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THE EFFECTS OF "CONTROLLED" INLET CONDITIONS ON THE PERFORMANCE OF CONICAL DIFFUSERS PRECEDED BY NORMAL SHOCK BOUNDARY LAYER INTERACTION.

by

W. A. KAMAL A. O. ODUKWE and J. L. LIVESEY

S U M M A R Y.

The performance of conical diffusers preceded by a normal shockwave turbulent boundary layer interaction has been investigated while diffuser inlet conditions were very well controlled. Diffuser angles of 5, 8, 12 and 20° and area ratios up to 4 were studied experimentally for inlet Mach numbers varying from 0.8 up to choking. The ranges of Reynolds number and blockage variation were limited by the necessity of positioning the shock wave within the diffuser entry pipe length. Diffuser performance dependence on isolated parameters has been studied and the possibility of correlating diffuser pressure recovery and efficiency with inlet and geometric variables has been explored. Performance maps have been established for two values of the inlet Mach number at constant values of R_e and blockage.

W. A. Kamal - Research Student)
A. O. Odukwe - Lecturer) University of Salford,
J. L. Livesey - Professor of Fluid Mechanics) England.

NOTATION

EL	$\frac{L}{D}$		KE	Mean kinetic energy at a section
N	Diffuser axial length		AR	Area ratio at a given section = $\frac{A}{A}$
$\mathcal{R}$	Gas constant		ρ, p, T, u, P	Density, pressure, absolute temperature, axial velocity and total pressure at a point
θ	Boundary layer momentum thickness		R	Diffuser radius at a section
2ϕ	Diffuser total angle			
L,D	Inlet pipe length and diameter			
A	Diffuser area at a section			

SUBSCRIPTS : 1 and 2 refer to diffuser inlet and exit
t refers to total (stagnation) conditions
Bars indicate mean values over cross section

HIGH SUBSONIC MACH NUMBER DIFFUSER PERFORMANCE GOVERNING PARAMETERS

Diffuser performance is generally governed by two main factors, namely:- diffuser geometry and inlet conditions. For a conical diffuser, geometry is characterised by the non-dimensional quantities; diffuser angle 2ϕ and length to inlet radius ratio $\frac{N}{R_1}$ (or area ratio AR). The following parameters suffice to specify diffuser inlet flow situation.

(i) The Mach number $M = \frac{\bar{u}}{\sqrt{\gamma \mathcal{R} \bar{T}}}$

(ii) The Reynolds Number $R_e = \frac{\bar{u}D}{\bar{\nu}}$ ($\bar{\nu}$ = mean kinematic viscosity)

(iii) An inlet velocity profile parameter :-
Instead of using a characteristic boundary layer thickness, Sovran and Klomp[(1)] found that the performance of diffusers having different geometries could be better correlated using an inlet blockage factor. Inlet blockage is defined as

$B = \frac{A_B}{A} = \frac{A - A_E}{A}$ where A_E is the effective flow area defined by

$$\bar{\rho}\ A_E\ \bar{u} = \int^A \rho\ u dA$$

(iv) Turbulence structure of the inlet flow. Turbulence intensity at diffuser inlet has an unquestionable effect on diffuser pressure recovery and flow regimes within the diffuser. While the results reported here do not include a systematic study of this parameter, work is continuing to examine its influence at high Mach numbers.

DIFFUSER CHARACTERISTICS (Diffuser performance describing parameters).

(i) Diffuser pressure recovery :-
Relative measures of pressure producing capabilities are obtained by comparing the measured pressure rise with either the 'maximum' value that could be theoretically obtained at the particular flow rate, or with the 'ideal' pressure rise that was possible to achieve with the particular diffuser geometry. In each case an inviscid flow process is assumed, with the first also employing the use of an infinite area ratio to produce complete diffusion. Thus we have the following two performance parameters :-

(a) Pressure recovery coefficient $C_p = \frac{\bar{p}_2 - \bar{p}_1}{\bar{P}_1 - \bar{p}_1}$

(b) Overall diffuser effectiveness $\zeta = \frac{\Delta p}{\Delta p_i} = \frac{C_p}{C_{pi}}$ where $C_{pi} = 1 - \frac{1}{AR^2}$

(ii) Diffuser energy conversion efficiency η : which is a measure of the reversibility of the diffusion process

$$\eta = \frac{\text{Output}}{\text{Input}} = 1 - \frac{\text{losses}}{\text{input}} = 1 - \frac{\mathcal{R} T \ln (\bar{P}_1/\bar{P}_2)}{KE_1 - KE_2}$$

η is complementary to the usually used loss coefficient C_L which relates the loss at each section to the K.E. at diffuser inlet.

(iii) There are instances, where the uniformity and steadiness of the diffuser discharge flow are of as much importance as the velocity reduction or static pressure rise produced. For this reason an exit profile distortion coefficient is defined as

$$\varepsilon_3 = \frac{\int \rho\, u^3 dA}{A \bar{\rho} \bar{u}^3}$$

AVERAGING TECHNIQUE.

To calculate the mean values of the flow variables at each diffuser station, the averaging procedure of Livesey and Hugh[2,3] is employed.

APPARATUS.

The overall test rig layout is shown in Fig. (1). For details see reference (4). The downstream throttle valve was used to control the shock position within the entry length at various upstream driving pressures. The valve was installed at a sufficient distance downstream of the diffuser tail pipe to ensure that the valve would cause no change of the flow regimes within the diffuser nor promote flow separation.

Four diffusers were tested with cone angles of 5, 8, 12 and 20° and overall area ratio of 4, with a sharp transition from the inlet pipe. To avoid the effects of the sharp entry (non-uniform static pressure distribution) and the strong streamline curvature encountered, the diffuser inlet conditions were evaluated from measurements in aplane 1.5 diameters upstream of the sharp transition, thus allowing the entry losses to be correctly attributed to the diffuser.

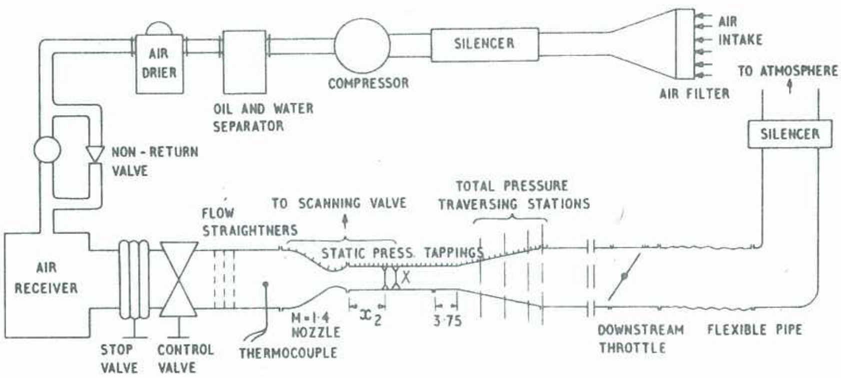

FIG. 1 APPARATUS

EXPERIMENTAL PROCEDURES.

i) Establishing Inlet Conditions :-
The key parameters to change M, R_e and B_1 individually were : the shock position, the supply pressure and the entry pipe length respectively. It was believed that for a certain entry length - diffuser combination, keeping the shock at the same distance from diffuser inlet at different values of the upstream driving pressure P_c, will keep the Mach number at diffuser inlet constant. From a one-dimensional point of view the flow can be simplified to

Fanno flow ⟶ normal shockwave ⟶ Fanno flow

Deviations were expected because of the two-dimensionality of the flow and because of the nature of the shock-boundary layer interaction. However, after construction of charts of shock position versus downstream valve opening for different upstream pressures, the Mach number at diffuser inlet could be kept constant to within 1%. Changing shock location within the entry pipe was expected to change slightly the value of the inlet boundary layer blockage. A similar effect was expected with the variation of R_e. However, examination of results showed that the variation of blockage with R_e followed no obvious trend and was generally very slight. Though the variation of inlet blockage with shock position showed a constant trend yet its magnitude was insignificant. The only method for changing the inlet blockage was to change the entry pipe length. For details, see reference (5).

ii) Diffuser systematic tests:-
The tests includes, for all configurations studied, and for all inlet conditions, measurements of static pressure distribution along the entry pipe and diffuser and total pressure traverses at the inlet section and at AR's 1.5, 2, 3 and 4. The traverses at inlet section were carried out using a 0.75 mm diameter single pitot tube instead of the fifteen probe pitot rakes used at other sections, in order to avoid variation of shock location when probe is inserted. In view of the noticeable unsteadiness of the flow at large AR's especially with separated flow, the basic uncertainty of the total pressure measurements is between 3% and 6%.

RESULTS AND DISCUSSION.

Range of parameters :

M	Mach number	0.833	-	1.0
R_e	Reynolds Number	0.76×10^6	-	0.98×10^6
B_1	Inlet Blockage	0.055	-	0.078

A) Performance dependence on inlet variables :-

1. Effect of R_e :-

Fig. (2) shows the variation of diffuser pressure recovery with R_e (the Mach number as a parameter) for the 4 diffusers tested. Similar results were obtained when η was plotted instead of C_p. From the figures, the following features can be outlined:

(i) For the 5^o diffuser (at constant Mach number) both C_p and η improve significantly at all area ratios with increasing R_e.

(ii) For the 8^o diffuser, the effect of changing R_e on performance showed no obvious trends and in many values of Mach number C_p and η were nearly constant while R_e was changing.

(iii) For the 12^o diffuser, performance starts to deteriorate with increasing R_e, its effect becoming more pronounced at higher values of the Mach number.

(iv) For the 20^o diffuser, obvious deterioration of performance is observed with increasing R_e.

The above results can be understood as follows :-

The 5^o diffuser (which according to McDonald and Fox (6) flow regime chart shows no sign of stall at the largest diffuser length investigated) shows an appreciable improvement in performance with increase of R_e. Being unstalled, diffuser losses are mainly due to viscous friction. An increase of R_e decreases the viscous effects in the flow, thus leading to higher C_p and η .

In the 12 and 20^o diffusers the flow is separated over most of diffuser length and it is concluded that an increase of inlet R_e to a stalled diffuser leads to a definite deterioration of both C_p and η .

For the 8^o diffuser R_e has no significant effect on performance.

As was mentioned before, there was a slight variation in the value of inlet blockage accompanying the change in R_e. Since it was stressed, in diffuser literature, that blockage has a significant effect on performance, it was desirable to isolate the effect of the slight change in blockage to allow for a study of the explicit effect of R_e. A few cases were investigated in which, for a constant Mach number, the inlet blockage could be kept very nearly constant (variation within ½%) while R_e changing. The effects of R_e on C_p, η , and ε_3 are shown in Fig. (3). Generally, the results confirm the above made conclusions. Besides, two important observations can be made:-

(i) It is noticed that for the 12 and 20^o diffusers at AR = 2, C_p and η increase with R_e. Returning to the McDonald and Fox chart, it was found that for both diffusers at that AR flow is still unstalled. This result confirms the above made conclusions.

(ii) For all diffuser angles at all AR, an appreciable decrease in ε_3 is affected by increasing R_e. The decrease in ε_3 is very slight for unstalled geometries and for geometries in the transitory stall region, but it becomes larger for wide angle diffusers and increases as separation becomes more fully developed.

2. Effect of Mach number :-

Figs. (2) and (3) show a definite deterioration of performance for all diffuser angles at all AR's, with increasing the inlet Mach number. This is expected, since the Mach number at diffuser inlet increases as the shock approaches the diffuser, with any flow discontinuities due to the presence of the shock becoming closer to the start of the diffusion.

The result is in agreement with the widely held concept of a 'subsonic critical Mach number'. From Haleen and Johnston's (7) correlation of the critical Mach number with inlet blockage ratio, the critical Mach number corresponding to the range of blockage covered in the present investigation is nearly 0.7, consequently we expect a deterioration of performance with increasing M since the Mach numbers involved were always larger than 0.8.

3. Effect of inlet blockage (entry pipe length) :-

A typical plot of the variation of diffuser performance characteristics with inlet blockage as a parameter for a constant Mach number is shown in Fig. (4). From the figure it is clear that an increase in throat blockage results in decreasing diffuser pressure recovery and efficiency and increasing exit profile non-uniformity. The effect on C_p and η was more obvious at the beginning of the diffusion (small AR's) while the effect on ε_3 is more pronounced at the large AR's (the diffuser magnifies its inlet profile non-uniformity).

It has been claimed that it is possible for incompressible conical diffuser flow to correlate C_p for diffusers of different geometries with the product of diffuser angle and θ_1/D_1 (which varies linearly with the entry length).

For the present flow situation, C_p, at different area ratios showed good correlation with the product (2ϕ XEL) as shown in Fig. (6). While data for incompressible flow (Winternitz and Ramsay (8) showed a linear dependence on the product $2\phi X\ \theta_1/D_1$, the relation is not linear in the present case.

Diffuser effectiveness ζ at the exit plane (AR = 4) could be also correlated successfully with the same product, while η showed no similar behaviour.

Sovran and Klomp (1) showed that diffuser effectiveness may be determined by the effective area fraction at diffuser exit E_2. Based on analytical argument they suggested that E_2 might correlate with inlet blockage area ratio and their correlation covered diffusers of different geometrical shapes with incompressible flow.

A correlation similar to that of Sovran and Klomp was attempted for the present data and different functions of AR and B_1 were used, but it was found that the best correlation was accomplished using the same independent variable for incompressible flow, i.e., AR $(B_1)^{\frac{1}{4}}$ (Fig. 5). The important feature is that, Sovran's correlation is obtained for geometries on the optimum C_p line only, whereas the present correlation is made for a general diffuser geometry.

B). <u>Performance dependence on diffuser geometry.</u>

1. Effect of diffuser angle 2ϕ :-

At all AR's for given inlet conditions, diffuser performance deteriorates with increasing diffuser angle.

2. Effect of AR :-

(i) on C_p, a very sharp rise of C_p until AR = 2, then rate of press recovery decreases sharply either because of excessive friction (5°, 8°) or excessive flow separation (12° and 20°).

(ii) on η, η increases up to AR = 2 then falls steadily. Effect of AR is small compared to that of diffuser angle.

(iii) on ε_3, profile distortion increases steadily with AR.

3. Performance maps :-

Because of the difference in diffuser losses and consequently the differences in the range of upstream pressures required to maintain the shock within the entry length, overlapping of inlet conditions for all diffusers was achieved only in two cases. A contour plot for one of those cases in shown in Fig. (7). Line C_p* is the line of maximum pressure recovery at constant diffuser length, so, it indicates what AR to choose and the corresponding 2 ϕ for any diffuser length.

In Fig. (8) C_p* lines for the 2 cases (same blockage and different Mach number) are compared. It can be clearly seen that diffuser performance degenerates rapidly as inlet Mach number approaches choking. Dewoestine and Fox (9) results for diffusers preceded by wholly subsonic flow lead them to conclude that there is no significant variation in the location of the C_p* line with change of inlet M. Fig. (8) shows clearly that this is not the case with diffusers preceded by a shock - boundary layer interaction and that for a constant diffuser length an increase of the inlet Mach number limits considerably the diffuser angle which gives stall-free operation.

Results of Reneau et al (10) for 2-D diffuser flow and of Sovran and Klomp (1) and Bradley and Cockrell (11) for incompressible conical diffuser flow showed that C_p* lines obtained with different inlet boundary layer thicknesses, very nearly coincide. Hence, it is suggested that the present C_p* lines can be adequately employed in choosing the optimum geometries in the range of boundary layer blockage covered in the present investigation.

The AR vs $\frac{N}{R_1}$ log plot is most suitable for 2-D diffusers while a plot of constant C_p lines on a (2ϕ vs $\frac{N}{R_1}$) map seems more suitable for conical diffusers, where constant AR lines appear as straight lines. The data of Fig. (7) is replotted on the new coordinates in Fig. (9).

A very useful cross plot from the contour maps is shown in Fig. (10). Values of pressure recovery are plotted against AR for various values of the length ratio. From this plot, one can readily determine the optimum length ratio for maximum C_p at a given AR, e.g., for AR = 1.7 the figure indicates that, no increase in pressure recovery is gained by going to an $\frac{N}{R_1}$ above 6.0.

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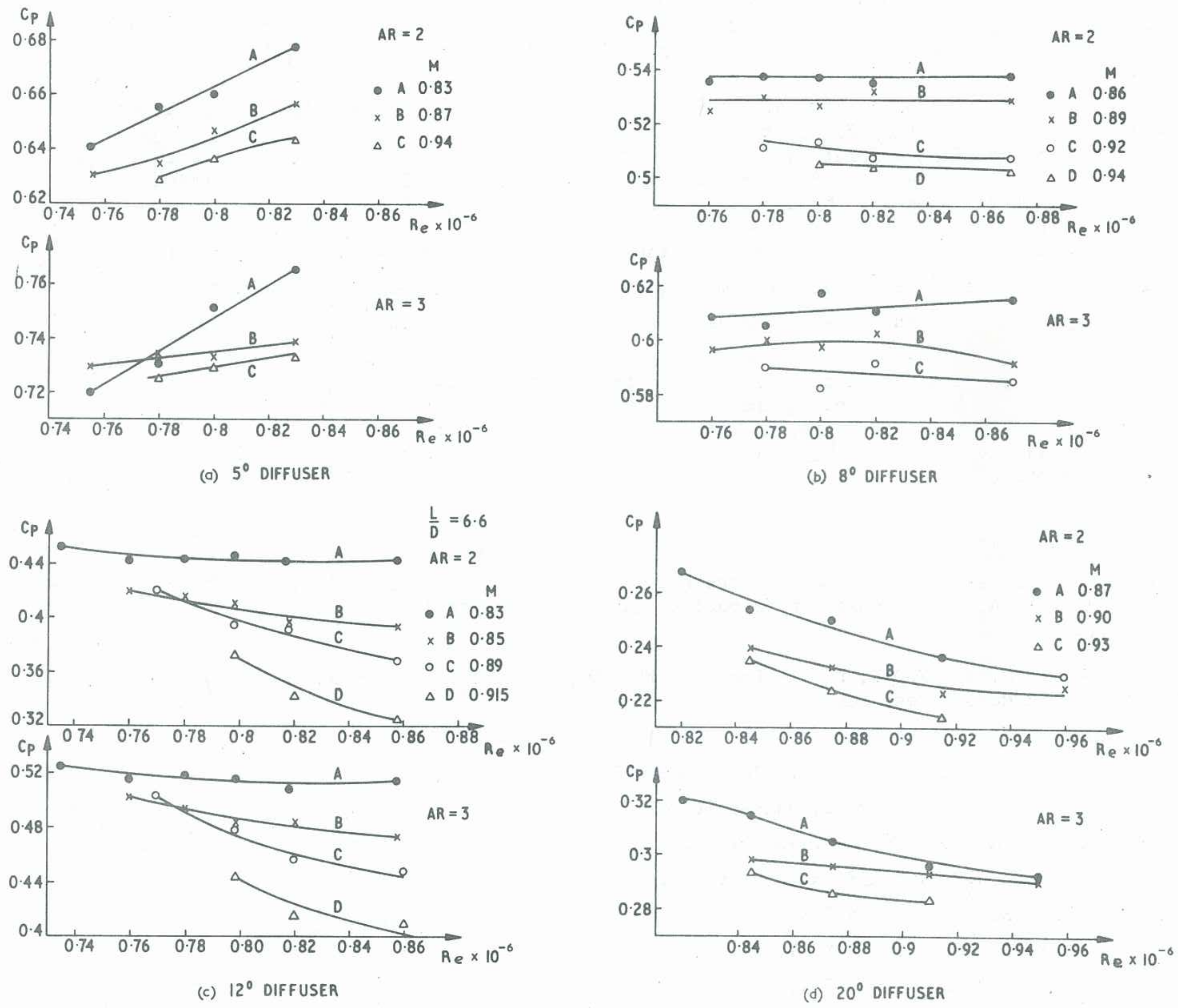

FIG. 2 EFFECT OF INLET REYNOLD NUMBER AND MACH NUMBER ON PRESSURE RECOVERY
(ENTRY LENGTH = 6·6 DIAMETERS)

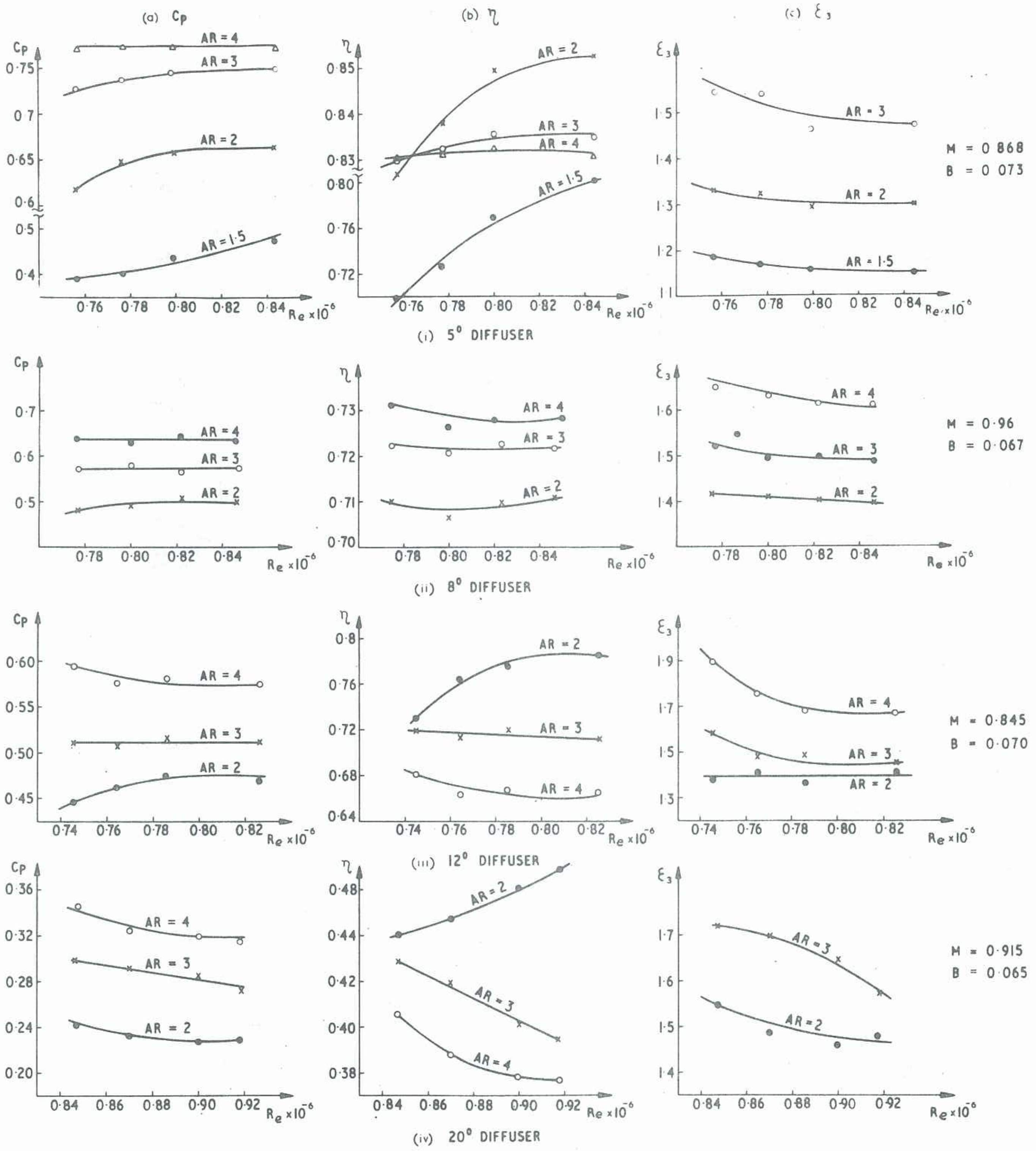

FIG. 3 EFFECT OF INLET REYNOLD NUMBER ON DIFFUSER PERFORMANCE (C_p, η, ε_3) AT CONSTANT INLET MACH NUMBER AND BLOCKAGE.

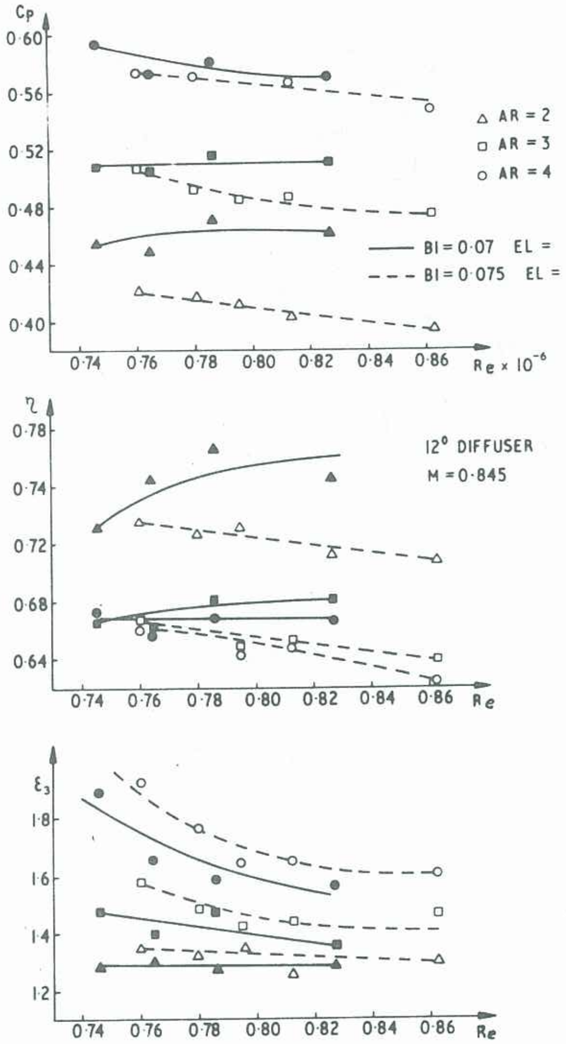

FIG. 4 EFFECT OF INLET BOUNDARY LAYER BLOCKAGE ON DIFFUSER PERFORMANCE (C_p, η AND ε_3).

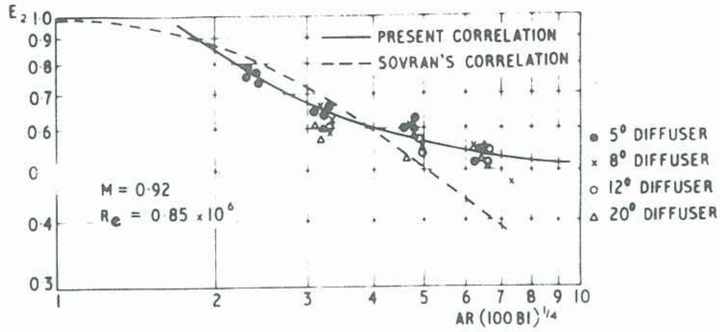

FIG. 5 CORRELATION OF EFFECTIVE EXIT AREA FRACTION WITH LOCAL AREA RATIO AND INLET BLOCKAGE

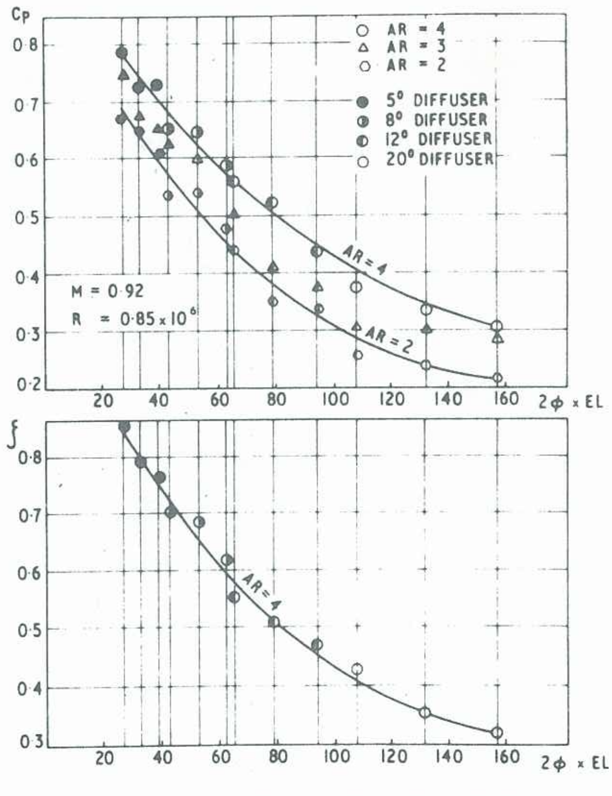

FIG. 6 EFFECT OF ENTRY LENGTH AND DIFFUSER ANGLE ON BOTH PRESSURE RECOVERY AND EFFECTIVENESS.

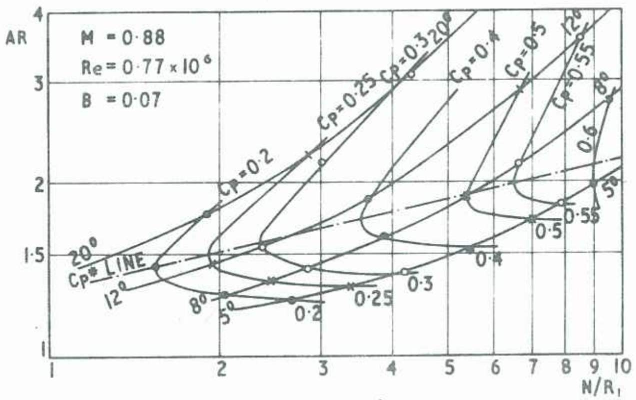

FIG. 7 PERFORMANCE MAP (CONSTANT Cp LINES ON AR − $\frac{N}{R_1}$ PLANE)

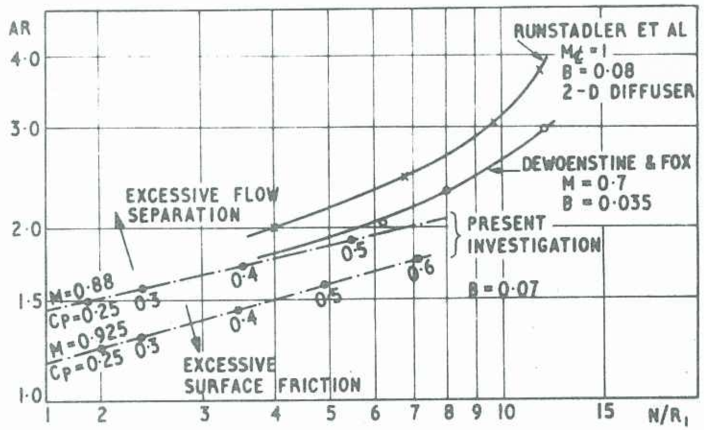

FIG. 8 C_p^* LINES FOR M = 0·88 AND 0·925 (BLOCKAGE CONSTANT).

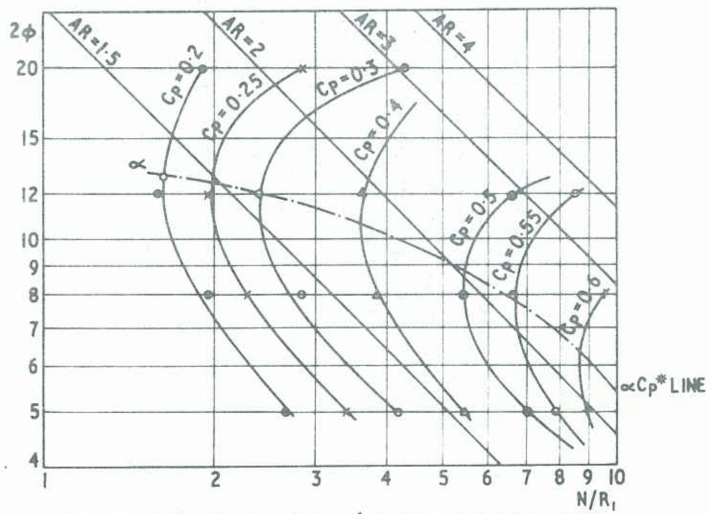

FIG. 9 PERFORMANCE MAP (MORE SUITABLE FOR CONICAL DIFFUSER).

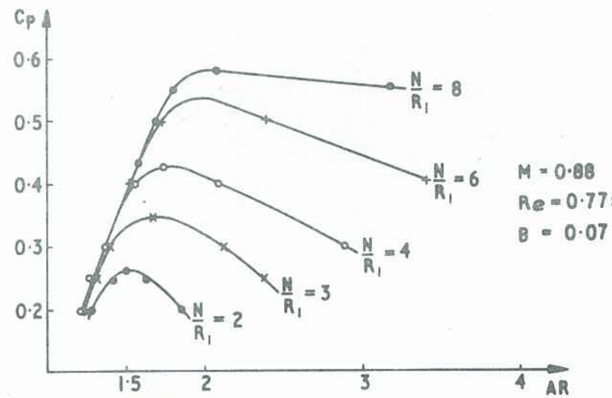

FIG. 10 DIFFUSER PRESSURE RECOVERY vs. GEOMETRY (CROSS PLOT FROM FIG. 7).