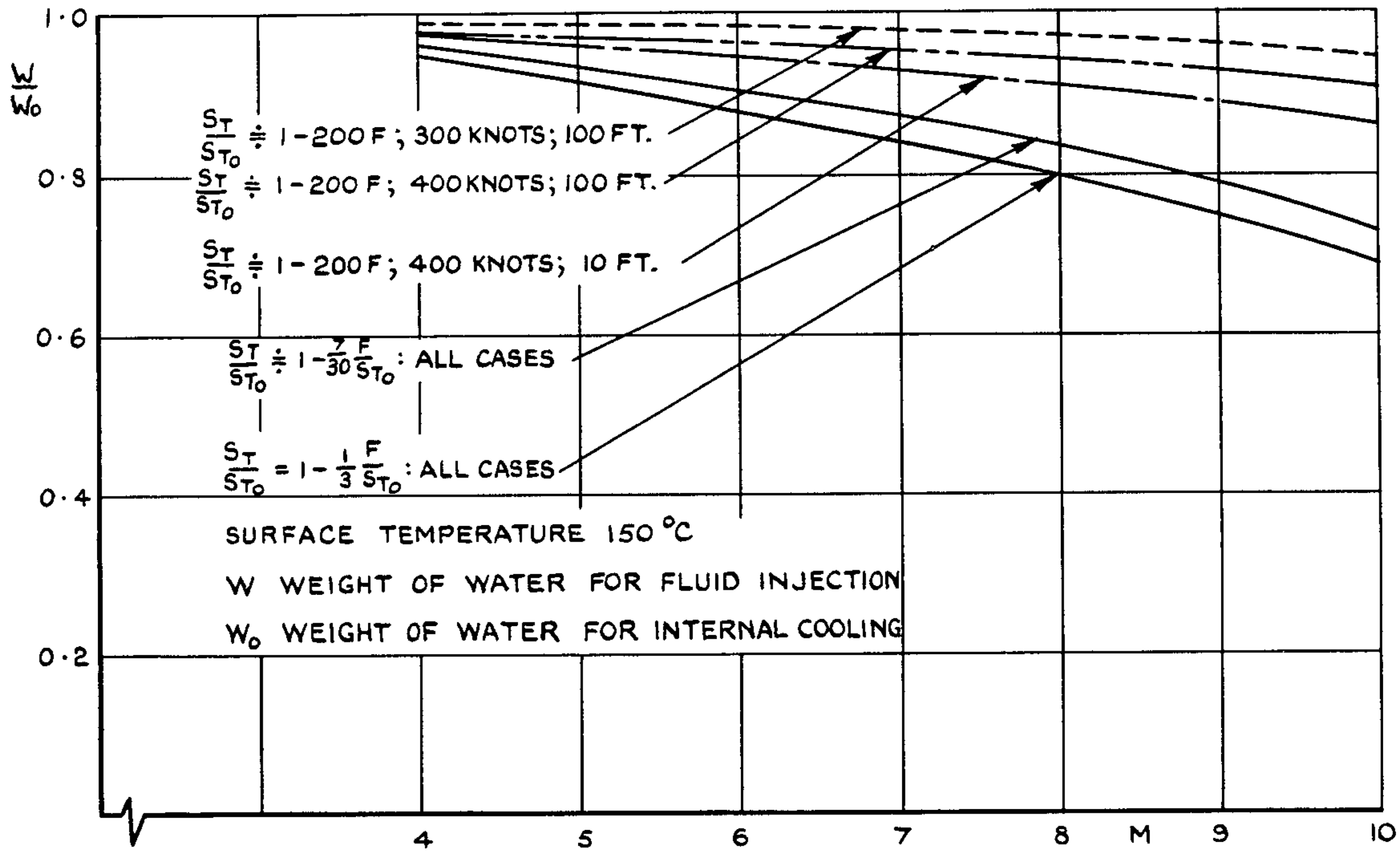


FIG. 6. COMPARISON OF INTERNAL AND FLUID INJECTION COOLING.

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SOME NOTES ON TURBULENT BOUNDARY LAYERS WITH FLUID INJECTION AT HIGH SUPERSONIC SPEEDS. Squire, L.C. July, 1963.

Transpiration cooling has been suggested as a research topic for the High Supersonic Speed wind tunnel (M = 2.5 to 5.0) at R.A.E. Bedford. In these notes a brief review of existing work on this subject is given and regions where more experimental work is needed are pointed out.

Using existing data an attempt is made to assess the importance of transpiration cooling for a long range aircraft flying at high supersonic speeds.

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