CoA NOTE AERO No. 169

CoA NOTE AERO No. 169

THE COLLEGE OF AERONAUTICS
CRANFIELD

13005

'A DESIGN METHOD FOR THE DILUTION ZONES OF GAS TURBINE COMBUSTION CHAMBERS'

by

A. H. Lefebvre and E. R. Norster

CoA Note Aero. No. 169

February, 1966

THE COLLEGE OF AERONAUTICS

DEPARTMENT OF PROPULSION

'A design method for the dilution zones of gas turbine combustion chambers'

- by -

A.H. Lefebvre, B.Sc.(Eng.)., D.I.C., Ph.D., M.I.Mech.E., F.R.Ae.S.,

and

E.R. Norster, D.C.Ae.

The substance of this Note was contained in a CoA Memo entitled 'Aerodynamic influences on dilution zone design', which had a limited circulation in September, 1963.

Contents

List of Symbols

A = maximum cross-sectional area of outer casing, ins^2.

D = diameter or width of outer casing corresponding to A, ins.

i.e. $A = \frac{\pi}{4} D^2$ for tubular systems, and

$A = 2\pi r D$ for annular and tubo-annular systems, where r is the mean radius of the chamber.

A_f = flametube area, ins^2.

A_{an} = annulus area, ins^2.

A_c = compressor outlet area, ins^2.

D_f = flametube outlet area, ins^2.

d = dilution hole diameter, ins.

x = dilution zone length, ins.

M = total chamber air mass flow, lb/s.

M_g = mass flow of combustion products, lb/s.

M_{an} = mass flow of annulus air, lb/s.
(note: $M = M_g + M_{an}$)

V_g = velocity of combustion products, ft/s.

T_g = temperature of combustion products, °K

V_{an} = velocity of annulus air, ft/s.

T_{an} = temperature of annulus air, °K

V_j = dilution jet velocity, ft/s.

P_2 = chamber inlet pressure, p.s.i.a.

P_3 = chamber outlet pressure, p.s.i.a.

T_2 = inlet temperature, °K

T_3 = mean outlet temperature, °K

T_{max} = maximum outlet temperature, °K

ΔP_{2-3}	=	overall pressure loss, p.s.i.a.
ΔP_{diff}	=	pressure loss in diffuser, p.s.i.a.
ΔP_{f}	=	pressure loss across flametube, p.s.i.a. (Note: $\Delta P_{diff} + \Delta P_{f} = \Delta P_{2-3}$)
q_{an}	=	dynamic head in annulus, p.s.i.a.
q_{ref}	=	reference dynamic head, based on V_{ref}.
V_{ref}	=	mean velocity at A, ft/s.

Introduction and Summary

Perhaps the most important and, at the same time, most difficult problem in the design and development of gas turbine combustion chambers, is that of achieving a satisfactory and consistent distribution of temperature in the efflux gases discharging into the turbine. In the past, experience has played a major role in the determination of dilution-zone geometry, and trial and error methods have of necessity been employed in developing the temperature-traverse quality of individual combustor designs to a satisfactory standard. Experimental investigations into dilution-zone performance carried out on actual chambers have led to useful empirical-design data, but very often it has proved difficult or impossible to distinguish the separate influences of all the variables involved. Thus although it is now generally accepted that a satisfactory temperature profile is dependent upon adequate penetration of the dilution jets, coupled with the correct number of jets to form sufficient localized mixing regions, the manner in which the total dilution-hole area is utilized in terms of number and size of holes is still largely a matter of experience. Unfortunately, more basic studies of jet mixing do not usually yield results that can readily be expressed in the parameters which are most familiar to those concerned with combustion-chamber design. However, some of these investigations can provide a useful guide to the relationships involved.

One such investigation[1] resulted in the accumulation of a large amount of data on the mixing of cold jets when injected into hot streams under conditions where the temperature and velocity of the hot and cold streams, the injection-hole diameter, the angle of injection, and the mixing length could be accurately controlled and varied over a wide range. These data are used here, firstly to demonstrate a logical method of dilution zone design and, secondly, to provide quantitative data on the rate of exchange between temperature traverse quality and the relevant design parameters such as dilution zone length, dilution hole diameter and pressure loss factor. The effects of chamber inlet velocity and inlet velocity profile are also examined.

Finally, it is proposed that the aerodynamic performance and stability of a combustion chamber may, for most practical purposes, be adequately described in terms of a parameter β which is the ratio of the flametube pressure loss to the overall pressure loss. Evidence is presented in support of this proposal and its practical implications are discussed.

Dilution Zone Design Procedure

At this stage in the design process the overall pressure loss factor has been established and the cross-sectional area of the outer casing determined. A tentative value for the flametube area will also have been arrived at, based on considerations of pressure loss and combustion performance, although it may need modification in the light of the results obtained from the following calculations.

The dilution zone procedure is carried out in a number of steps which are described below in turn.

Step 1. Determination of ratio $^{M_g}/_{M}$

This is the ratio of the mass of the hot combustion products entering the dilution zone to the total chamber mass flow. It depends primarily on the chamber inlet and outlet temperatures, T_2 and T_3 respectively, and on the temperature of the combustion products, Tg. The actual relationship is shown graphically in figure 1 for a value of Tg of 1,800°K. It is considered that 1,800°K represents a near optimum value of Tg for the following reasons. If temperatures are much in excess of 1,800°K, the gases will contain a high proportion of dissociated products which could become 'chilled' on contact with the cold dilution jets and hence give rise to combustion inefficiency. On the other hand, if Tg is much below 1,800°K, this necessarily means that too large a proportion of the total airflow has been injected into the flametube upstream of the dilution zone. In consequence, the amount of air left for the 'true' dilution process will be insufficient to achieve adequate penetration and mixing.

For any given design the relevant ratio of $^{M_g}/_{M}$ is read off figure 1, using the values of T_2 and T_3 corresponding to the maximum rating of the engine. This is the engine condition at which temperature traverse quality is at a premium. It usually corresponds to a value of overall A.F.R. of somewhere between 40 and 60. Thus, according to figure 1, $^{M_g}/_{M}$ will normally lie between 0.4 and 0.7.

Step 2. Determination of flametube pressure loss factor

The total pressure loss of the chamber is equal to the sum of the pressure loss in the diffuser and the pressure loss in the flametube.

Hence:

$$\frac{\Delta P_{2-3}}{q_{ref}} = \frac{\Delta P_{diff}}{q_{ref}} + \frac{\Delta P_f}{q_{ref}} \qquad (1)$$

Now the diffuser pressure loss may be expressed as:-

$$\frac{\Delta P_{diff}}{q_{ref}} = \eta \left[\left(\frac{A}{A_c} \right)^2 - 1 \right]$$

A curve of η is shown plotted against total diffuser angle 2Φ in figure 2. This curve was derived by R.J. McLaren (C. of A.) and is based on data obtained from conical and two-dimensional diffusers.

$\eta = 0.087 \quad \frac{A}{A_c} = \frac{45^2}{30^2} \quad \frac{\Delta P_{diff}}{q_{ref}} = 0.28$

The flametube pressure loss factor is then obtained by re-writing equation (1) as:

$$\frac{\Delta P_f}{q_{ref}} = \frac{\Delta P_{2-3}}{q_{ref}} - \frac{\Delta P_{diff}}{q_{ref}}$$

in which both terms on the right hand side are now known.

Step 3. Determination of $\frac{\Delta P_f}{q_{an}}$

The path and penetration of the dilution jets is governed largely by the term $\frac{\Delta P_f}{q_{an}}$, which is the ratio of the pressure drop across the flametube to the dynamic head in the annulus.

We have

$$\frac{\Delta P_f}{q_{an}} = \frac{\Delta P_f}{q_{ref}} \times \frac{q_{ref}}{q_{an}}$$

where $\frac{\Delta P_f}{q_{ref}}$ is the familiar flametube pressure loss factor based on the 'reference' dynamic head.

i.e.

$$\frac{\Delta P_f}{q_{an}} = \frac{\Delta P_f}{q_{ref}} \times \left(\frac{V_{ref}}{V_{an}}\right)^2$$ 不可压缩ρ= const

hence

$$\frac{\Delta P_f}{q_{an}} = \frac{\Delta P_f}{q_{ref}} \times \frac{(1 - {}^{A_f}/A)^2}{(1 - {}^{m_g}/M)^2} \qquad (2)$$

The above equation is shown graphically in figure 3 in which curves of ${}^{\Delta P_f}/q_{an} / {}^{\Delta P_f}/q_{ref}$ are plotted against ${}^{A_f}/A$ for various values of ${}^{M_g}/M$.

Since ${}^{\Delta P_f}/q_{ref}$, $\frac{A_f}{A}$ and $\frac{M_g}{M}$ are known, either equation (2) or figure 3 may be used to derive $\frac{\Delta P_f}{q_{an}}$.

Step 4. Determination of $^{V_g}/V_{an}$

This term represents the ratio of the velocity of the hot gases flowing inside the flametube to the velocity of the air in the surrounding annulus. It may be expressed quite conveniently in terms of $^{M_g}/M$ and $^{A_f}/A$ from the continuity equation as shown below.

We have,

$$\frac{V_g}{V_{an}} = \frac{M_g \rho_{an} \cdot A_{an}}{M_{an} \rho_g A_g \cdot}$$

$$= \frac{T_g}{T_{an}} \cdot \frac{\left(\frac{1}{M_g/M} - 1\right)}{\left(\frac{1}{A_f/A} - 1\right)}$$

or

$$\frac{V_g/V_{an}}{T_g/T_{an}} = \frac{\left(\frac{1}{M_g/M} - 1\right)}{\left(\frac{1}{A_f/A} - 1\right)} \qquad (3)$$

The left hand side of the above equation is shown plotted against $^{A_f}/A$ for various values of $^{M_g}/M$ in figure 4. The ratio $^{V_g}/V_{an}$ is obtained from this figure by using the appropriate values of $^{A_f}/A$ and $^{M_g}/M$, and substituting T_2 for T_{an} and 1,800°K for T_g.

Step 5. Determination of dilution hole area and drag coefficient

We have,

$$\frac{\Delta P_f}{q_{an}} = \frac{V_j^2}{2g} \cdot \frac{2g}{V_{an}^2} = \left(\frac{V_j}{V_{an}}\right)^2 \qquad (4)$$

Also,

$$\frac{V_{an}}{V_j} = \frac{A_D \cdot C_D \cdot}{A_{an}} \qquad (5)$$

assuming that the pressure ratio across the dilution holes is close to unity and that all the annulus air subsequently flows through the dilution holes.

Substituting for $\frac{V_j}{V_{an}}$ in equations (4) and (5) gives:-

$$\frac{A_D \,.\, C_D}{A_{an}} = \left(\frac{\Delta P_f}{q_{an}}\right)^{-0.5} \qquad (6)$$

The above equation contains two unknown variables - the ratio of the total dilution hole area to the annulus area, $\frac{A_D}{A_{an}}$ and the discharge coefficient of the dilution holes, C_D. Fortunately, these variables are not independent and adequate and reliable experimental data to connect them has been provided by Dittrich and Graves[2]. These data have been incorporated with equation (6) into figure 5, which represents a composite plot of the relevant parameters.

The ratio $^{A_D}/A_{an}$ is given in figure 5 and, since this is equal to $^{A_D}/A(1 - \frac{A_f}{A})$, A_D is obtained by substitution for A and $^{A_f}/A$.

Step 6. Determination of dilution hole diameter

In order to achieve a satisfactory temperature profile at the chamber outlet it is generally recognized that there must be adequate penetration of the dilution jet coupled with the correct number of jets to form sufficient localized mixing regions. The derivation of the total dilution hole area is relatively straightforward, as described above. However, the manner in which this area is utilized in terms of number and size of holes is still largely a matter of experience. Penetration studies, however, have produced relationships which allow assessments to be made of the effects of design variables on the ratio of max. jet penetration/dilution hole diameter. According to Cranfield data[1] we have

$$\frac{Y_{max}}{d_j} = \sqrt{\frac{\rho_j V_j^2}{\rho_g V_g^2}} \,.\, \sin \phi \qquad (7)$$

ϕ being the angle of penetration.

Substituting for ρ, and equating $d_j = \sqrt{C_D} \,.\, d$, gives

$$\frac{Y_{max}}{\sqrt{C_D}.d} = \sqrt{\frac{T_g}{T_2}} \,.\, \frac{V_j}{V_g} \,.\, \sin \phi \qquad (8)$$

Now it has been shown[4] that ϕ is related to the C_D of a plain hole by the expression

$$C_d = C_{d_o} \cdot \sin^2\phi$$

Hence

$$\frac{Y_{max}}{d} = \sqrt{\frac{T_g}{T_2}} \cdot \frac{V_j}{V_g} \cdot \sqrt{\frac{C_d}{C_{d_o}}} \qquad (9)$$

Substituting in equation (9) for $C_{d_o} = 0.64$ and re-writing, gives

$$\frac{Y_{max}}{d} \cdot \frac{V_g}{V_{an}} = 1.25 \sqrt{\frac{T_g}{T_2}} \cdot \frac{V_j}{V_{an}} \cdot C_D \qquad (10)$$

It was shown earlier that C_d is a function of $^{\Delta P_f}/_{q_{an}}$ and, since compressible flow theory may be used to show that $\frac{V_j}{V_{an}}$ is also a function of $\frac{\Delta P_f}{q_{an}}$ (see figure 6), we have,

$$\frac{Y_{max}}{d} \cdot \frac{V_g}{V_{an}} = 1.25 \sqrt{\frac{T_g}{T_2}} \cdot f\left(\frac{\Delta P_f}{q_{an}}\right) \qquad (11)$$

The actual relationship is rather cumbersome and is omitted here, but it is shown graphically in figure 7. The ratio $^{Y\,max}/_d$ is obtained from this figure using the previously determined values of $^{\Delta P_f}/_{q_{an}}$, $^{T_g}/_{T_2}$ and $\frac{V_g}{V_{an}}$. If Y_{max} is then stipulated, d is known, as is also the number of dilution holes, n, since $A_D = 0.785 \cdot n\, d^2$.

On tubular and tubo-annular chambers, it is recommended that Y_{max} should be made equal to the flametube radius. On conventional annular systems it should be equated to half the flametube width.

Step 7. Determination of dilution zone length

The length of the dilution zone is obtained from figure 8 in which temperature traverse quality, expressed in terms of $T_{max} - {T_3}/{T_3 - T_2}$, is plotted against the ratio of dilution zone length to flametube diameter for various levels of overall pressure loss factor. It should be emphasized that figure 8 can only provide an approximate guide, since it is based on a small amount of experimental data and, in any case, the relevant pressure loss factor should ideally be that of the flametube and not the overall as plotted. Unfortunately the original data employed in constructing this figure did not include breakdowns of the overall pressure loss and hence flametube pressure loss factors could not be deduced.

The design of the dilution zone is now complete. If, for any reason, it is considered unsatisfactory, a different value of $^{A_f}/_{A}$ should be chosen and the design procedure repeated from step 3 onwards.

Dilution Zone Performance - Further Considerations

Experimental investigations into dilution zone performance carried out on practical systems have resulted in charts, of the type shown in figure 8, which are useful in design but in which it is difficult or impossible to distinguish the separate influences of all the variables involved. On the other hand more basic studies of jet mixing do not usually yield results which can readily be applied to combustion chamber design. However, some of these investigations can provide a useful guide to the relationships involved.

Some typical results from one such investigation[1] are presented in figure 9. They are shown as plots of temperature traverse quality against $\frac{x}{d} \cdot \frac{V_{an}}{V_g}$ for various values of $^{\Delta P_f}/q_{an}$. It should be noted that in this figure traverse quality is denoted by $\frac{T_g - T_j}{T_g - T_2}$, T_j being the measured local jet temperature, instead of the more familiar form of $\frac{T_{max} - T_{mean}}{T_3 - T_2}$. This is because the latter ratio has no significance when applied to the particular conditions of the Cranfield experiments. For the same reason the traverse qualities shown in figure 9 cannot be applied directly to practical combustion systems in terms which would be meaningful to the combustion engineer. Nevertheless, the work has resulted in the accumulation of a large amount of data on the mixing of cold jets when injected into hot streams under conditions where the temperature and velocity of the hot and cold streams, the injection hole diameter, the angle of injection and the mixing length could be accurately controlled and varied over a wide range. In utilizing this data for practical purposes, any difficulties arising from the definition of traverse quality have been eliminated by fixing the traverse quality at various representative values and then examining the inter-relationship of the other important variables. The results of this analysis are summarized in figures 10 to 12. In deriving these figures, the overall A.F.R. and the ratio $^x/d$ were fixed at 50 and 6 respectively, these being regarded as representative values.

Figure 10 shows the extent to which the overall pressure loss factor must be increased, if the chamber inlet velocity is increased, in order to achieve the same traverse quality in the same length. Results are shown for reference velocities of 80 and 120 ft/s, these being typical values for tuboannular and annular combustion chambers respectively, and also for two values of diffuser loss coefficient, η. It is apparent from this figure that the effect of increased inlet velocity is most pronounced when the diffuser pressure loss is high and the reference velocity low.

The influence of inlet velocity is further illustrated in figure 11, in which results are presented for two values of reference velocity and a range of overall pressure loss factors. They show that under conditions where an increase in inlet velocity cannot be accommodated by an increase in pressure loss factor, then the same standard of traverse quality can be maintained by an increase in dilution zone length. The amount of extra length required is greatest when both the overall pressure loss factor and the reference velocity are low.

The effect of inlet velocity profile on dilution zone performance is illustrated in figure 12. Calculations have been carried out for three profiles of parabolic form and having values of V_{max}/V_{mean} of 1.1, 1.2, and 1.3. In these calculations it was assumed that 25% of the total inlet air entered the primary snout at the peak velocity, and the remainder flowed over the flametube head. The results obtained with the peakiest profile are shown in figure 12, along with those for a flat profile. As plotted they show that any increase in profile 'peakiness' must be accompanied by an increase in dilution zone length in order to achieve the same traverse quality. It will be appreciated that these results can also be interpreted in terms of extra pressure loss factor or increase in reference velocity by transposition between figures 10, 11 and 12.

The main purpose of figures 10 to 12 is to provide quantitative relationships between the chamber entry conditions of velocity and velocity profile and the main dilution zone design parameters. Perhaps the most striking point brought out by these figures is that the trend towards combustion chambers of lower pressure loss, which for many years has been a primary research and development objective, must inevitably result in systems whose dilution zone performance and general aerodynamic stability are more sensitive to increases in inlet velocity and changes in velocity profile.

Definition of Aerodynamic Performance

The overall pressure loss factor of a combustion chamber represents the sum of two sources of pressure loss (a) the pressure loss in the diffuser and (b) the pressure loss across the flametube.

Thus,

$$\Delta P_{2-3} = \Delta P_{diff} + \Delta P_f$$

Even the most efficient diffuser constitutes wasted pressure loss in the sense that the pressure loss involved makes no contribution to combustion. It is important, therefore, to keep ΔP_{diff} to a minimum, although in practice there is little the combustion engineer can do other than to observe the established principles of diffuser design.

It is, of course, equally important to keep the flametube pressure loss factor to a minimum, although in this case there is an important difference in that all the pressure loss incurred is beneficial to both combustion and dilution processes. A high value of ΔP_f implies small air injection holes in the flametube. These small holes result in high air injection velocities, steep penetration angles, and a high level of turbulence which, in turn, promotes good mixing. Thus for any given value of overall pressure loss factor it is important that the ratio of the flametube pressure loss to the overall pressure loss should be made as large as possible. Defining this ratio as β where

$$\beta = \frac{\Delta P_f}{\Delta P_{2-3}}$$

it can be stated that, in general, any increase in the value of β will promote more stable flow conditions, with the exit temperature traverse less sensitive to changes in inlet velocity and inlet velocity profile.

The manner in which β varies with changes in inlet velocity, reference velocity and overall pressure loss factor is illustrated in figure 13. It is apparent from this figure that from a purely aerodynamic standpoint the most satisfactory combustion chamber is one having a low inlet velocity, a high reference velocity and not too low an overall pressure loss factor. Some indication of the increase in dilution zone length required to compensate for a decrease in β is provided in figure 14.

A practical illustration of the significance of β is gained by considering how it is affected by a reduction in the overall pressure loss factor of a chamber, which may be accomplished in practice in one of two ways. One method is by reduction of ΔP_f, which inevitably decreases β, by definition. The other method is to increase the chamber casing area which, for constant $\Delta P_f/q_{ref}$, leads to an increase in $\Delta P_{diff}/q_{ref}$. Thus it is impossible to reduce the overall pressure loss of a combustion chamber without reducing β, and hence without impairing its aerodynamic performance.

Conclusions

It is confirmed that combustion chamber traverse quality is adversely affected by an increase in inlet velocity, a more peaked velocity profile, a reduction in chamber reference velocity, an increase in diffuser pressure loss factor, a reduction in flametube pressure loss factor, and a reduction in dilution zone length. Most of these effects have been recognised for some time but in this paper a contribution is made towards expressing some of the more important relationships quantitatively. The presentation is by no means comprehensive but the same methods could, if required, be employed to extend the number and range of the variables considered.

For many practical purposes the aerodynamic performance of a combustion chamber may be conveniently and adequately defined in terms of the parameter β, where β is the ratio of the flametube pressure loss factor to the overall pressure loss factor. It is believed that β could provide a useful tool in comparing (a) the aerodynamic quality of two different designs of combustion chamber, or (b) the same chamber before and after one or more design modifications or (c) the same design of chamber subjected to variations in inlet velocity or velocity profile.

References

1. Norster, E.R. College of Aeronautics Note Aero. No. 170.

2. Dittrick, R.T. and Graves, C.C., NACA Tech. Note 3663, April, 1956.

3. Norster, E.R., College of Aeronautics Report Aero No. (To be published).

4. Cox, M. N.G.T.E. Report No. N.T.281, April 1957.

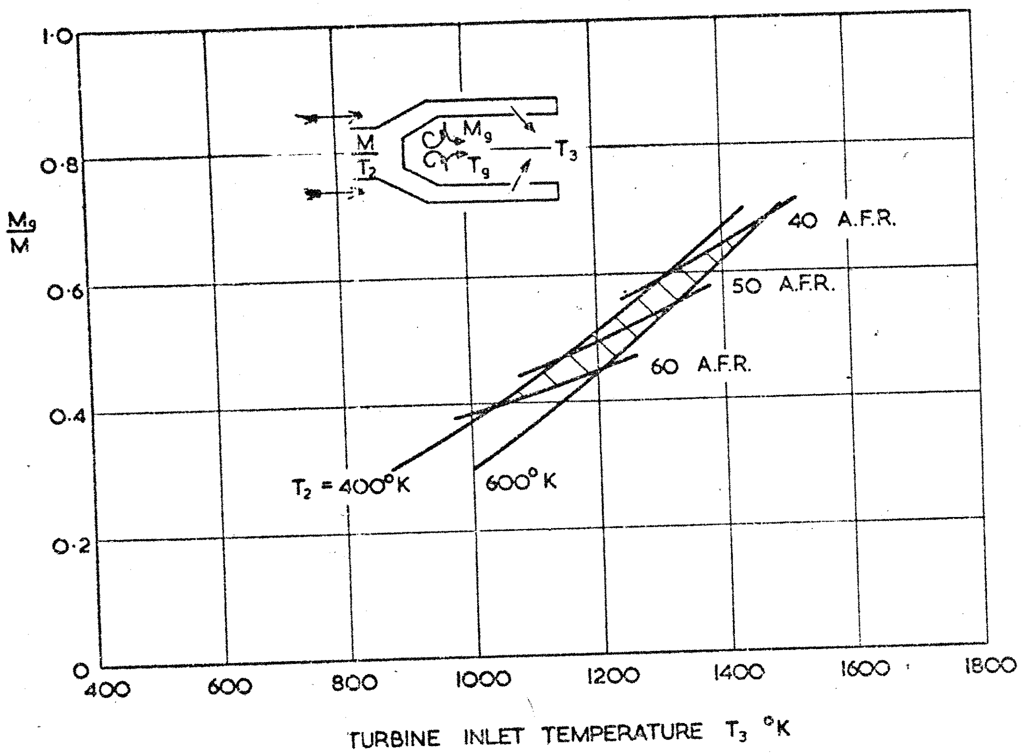

FIG. 1 DILUTION ZONE FLOW PROPORTIONS AS A FUNCTION OF TURBINE INLET TEMPERATURE FOR T_g = 1800°K. (SHADED AREA REPRESENTS CURRENT DESIGN REGION)

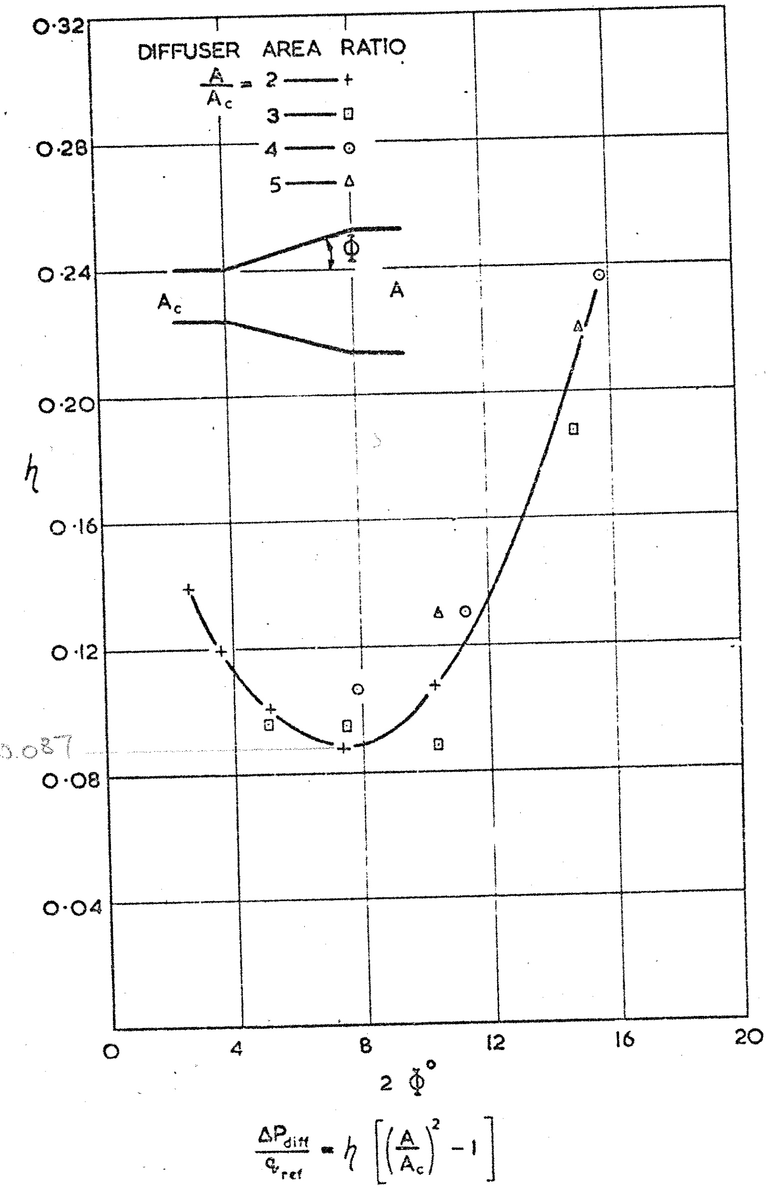

FIG. 2 VARIATION OF DIFFUSER PRESSURE LOSS FACTOR WITH DIVERGENCE ANGLE

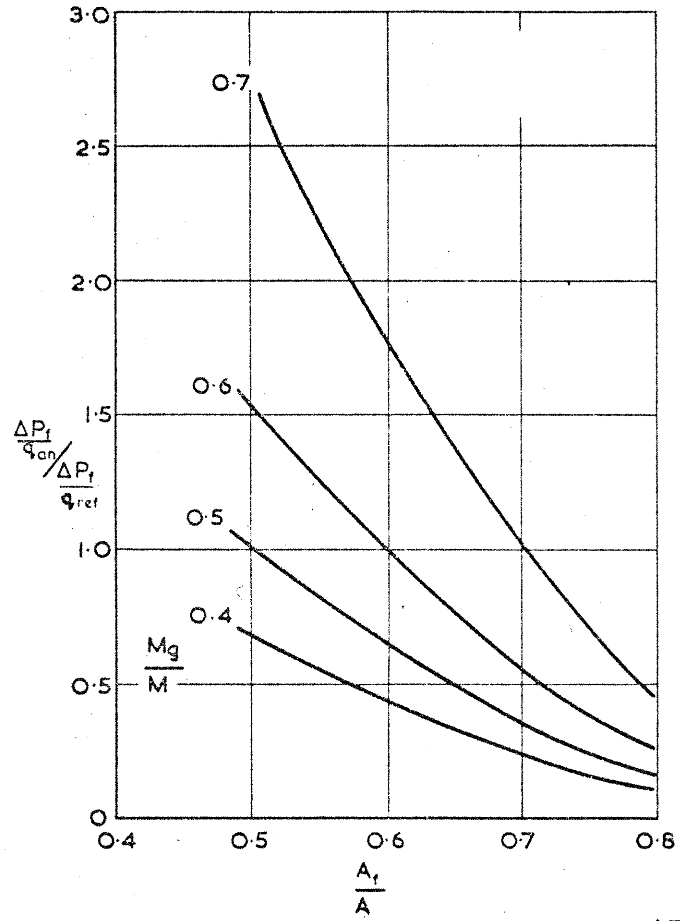

FIG. 3 GRAPH FOR DETERMINATION OF RATIO $\frac{\Delta P_f}{q_{an}}$

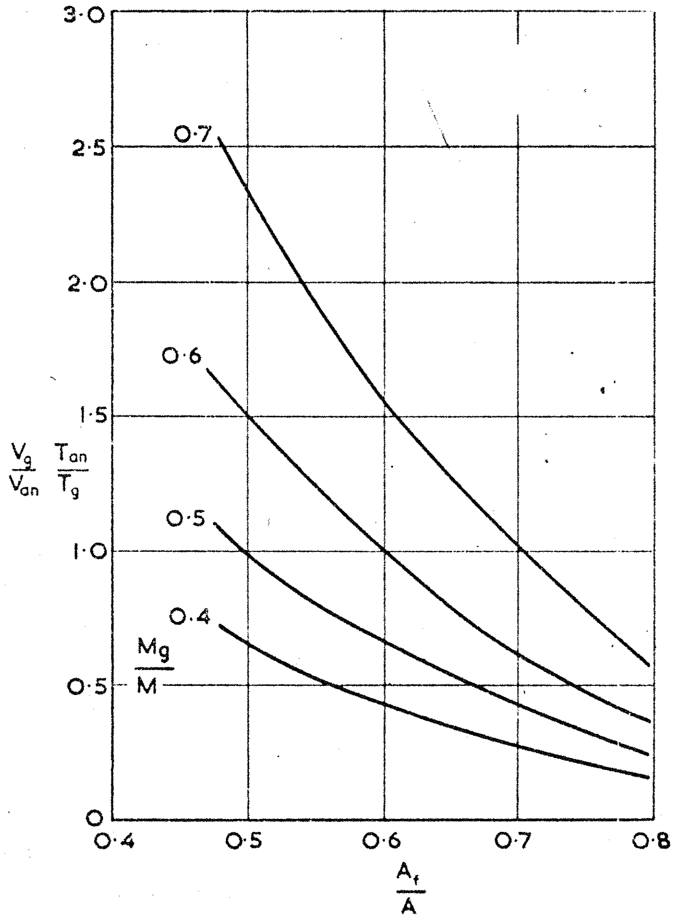

FIG. 4 GRAPH FOR DETERMINATION OF RATIO $\frac{V_g}{V_{an}}$

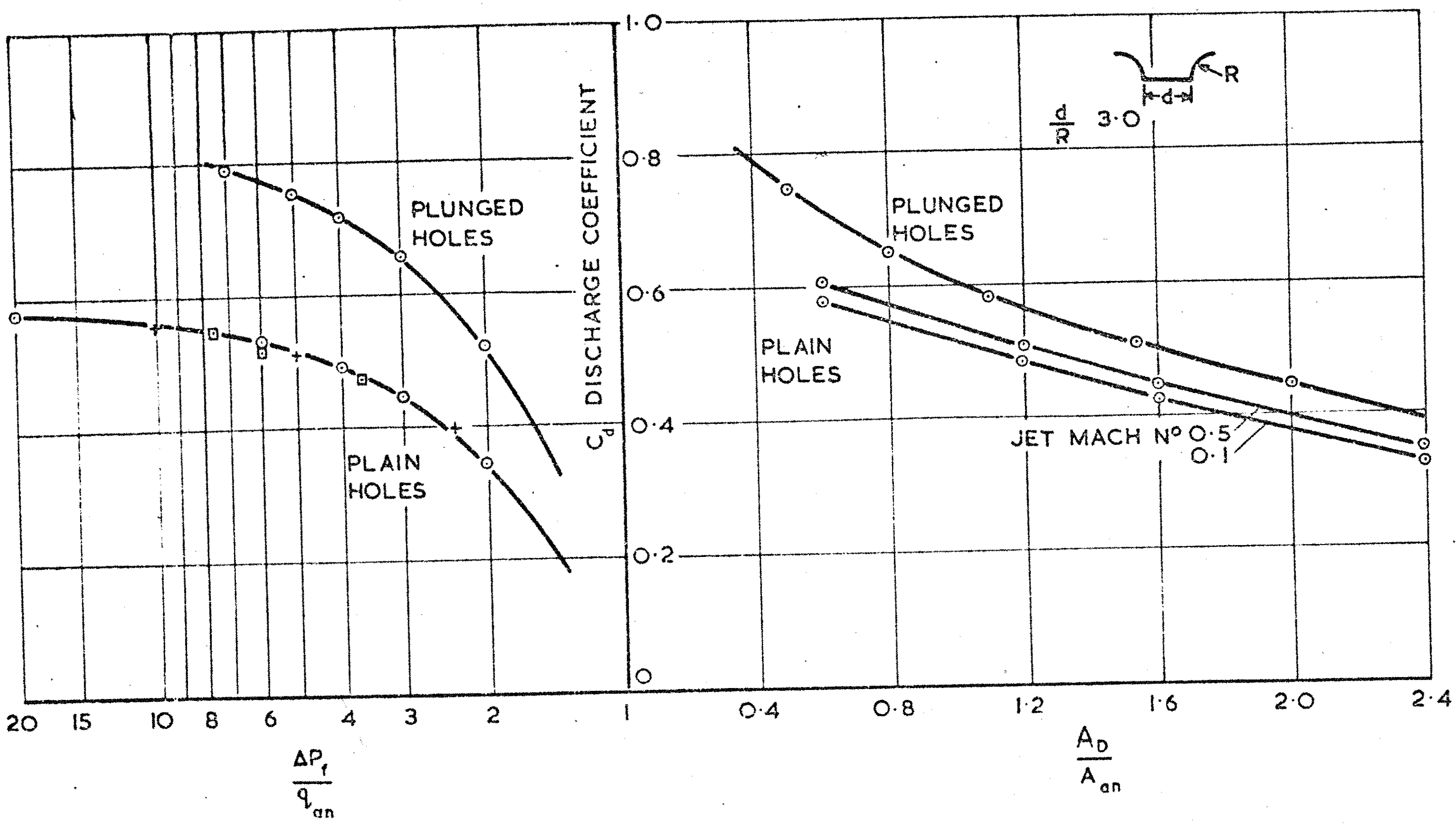

FIG. 5 DILUTION HOLE FLOW PARAMETERS

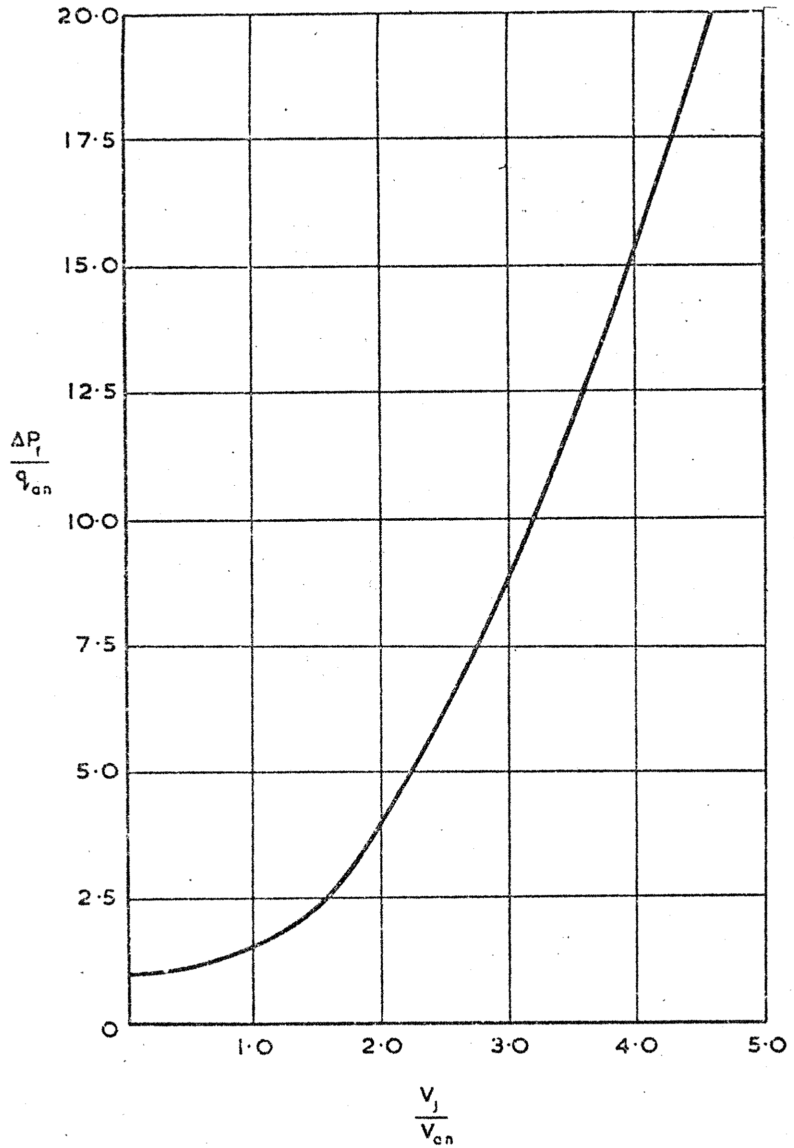

FIG. 6 RATIO OF DILUTION JET VELOCITY TO ANNULUS VELOCITY AS A FUNCTION OF FLAME-TUBE PRESSURE LOSS FACTOR

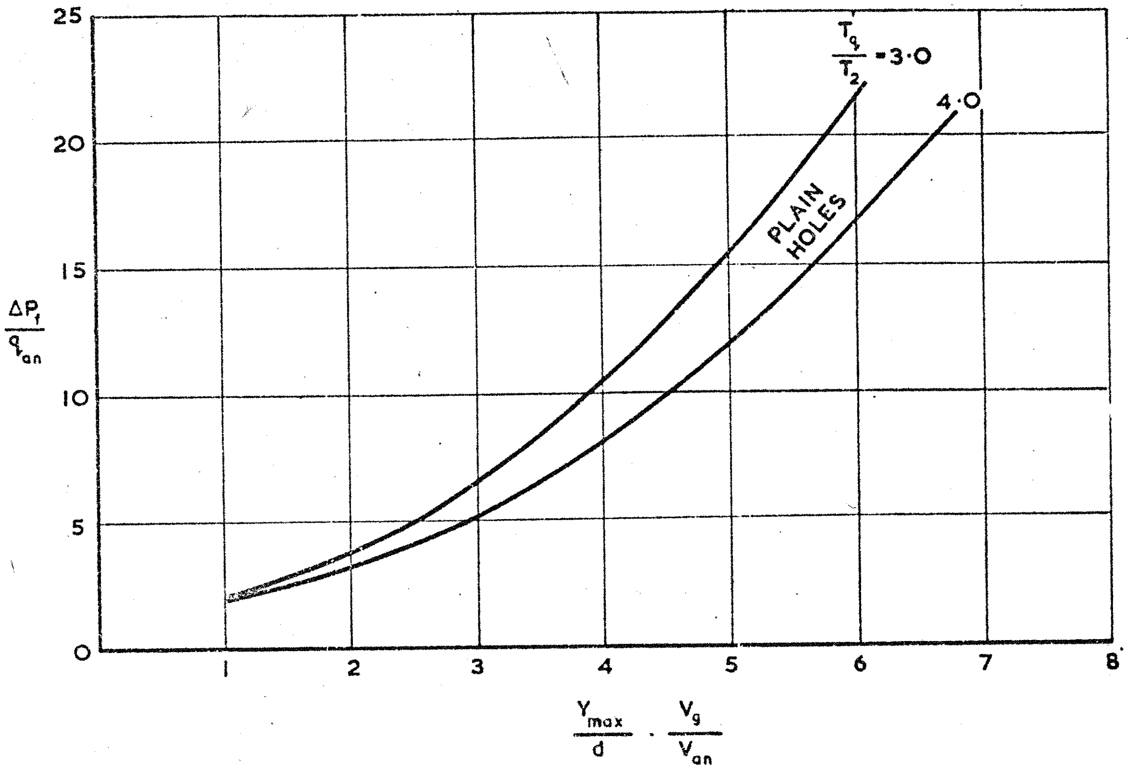

FIG. 7 RATIO OF JET MAXIMUM PENETRATION TO DILUTION SIZE AS A FUNCTION OF FLAME-TUBE PRESSURE LOSS

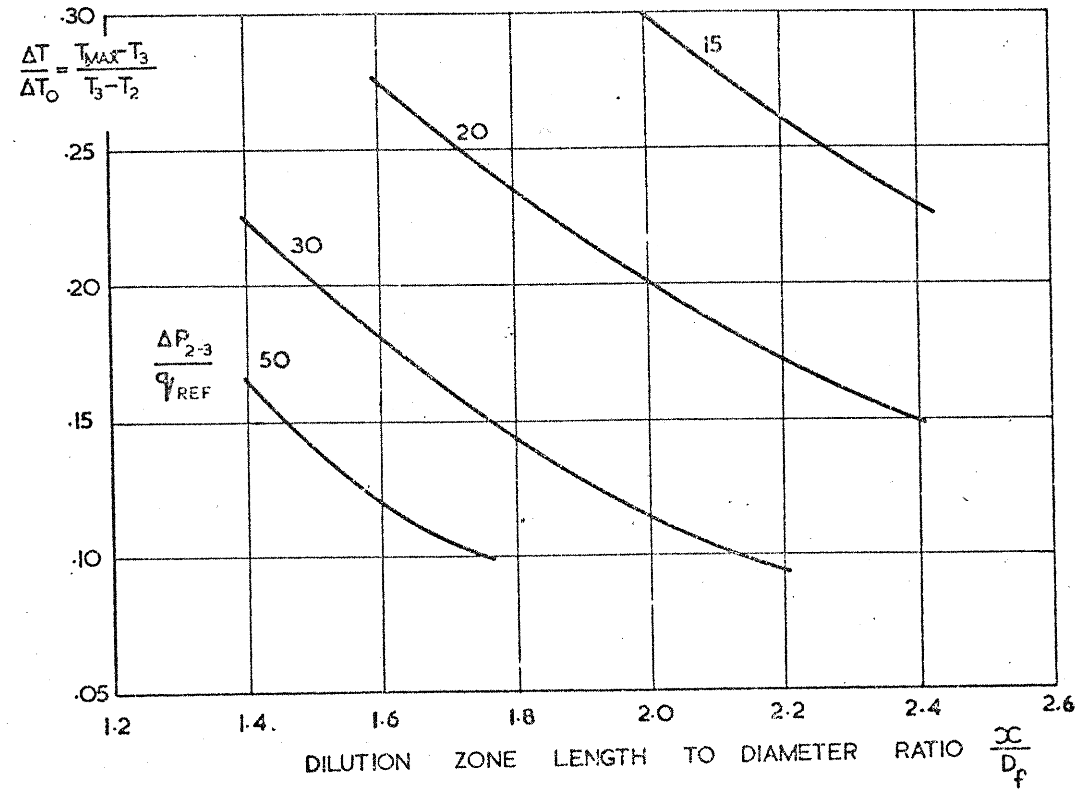

FIG. 8 DILUTION ZONE MIXING PERFORMANCE

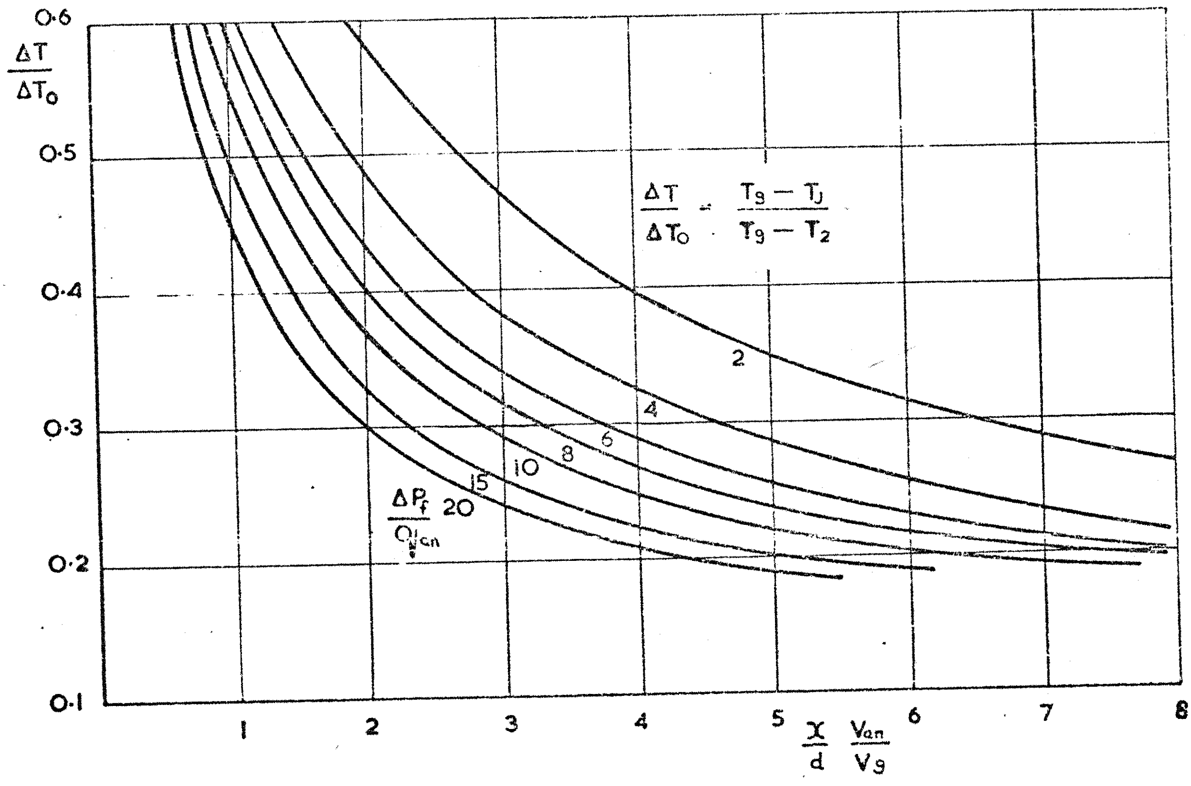

FIG. 9 TEMPERATURE TRAVERSE QUALITY AS A FUNCTION OF DILUTION ZONE DIMENSIONS AND FLAME TUBE PRESSURE LOSS

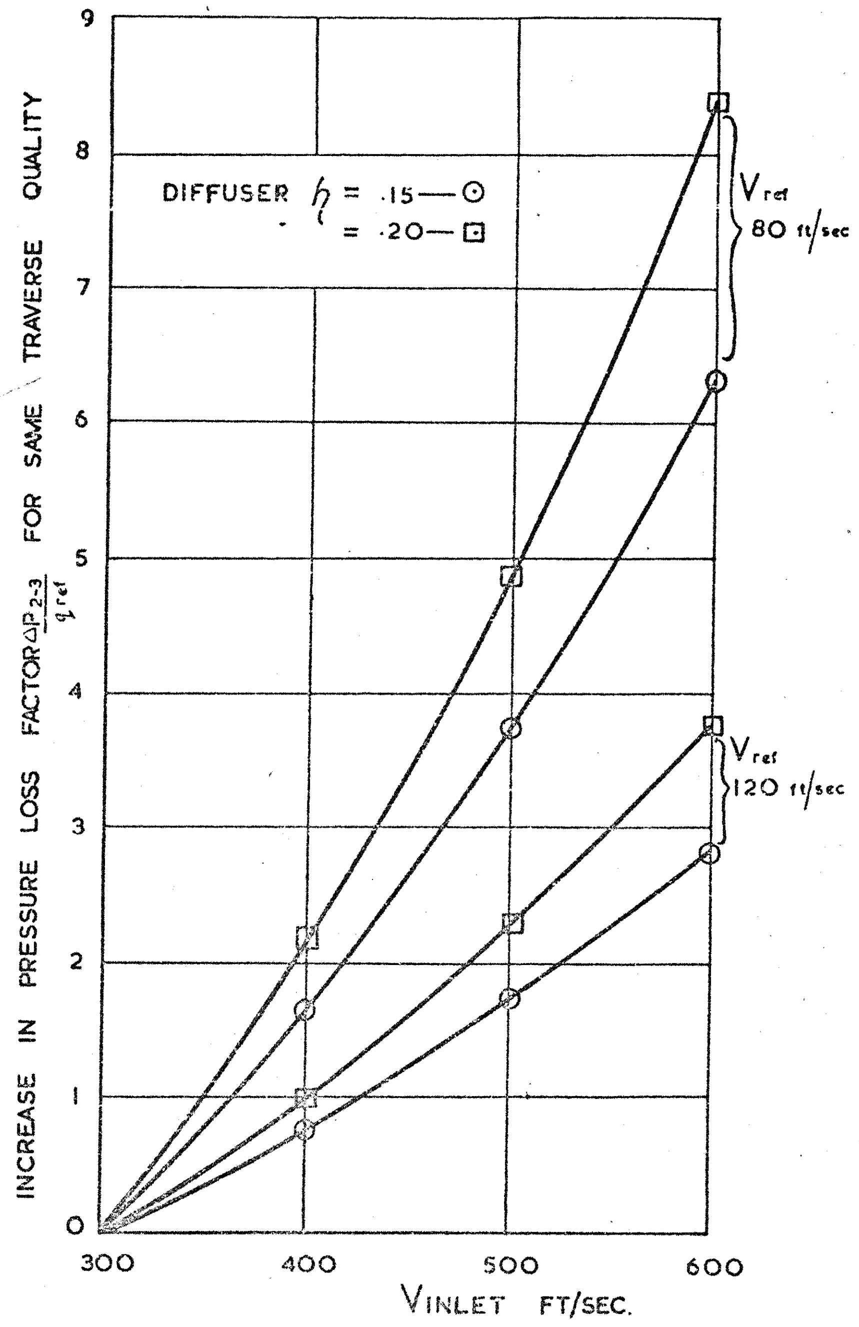

FIG. 10 RELATIONSHIP BETWEEN INLET VELOCITY AND CHAMBER PRESSURE LOSS FACTOR FOR CONSTANT TRAVERSE QUALITY

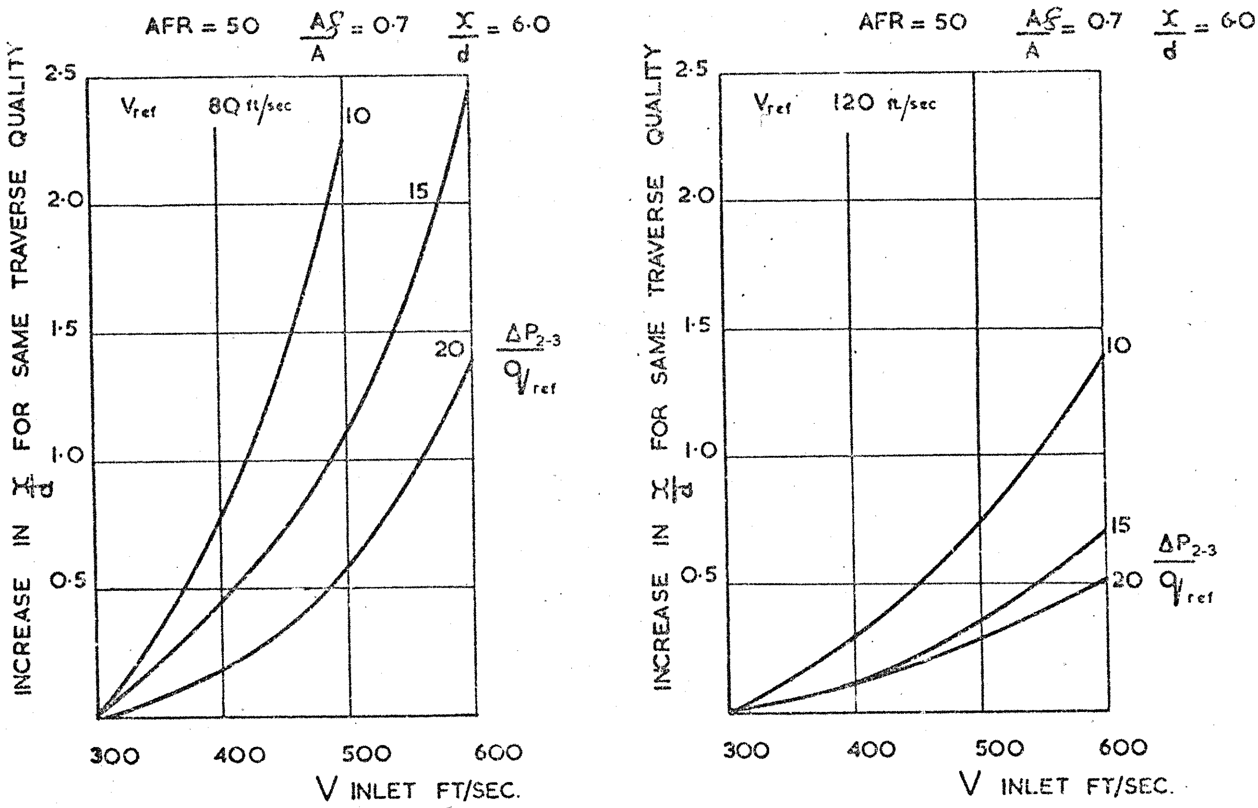

FIG. 11 MIXING LENGTH AS A FUNCTION OF INLET VELOCITY AND PRESSURE LOSS FACTOR

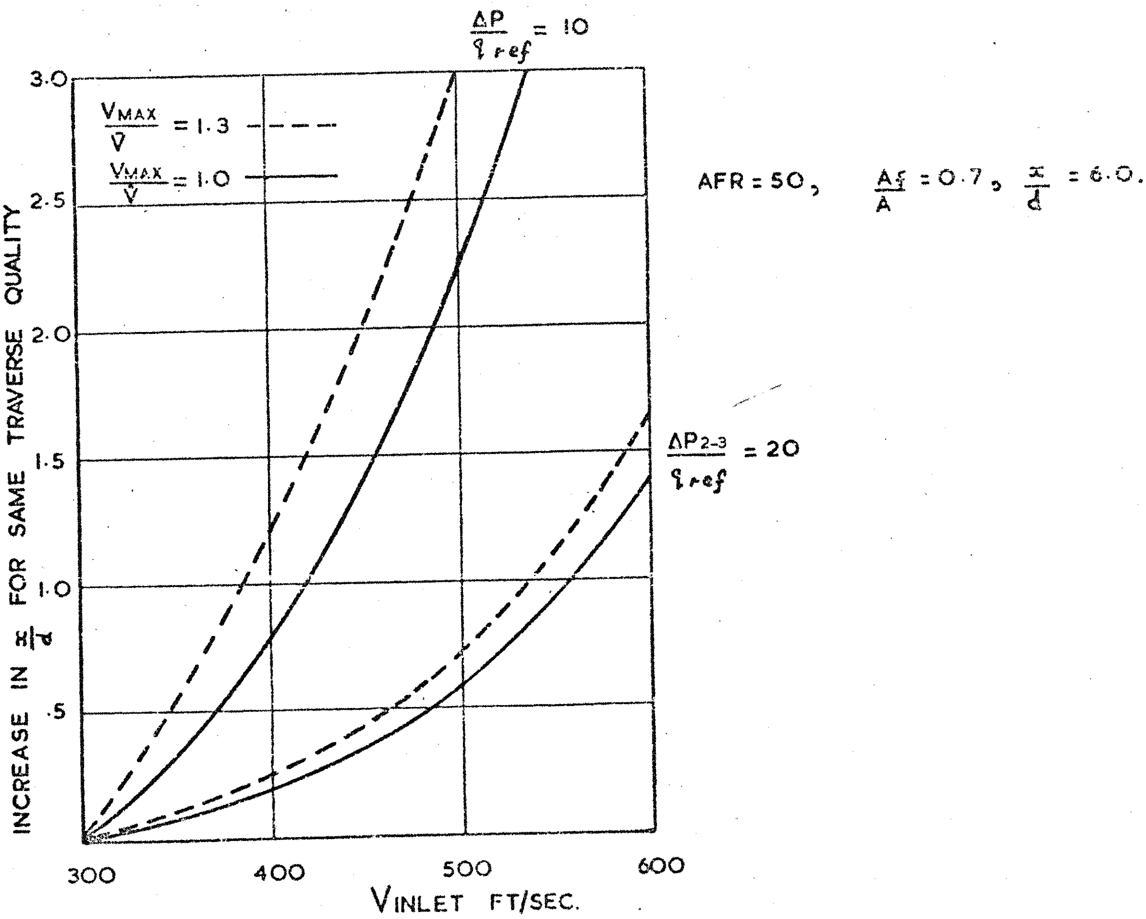

FIG. 12 EFFECT OF VELOCITY PROFILE ON MIXING LENGTH REQUIREMENT

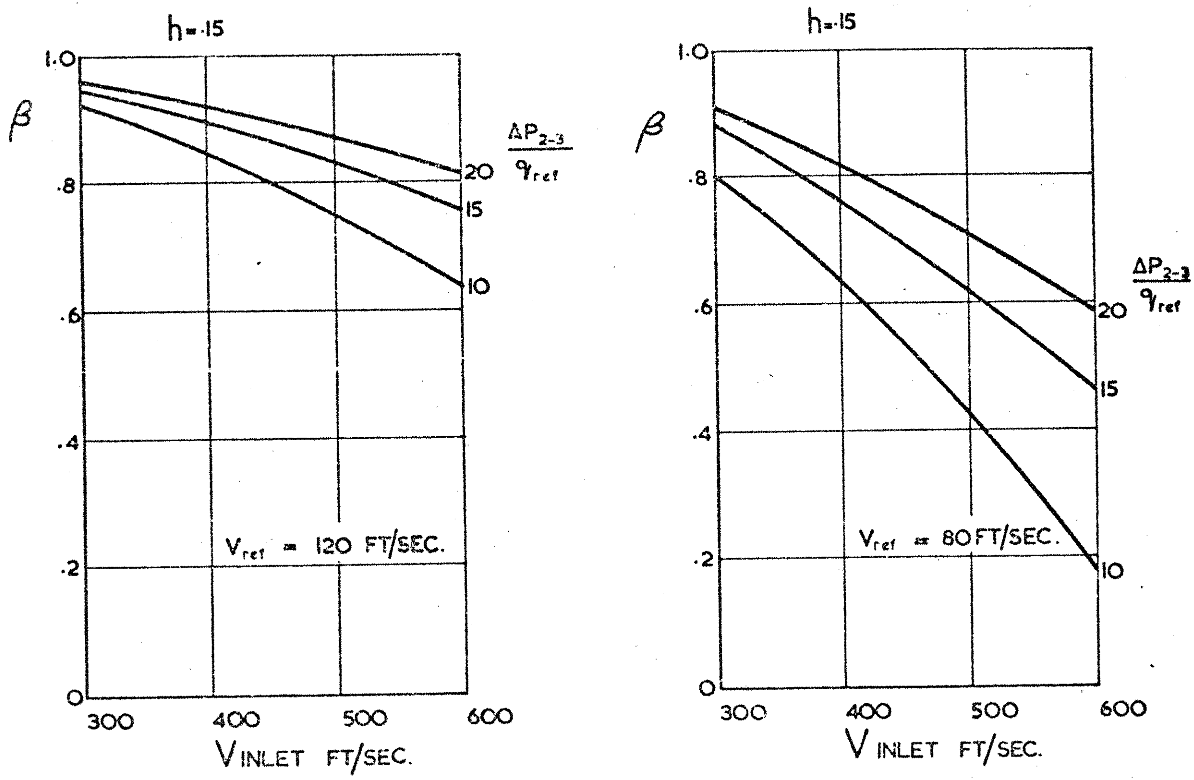

FIG. 13 INFLUENCE OF INLET VELOCITY AND PRESSURE LOSS FACTOR ON AERODYNAMIC PERFORMANCE PARAMETER, β

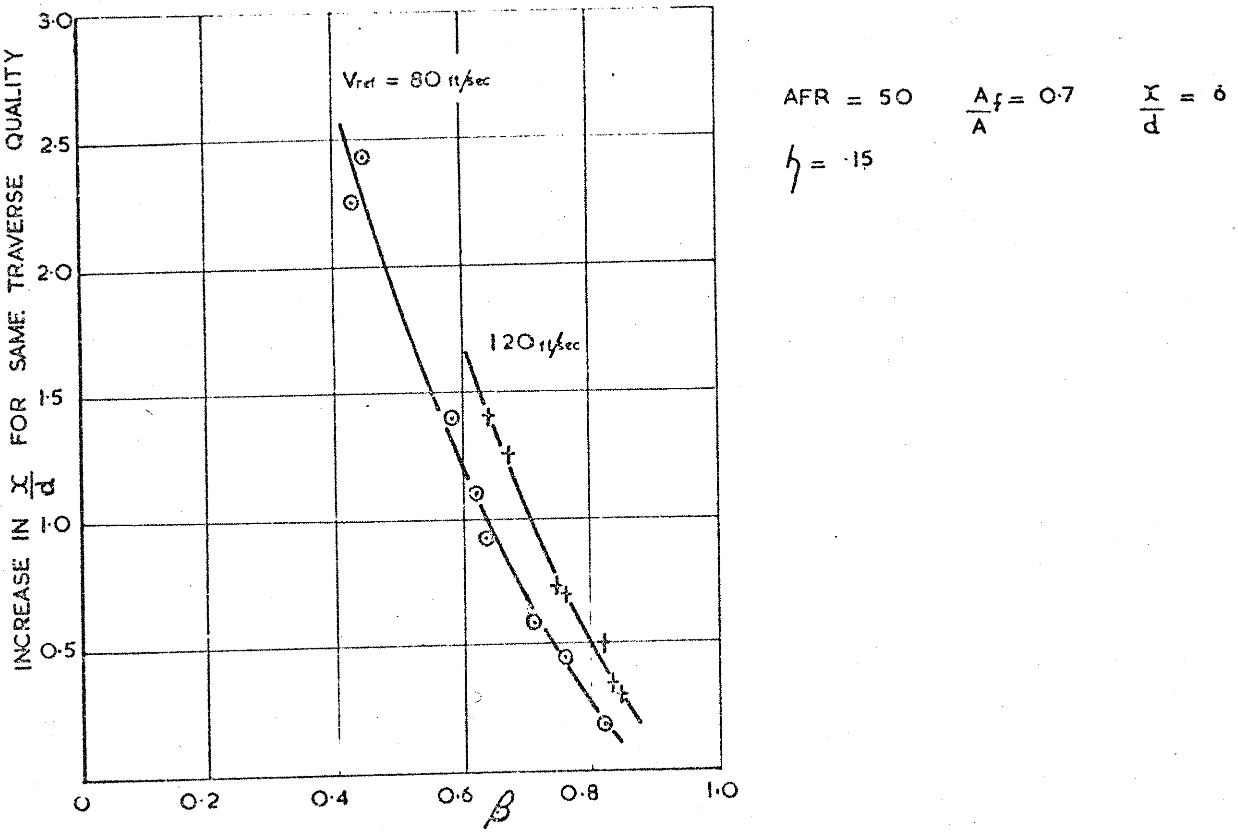

FIG. 14 RELATIONSHIP BETWEEN β AND DILUTION ZONE LENGTH FOR CONSTANT TRAVERSE QUALITY.