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Experimental Study of Supersonic Diffusers with Large Aspect Ratios and Low Reynolds Numbers

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Practical gasdynamic or other laser systems using supersonic flows usually require effective diffusers. Diffusers for lasers are characterized by slender flow cross sections and often small or moderate Reynolds numbers (*Re*). Presented herein is an experimental study of diffusers covering the ranges $470 < Re < 75{,}000$, $2.5 < M < 4.5$, and $3.13 < a < 12.94$. (M = Mach number, a = aspect ratio of flow cross section). The diffuser performance appears to be independent of M and a, but strongly dependent on *Re* in accordance with previous evidence for low-density wind-tunnel diffusers. An empirical formula predicting the performance of medium-quality supersonic diffusers for all applications is given for $M > 2.5$ and $Re < 180{,}000$. Experiments investigating the starting behavior showed that two starting modes are possible, as predicted by gasdynamic theory. Depending on a critical *Re* and on geometric properties, the experimental and the theoretical starting modes may agree or disagree. Below another critical *Re* which is a function of M, a supersonic diffuser seems no longer possible at all. The diffuser then decreases the pressure instead of increasing it, although the supersonic flow at the nozzle exit does not break down. The performances of a large variety of inserts used for area contractions in the diffusers is also discussed.

Nomenclature

A	= cross-sectional area
a	= aspect ratio of flow cross section at nozzle exit
C	= wetted perimeter of A
d_h	= hydraulic diameter
M	= Mach number
$\dot{m}$	= mass flow
p	= pressure
Re	= Reynolds number
v	= velocity
η	= viscosity
ρ	= density
σ	= recovery factor

Superscripts

$(\ )'$	= behind normal shock
$*$	= nozzle throat
$**$	= diffuser throat

Subscripts

o	= stagnation conditions
c	= center of flow cross section
E	= ambient at diffuser exit (vacuum tank)
e	= nozzle exit = diffuser entrance
w	= at the wall

(See Fig. 1 for the nozzle-diffuser geometry.)

Introduction

GASDYNAMIC and chemical lasers which require supersonic flows at low pressures may discharge the laser gas into the atmosphere or reuse it in a closed-cycle flow system. In the first case the gas is usually driven by a stagnation pressure much larger than atmospheric. In the second case, the gas is brought back to higher pressures by compressors. Both the high driving pressure and the pumps can partially be replaced by a diffuser. A diffuser is much simpler and lighter than the compressor it replaces because it converts the energy of the flow itself and needs no driving motors. On the other hand, this limits the use of diffusers as a substitute. The energy, which is turned into heat by viscous action in the flow, cannot be transformed in the diffuser and must be restored by an increase of the driving pressure or by compressors. The largest viscous losses in a flow system with a supersonic section are encountered in the diffuser itself. It is therefore the objective of diffuser research to keep these losses small in order to minimize the driving pressure or the size of the first and bulkiest stage of a compressor system.

Supersonic ejectors are particularly intimate combinations of a compressor and a diffuser. Special attention is being devoted to them as potential means to bring the exhaust of high-energy lasers (e.g., the HF laser) back to atmospheric pressure. While the present work does not describe research on diffusers in connection with ejectors, its results should be applicable to the diffusers of ejectors if the viscous mixing process in the ejector is thought to be completed before the flow enters the diffuser.

The viscous losses of a supersonic diffuser or, conversely, its performance can be predicted for flow channels of axisymmetric or nearly square cross sections and Reynolds numbers Re_e larger than 2×10^5. The pressure recovery of such diffusers is in the vicinity of that of a normal shock at diffuser entrance conditions. In lasers with supersonic cavity flows, the flow cross sections are usually very slender and the Reynolds numbers rather small, the range $10^3 < Re_e < 10^5$ being of particular interest. Some experimental evidence exists for small Re_e but axisymmetric cross sections,[1-3] or for slender cross sections but large Re_e.[4,5] For the above combination of conditions, however, the information is still scarce. Only Merkli[6] seems to have studied diffusers with slender cross sections in the transitional range $4 \times 10^4 < Re_e < 5 \times 10^5$. Experiments by Wu[7] were made at moderate *Re*, but were different from the other investigations[4-6] and this one in that his aspect ratio of 2.0 was defined in his subdivided diffuser rather than at the nozzle exit where it was 1.0. The present paper tries to fill the gap at small *Re* and large *a*.

All our experiments were made with steady-state flows.

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This permitted a much more exact, detailed, and convenient determination of the characteristic curves and hence of the starting behavior of the diffusers than would have been possible with shock tubes or similar unsteady equipment. Our results, however, should also be valid for unsteady flow applications. The instationary starting process itself and the starting times were not investigated here. These are discussed by Merkli and Abuaf.[8]

Dictated by practical considerations, our diffusers were all of the constant-area or fixed-area-contraction types. In spite of their superior performance, diffusers with variable area contractions[9] or boundary-layer control[10,11] have not been considered suitable for lasers because of their complex technology or the necessary additional energy input.

This paper is a condensed version of a detailed internal report.[12]

Experimental Apparatus and Procedure

Test gases were air taken from the atmosphere and nitrogen or a typical laser gas (He:CO = 2:1 by weight) taken from arrays of gas bottles. After flowing through the nozzle-diffuser channels, the gas entered a vacuum tank large in comparison with the diffuser. This tank was pumped by two sets of vacuum pumps capable of 17,000 and 30,000 m^3/h. When operated in parallel, the pumps could continuously compress 50 g/s of air from 0.350 to 100 kPa.

Whether the flow at the nozzle exit is supersonic or broken down, the diffuser will increase the pressure of the flowing gas to the value p_E in the vacuum tank. p_E was therefore taken as the pressure at the diffuser exit. This is questionable only if $p_E < p_e$ with supersonic flow established at the nozzle exit, but this case is irrelevant in a diffuser investigation. The pressure in the vacuum tank could be varied by adjustable valves located between the tank and the pumps, or by injecting air into the tank. With this equipment, stationary diffuser experiments could be made with Re_e up to 75,000 at M_e up to 4.5.

Four different nozzle-diffuser configurations were studied. Figure 1 gives the internal shapes of their channels. The sonic throats were smoothly rounded. Upstream of the throats were plenum chambers with the sizes and forms of the discharge tubes used in some of our lasers. The diffuser is defined to begin at the end of the geometrical expansion of the nozzle where one usually places a laser resonator in some kind of a test section. All configurations were two-dimensional except

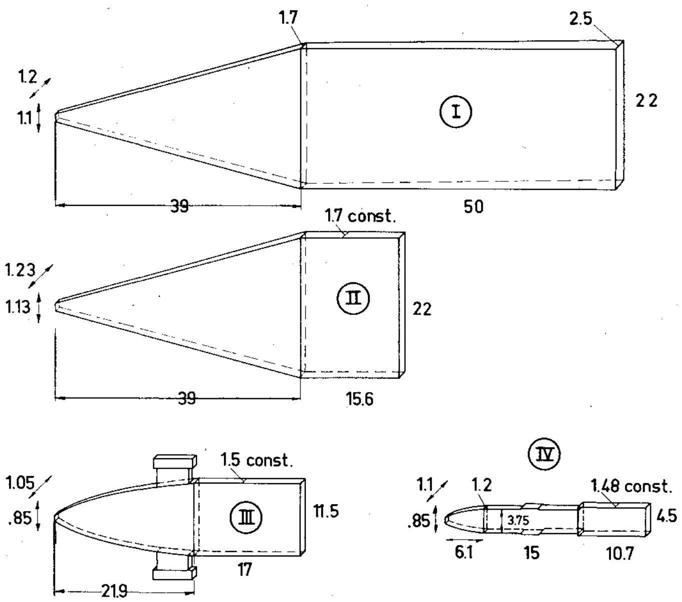

Fig. 1 Nozzle-diffuser configurations, drawn to common scale (numbers indicate lengths in centimeters).

for a rough boundary-layer correction in the form of a small linear increase in the flow direction of the smaller dimensions of the cross sections of the nozzles and of two of the diffusers. The remaining two diffusers had constant geometric cross sections to facilitate the fastening of inserts for area contractions. A central body, wall blocks, wedges, profiles, and plates could be screwed and/or cemented to the walls for inserts.

The nozzles were one-piece nozzles rather than nozzle rows or arrays, but pitot surveys showed that the velocity distributions in the direction of the larger walls of the cross sections were remarkably uniform. Generally, the diffusers were also one-piece diffusers. Diffuser rows were tested only in the form of several wedges arranged in a manner subdividing the one-piece diffuser.

Configurations I and II in Fig. 1 had nozzles with linearly increasing areas, while configurations III and IV had contoured nozzles. Configuration III may be called a diffuser with a "half-open test section" because of the large window recesses. It has not yet been shown definitely in the literature whether diffusers with open test sections make for better or inferior diffusers. The experiments with the configurations of Fig. 1 covered the ranges $470 < Re_e < 75{,}000$, $2.5 < M_{ce} < 4.5$, and $3.13 < a < 12.94$.

As in most previous work on diffusers, the maximum possible p_E/p_o' obtainable just before breakdown of the flow at the nozzle exit was taken as the measure of the diffuser performance. Unlike the more intuitive pressure recovery p_E/p_o or the pressure ratio p_E/p_e over the diffuser, the quantity p_E/p_o' has the advantage that it is independent of the Mach number – as is well established for large Re_e. This has been explained by the fact that the system of λ- or x-shaped shocks which performs the pressure increase in supersonic diffusers is equivalent to a normal shock at the same conditions.[13]

Seeking the experimental relation p_E/p_o' (Re_e), the quantities p_E, p_o', and Re_e must first be defined. Unfortunately, previous papers on diffusers at small Re usually did not give such definitions. Thus their comparison and comparison with the present results are not entirely satisfactory.

As explained above, the pressure in the vacuum tank into which the diffusers discharged was taken as p_E. Since subsonic diffusers were not attached to the supersonic ones, this means that the kinetic energy in the subsonic flow leaving the diffuser, which would have enabled a further increase of p_E, was not taken into account. Its contribution to p_E, however, is very small[14] if $M > 2.5$ as in the present experiments.

p_o' must be taken at the nozzle exit. The most correct $p_{o\,e}'$ would be a mean value over the cross section, but its determination would involve complicated probe measurements of p_o' and v with low Re corrections. We therefore simply chose the pitot pressure in the center of the cross section, $p_{o\,ce}'$, which did not need to be measured directly. It was calculated together with M_{ce} from the measured pressures p_o and p_e using the well-known isentropic and normal shock relations. This method takes care of the boundary layer and gives the correct $p_{o\,ce}'$ if the flow through the nozzle has an isentropic core. It becomes questionable as the flow becomes completely viscous which in our experiments it did when $Re_e < 6000$. Yet being a matter of definition, $p_{o\,ce}'$ was also calculated in the described manner for $Re < 6000$. Since then the calculated $p_{o\,ce}'$ is always larger than the actually measured $p_{o\,ce}'$ – as verified in some tests – our experimental results for $Re_e < 6000$ might be called rather pessimistic.

Different from p_o', a definition on the basis of mean values (in this case $\overline{\rho v}$ and $\bar{\eta}$) over the flow cross section at the nozzle exit, permits a simple determination of Re_e,

$$Re_e = \overline{\rho v} d_h / \bar{\eta} \tag{1}$$

d_h is the hydraulic diameter $4A_e/C$. $\overline{\rho v}$ may be expressed in terms of the given quantities $\dot{m}$ and A_e,

$$\dot{m} = \int_{A_e} \rho v \mathrm{d}A_e = \overline{\rho v} A_e \tag{2}$$

such that

$$Re_e = \dot{m} d_h / \bar{\eta} A_e \tag{3}$$

$\bar{\eta}$ is the viscosity at the arithmetic mean temperature

$$\bar{T} = (T_{ce} + T_{we})/2 \tag{4}$$

with T_{we} calculated from the definition of the recovery factor,

$$\sigma = \frac{T_{we} - T_{ce}}{T_{oe} - T_{ce}} \tag{5}$$

and with T_{ce} calculated as M_{ce} from the measured quantities p_e, p_o, and $T_{oe} = T_o$. The latter implies again that this definition of Re_e is questionable for $Re_e < 6000$.

Experimental Reults

Parameters Influencing the Diffuser Performance

Previous work and all experimental results of the present study are summarized in Fig. 2 in a diagram showing $p_E/p_o' = f(Re_e)$. A diagram in this form was first published by Boylan and Potter.[1] The definitions of p_E, $p'_{o\,ce}$, and Re_e may be different from those given above for the experimental points of the previous studies included in Fig. 2.

Among the author's results in Fig. 2, small symbols mean individual tests, elongated symbols cover complete test series with too many points to be shown indvidually. The two open elongated symbols, for example, represent 17 tests each. Each test signifies a combination of one particular internal diffuser geometry with one particular Re_e. Usually Re_e was adjusted through $\dot{m}$.

With the exception of the open circles for $470 < Re_e < 3200$, the author's experimental points were calculated from

$$\frac{p_E}{p'_{o\,ce}} = \frac{p_E}{p_e} \frac{p_e}{p_o} \frac{p_o}{p'_{o\,ce}} \tag{6}$$

using the maximum possible p_E/p_e for operation, the measured quantities p_e and p_o, and $p'_{o\,ce}/p_o$ as calculated from p_e and p_o. The maximum p_E/p_e was obtained from the tangents to the experimental characteristic curves $p_e(p_E)$ as discussed in conjunction with the starting problem. The experimental points for $470 < Re_e < 3200$ are "at least" values. This means that the diffuser worked well at these conditions in a laser system with a closed-cycle flow,[15] but it may be able to work better.

Internal Diffuser Geometry

The lower points in Fig. 2 were obtained with diffusers with constant or nearly constant cross sections. Increasingly higher points in test series with equal symbols were obtained with increasingly more sophisticated inserts for area contractions. The influence of the internal diffuser geometry together with the influence of the Reynolds number and the effectiveness of particular types of inserts are discussed in subsequent sections.

Mach Number

The combined former and present results show that p_E/p_o' is independent of the Mach number for $2.5 < M < 22$ not only for large Re and aspect ratios a of the order of one, but for all Re_e and all a.

This conclusion will probably not be true for $M < 2.5$ for which diffusers have not yet been tested at small Re. The subsonic portion of a diffuser, which is negligible for $M > 2.5$, becomes increasingly more important for $M < 2.5$.[14] The shock system must then no longer be considered alone responsible for the pressure recovery, and the ratio p_E/p_o' therefore no longer correlates the performance with respect to the Mach number.

Isentropic Exponent

The experimental results of Fig. 2 as obtained for two different isentropic exponents, $\gamma = 1.4$ (air and N_2) and $\gamma = 1.638$ (laser gas) are also indicative of an independence of $p_E/p'_{o\,ce}$ of γ. This is understandable because Re_e is calculated without γ, and the parameter γ is eliminated together with M – for the same reasons as for M – if p_E/p_o' is taken for the diffuser performance.

Aspect Ratio

The aspect ratios represented in Fig. 2 are 12.94, 12.94, 7.93, and 3.13 for configurations I, II, III, and IV, respectively, and approximately 1.0 for most former experiments. It appears that the aspect ratio does not affect the diffuser performance either. This is apparently brought about by using the hydraulic diameter for the characteristic length in the calculation of Re_e.

Reynolds Number

As evident from Fig. 2, the Reynolds number influences the diffuser performance very strongly. The straight line correlating the experimental points in the region

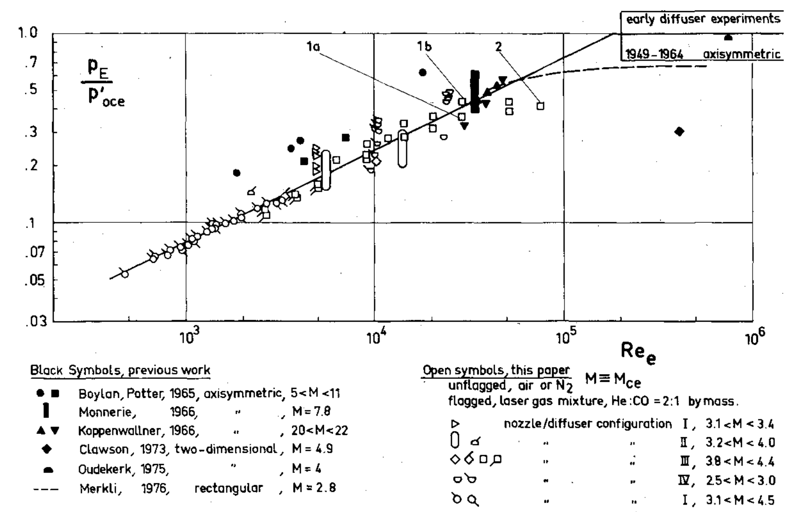

Fig. 2 Experimental diffuser performances.

$470 < Re_e < 50{,}000$ in the diagram of Fig. 2 is given by

$$p_E/p'_{o\,ce} = 0.00272 Re_e^{0.487} \approx 0.00272 Re_e^{1/2} \qquad (7)$$

It represents a "medium-quality" diffuser with respect to the internal geometry and may be used in the conception of all supersonic flow systems using diffusers. According to Fig. 2, constant area diffusers (generally the lower points) may give performances smaller than this estimate by a factor up to 1.4. Diffusers with optimized internal geometries (upper points) may be better by the same factor.

The correlating equation does not cover the transitional region $5\times10^4 < Re_e < 5\times10^5$ adequately. An indication of the transitional behavior is given by the broken line in Fig. 2, which was obtained from Merkli's experiments[6] with a diffuser without area contractions and with $a = 2.01$.

Diffuser Limits at Small *Re* and *M*

We have observed that the pressure at the exit of the diffuser may become smaller than the pressure at its entrance, i.e., $p_E/p_e < 1$, without the flow at the nozzle exit breaking down, if Re_e and/or M_{ce} become sufficiently small. The two experimental points at the extreme left-hand side of Fig. 2, with $p_E/p_e = 0.8$ and 0.97, respectively, have been identified as examples of such a situation.

This phenomenon may be explained in that the supersonic core of the flow at the nozzle exit becomes much smaller than the annulus of subsonic flow surrounding it. In the diffuser the frictional losses in the latter then exceed the pressure recovery in the shock system of the former. If $p_E/p_e < 1$, a diffuser should, of course, no longer be termed a diffuser.

Figure 3 gives the limiting curve $Re_e(M_{ce})$ below which a diffuser must be expected to cease working as a diffuser. This curve was obtained from Eq. (6) using the isentropic relation $p_e/p_o(M_{ce},\gamma)$, the normal shock relation $p'_{o\,ce}/p_o(M_{ce},\gamma)$, applying the empirical Eq. (7) for $p_E/p'_{o\,ce}$, and setting $p_E/p_e = 1$.

The limiting curve depends on γ. Like Eq. (6) which has been used in its derivation, it is valid only for $M > 2.5$. Like Eq. (6), it represents an average curve which may be shifted by changes of the diffuser geometry. In particular, shortening and widening the diffuser should shift the limiting curve to smaller Re_e and M_{ce}. Shortening the diffuser for small Re_e is desired for some laser systems. It is not contradictory to the requirement of a minimum length/diameter ratio of the diffuser because the effective diameter is much smaller than the geometrical one for small Re_e.

Starting Behavior

To start a supersonic diffuser means to establish the desired supersonic flow at the preceeding nozzle exit/test section. According to the one-dimensional frictionless theory, starting a supersonic diffuser with an area contraction requires a transient increase† of p_o/p_E over the maximum possible operating pressure ratio p_o/p_E while starting a constant-area diffuser does not. In the following, area-contraction starting will therefore be defined as the starting mode which requires a transient increase of p_o/p_E over the maximum possible operating pressure ratio p_o/p_E, and constant-area starting as the starting mode which does not. Furthermore, diffusers with area contractions should not start at all if the area contraction A_e/A^{**} exceeds a certain limit depending on M and γ.

Although some information on the starting modes is available, a systematic investigation seems to be missing in the literature. Our stationary flow experiments permitted a convenient study of which starting mode does apply to the two

†In the present experiments, wherever necessary, the transient increase of p_o/p_E was realized by a transient decrease of p_E at unchanged p_o rather than by a transient increase of p_o as in many previous experiments.

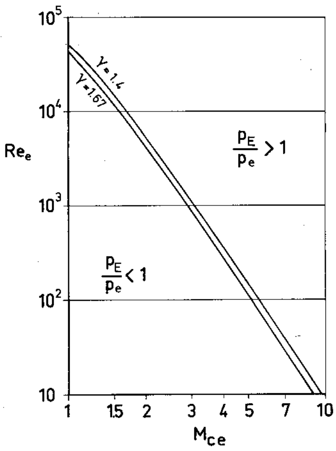

Fig. 3 Limiting curves obtained with $p_E/p_e = 1$.

types of diffusers. The conclusions from this study may be summarized in the following classification of diffusers with respect to their starting mode.

1) All diffusers with geometrical area contractions:

a) Constant-area starting occurs if $Re_e < Re_{e\,\mathrm{crit}}$.

b) Area-contraction starting occurs if $Re_e > Re_{e\,\mathrm{crit}}$.

2) Diffusers with geometrically constant areas, with smooth walls and smooth nozzle-diffuser junctions: constant-area starting occurs for all Re_e, $Re_{e\,\mathrm{crit}} \to \infty$.

3) Diffusers with geometrically constant areas, with shock-producing irregularities near the nozzle-diffuser junction and in the diffuser:

a) Constant-area starting occurs if $Re_e < Re_{e\,\mathrm{crit}}$.

b) Area-contraction starting occurs if $Re_e > Re_{e\,\mathrm{crit}}$.

This classification comprises the whole range of Reynolds numbers. $Re_{e\,\mathrm{crit}}$ is a critical Reynolds number which depends on the internal geometry of the nozzle-diffuser configuration.

With the exception of cases 1a and 3b, all of these experimental findings agree with the theoretical predictions. One reason for the disagreement for cases 1a and 3b is the lack of one-dimensionality in the experiment, but there are more pertinent explanations. Since basically area-contraction starting belongs to diffusers with area contractions and constant-area starting to constant-area diffusers, we may first of all conclude that in case 1a the diffuser with a geometrical area contraction is in reality a constant-area diffuser and that in case 3b the reverse is true. This happens in case 1a because for small Re_e the cushioning effect of the thick boundary layer smooths out wall irregularities, eventually including the area contraction itself. In case 3b for larger Re_e the irregularities at the walls cause strong shocks which in turn cause boundary-layer separations with a subsequent downstream reattachment of the flow at the diffuser walls. The resulting separation bubbles then assume the role of area contractions in constant-area diffusers.

The conclusions leading to the above classification were drawn from the experimental characteristic curves $p_e(p_E)$ of the diffusers. These were obtained in individual tests by recording p_e and p_E after stepwise increases and then decreases of p_E over the whole range of interest, including the points or regions of starting and maximum p_E/p_e for operation of the diffuser. In accordance with the basic differences of the two starting modes, the characteristic curve exhibits a hysteresis if area-contraction starting applies. For constant-area starting there is no hysteresis. Figure 4 shows how the characteristic curves change from the hysteresis type to the nonhysteresis type as Re_e is decreased in a particular example.

In the curves of Fig. 4 which show a hysteresis, the upper parts where the two branches of the hysteresis meet again are generally not shown because they are outside the region of interest in which the diffuser is started and operated. In starting a diffuser, one moves down the left-hand branch of

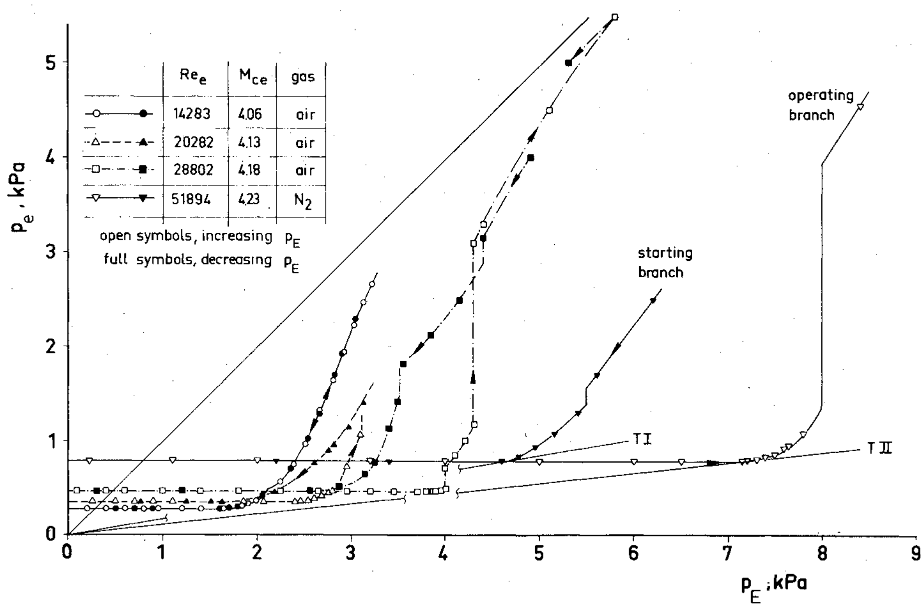

Fig. 4 Characteristic curves for different Re_e and constant geometry; configuration III.

the characteristic such that this branch may be called the starting branch. The diffuser is started once p_e has reached its constant minimum value. If p_E is now increased, one moves outward along the other branch of the characteristic. Since the diffuser usually operates along the constant p_e part of this branch, the whole branch may be called the operating branch.

The maximum operating pressure ratio p_E/p_e needed to calculate the diffuser performance by Eq. (6) is defined here as the pressure ratio determined by the tangent TII from $\{p_E, p_e\} = \{0, 0\}$ to the operating branch of the characteristic curve (shown in Fig. 4 for one of the characteristics only). In a similar way, a starting pressure ratio may be defined by the tangent TI to the starting branch of the curve (Fig. 4).

Some of the curves of Fig. 4 exhibit sudden steps which are certainly due to sudden changes of the flow in the diffuser. These changes are of little interest if they occur outside the starting and operating regions. In many instances (e. g., in the example of Fig. 5), however, they coincide with the points where the tangents touch their respective curves. Thus the breakdown of the flow at the nozzle exit/diffuser entrance may be initiated either continuously or abruptly.

In the example of Fig. 4, configuration III of Fig. 1 was tested with its whole geometry kept unchanged for all Re_e. Geometrical area contractions were absent but the shocks originating at the window recesses caused separation bubbles such that the diffuser belonged to case 3. By a simple procedure,[12] $Re_{e\,\mathrm{crit}}$ was determined from Fig. 4 to be 15,000. In a second experiment with the constant-area configuration II of Fig. 1, $Re_{e\,\mathrm{crit}}$ was found to be situated somewhere in the range $2160 < Re_e < 5500$. Configuration II with its corners at the nozzle-diffuser junction again represents case 3. If profiles were used for area contractions in configuration III, then the diffuser changed to case 1 and $Re_{e\,\mathrm{crit}}$ was somewhere within $4920 < Re_e < 14{,}260$. Filling the window recesses with blocks flush with the walls in configuration III resulted in a case 2 diffuser with $Re_{e\,\mathrm{crit}} \to \infty$. The observations made with the latter diffuser correspond to those of early experiments with an $a = 1$ diffuser.[16]

Diffusers with constant-area starting (no hysteresis in characteristic curve) might be considered superior because they do not need the transient increase of p_o/p_E necessary for area-contraction starting. Yet this is not always true as will be shown in the next paragraphs. Figures 5 and 6 each present a comparison between a diffuser with constant-area starting and one with area-contraction starting. Each comparison was made at the same Reynolds number and with the same nozzle-diffuser configuration. Only the internal diffuser geometry was different, which was responsible for the different starting modes.

The pressure ratio p_o/p_E required for starting and operating a diffuser should be as small as possible for economic reasons (compressor or vacuum pump requirements), regardless of whether p_E or p_o (or neither) is given in an application.‡ Therefore in comparing two types of diffusers as in Figs. 5 and 6, the diffuser with the smaller maximum p_o/p_E for starting and operation will be superior.

Now, $p_o/p_E = (p_o/p_e) \cdot (p_e/p_E)$, the pressures p_o were kept identical, and the experiments showed that the p_e were also identical for both characteristic curves in Figs. 5 and 6. Consequently, the requirement of the smaller p_o/p_E reduces to the requirement of the larger p_E/p_e for the superior diffuser. The maximum ratio p_E/p_e for starting and operation is given by the tangents as outlined in conjunction with Fig. 4.

On the basis of these tangents, it is thus immediately seen that in the case of Fig. 5 the diffuser with area-contraction starting (hysteresis) is superior, while in Fig. 6 the diffuser with constant-area starting (no hysteresis) is superior. In both comparisons the superiority applies to both operation and starting.

One of the two diffusers of Fig. 5 was geometrically a constant-area diffuser, the other had profiles for an area contraction (see Fig. 7). Hence Fig. 5 is also an indication that area contractions may definitely improve a diffuser down to relatively small Re.

The curves of Fig. 6 were obtained for configuration III of Fig. 1. The window recesses were open to the nozzle flow but not to the ambient for one curve, and they were closed by plugs flush with the walls for the other curve. Hence Fig. 6 compares cases 3b and 2, respectively, of the diffuser classification given above. It suggests that constant-area channels should be made as smooth as possible, which is in favor of the so-called closed-wall diffuser as opposed to the so-called open-wall diffuser. (Open-wall or free-jet diffusers differ from closed-wall diffusers in that there is a spacious chamber between the nozzle exit and the diffuser.[14] There is no agreement in the literature as to which of the two types performs better.)

‡For example, p_E is given for a laser exhausting into the atmosphere, and p_o is given for a wind tunnel blowing from the atmosphere into a vacuum.

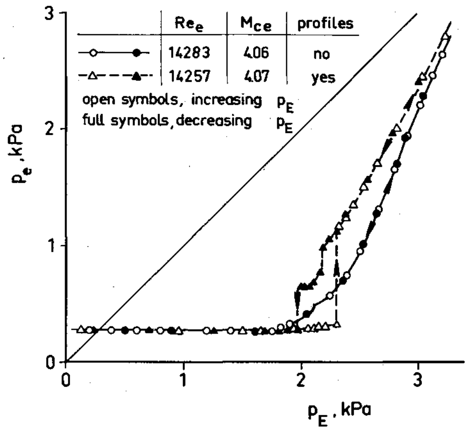

Fig. 5 Characteristic curves with and without profiles, configuration III.

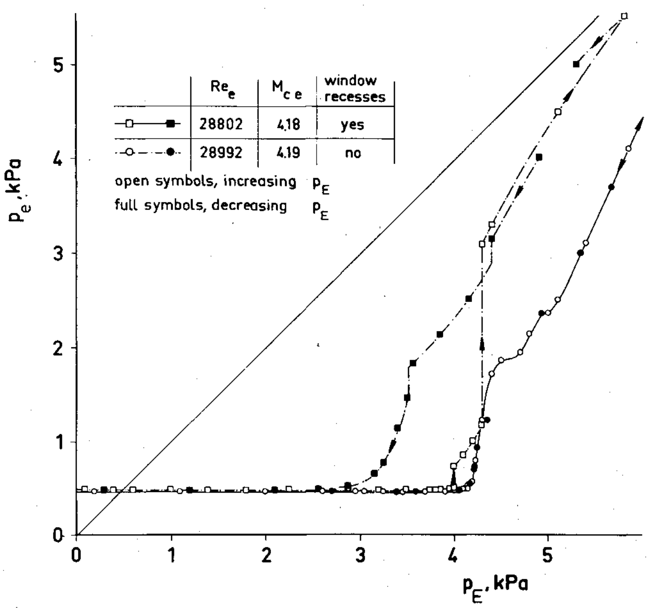

Fig. 6 Characteristic curves with and without window openings, configuration III.

Study of Different Area Contractions

Of the detailed study of the diffuser performances achieved with different types of inserts used for area contractions, only the results for configuration II will be discussed here. The results obtained with configurations I, III, and IV are given in detail in an internal report.[12]

Most of the inserts and their arrangements in the diffuser of configuration II are summarized in Fig. 7. Only the diffuser section is shown in each case. Approximate dimensions may be obtained from Fig. 7 using the measures of Fig. 1. The wedges, the wall blocks, and the central body (No. 28 in Fig. 7) extended from wall to wall. The profiles had the form of two-dimensional wings with the cross section of a thin sector of a circle. They were composed of several layers of adhesive tape and simply glued to the larger walls of the diffuser in symmetric pairs, as shown in Fig. 7 (Nos. 16-24). The wall plates (Nos. 34 and 35) were made of metal and fixed to the walls in pairs like the profiles.

With the exception of those diffusers which could not be started at all, the performances of all diffusers of Fig. 7 are included in Fig. 2. Most of the experiments were made with air at Reynolds numbers around 5400 and 14,000, and one experiment with the He/CO laser-gas mixture $Re_e = 2170$.

The best and about equal performances were obtained with diffusers using rows of five wedges at equal streamwise positions (Nos. 1-6 in Fig. 7), with profiles alone (Nos. 16, 17, 19, 20), or with wall plates (Nos. 34, 35). For all of these inserts, the performance was considerably better than with the empty diffuser (No. 7).

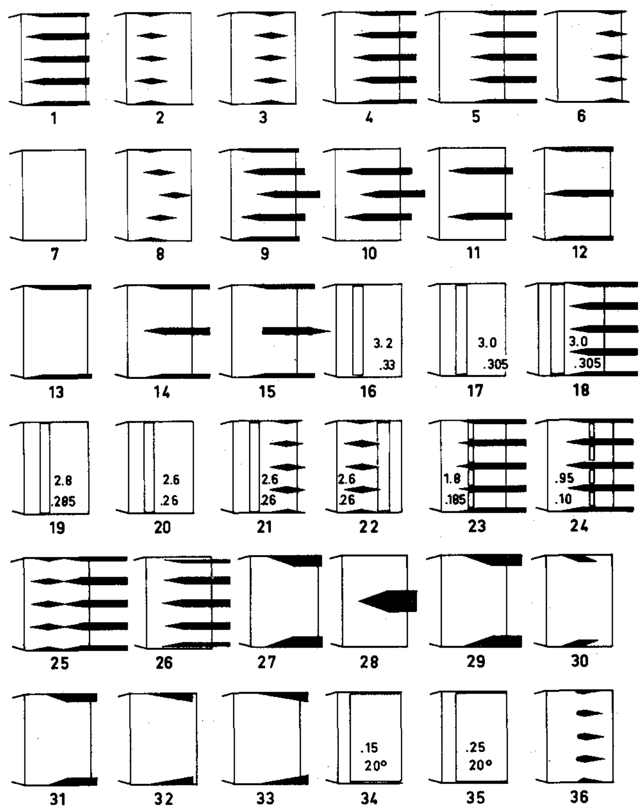

Fig. 7 Geometry of inserts used with configuration II: 1-6, 8-15, 25-33, 36, internal wedges and wall blocks; 7, empty diffuser; 16-24, profiles without and with wedges (numbers in diffusers indicate width and thickness of profiles in cm); 34-35, wall plates (numbers in diffusers indicate thickness in cm and angle at leading edge). Diffusers numbered in chronological order.

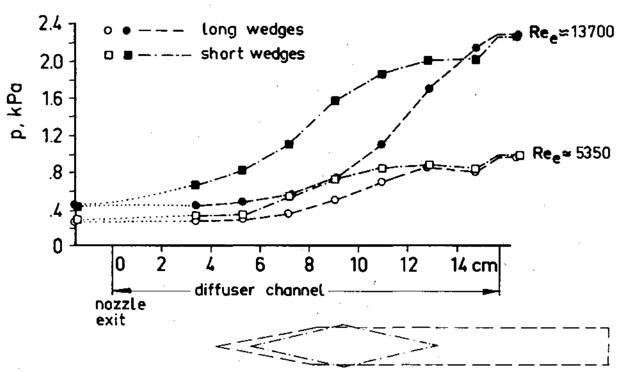

Fig. 8 Axial pressure distributions in diffuser of configuration II for long and short wedges (positions and relative sizes of wedges are indicated).

The use of wedges in low-aspect-ratio diffusers was first shown and discussed by Gerry.[17] In our experiments, the optimum streamwise position of the five wedges was that of Nos. 3 and 4 of Fig. 7. The long wedges yielded better results than the short ones, especially at larger Re_e. This is probably due to the requirement of sufficient streamwise length for the shock system between the individual wedges. The long wedges also cause a more favorable pressure distribution in the diffuser than the short ones. This is shown in Fig. 8 for Nos. 3 and 4 of Fig. 7 and for two Re_e in each case. The beginning of the pressure rise is much farther downstream with the long wedges, although their leading edges are located farther upstream. This is important for lasers with large streamwise extensions of the resonator at the diffuser entrance.

When used alone, the profiles were placed at the previously determined optimum axial positon. The thicknesses of the wedges had been chosen just below (long wedges, Nos. 1, 4, 5, etc. of Fig. 7) or just above (short wedges, Nos. 2, 3, 6, etc.) the theoretical geometrical limit of A_e/A^{**} beyond which starting should no longer be possible. It was surprising that also in the latter case the diffusers could be started, and that even the maximum diffuser performance was obtained with a profile thickness beyond the limit. This behavior may be explained in that although the geometrical area ratio was already beyond the limit, the effective area ratio was not because of the cushioning effect of the boundary layer. With the wall plates, the experiments did not approach the limit, but further improvements seem to be possible close to or just beyond it.

Considering the so far described diffusers of Fig. 7, we have found that the behavior of a diffuser may be seen from different viewpoints, and that from the different viewpoints different types and positions of the inserts give best results. Superiority with respect to all viewpoints was observed only with the larger wedges when compared to the short ones. The most important viewpoints are equivalent to the following requirements one may have to satisfy, depending on the needs of a particular diffuser application:

1) The maximum possible pressure ratio over the working diffuser should be large.

2) The maximum possible pressure at the exit of the working diffuser should be large.

3) The pressure at the nozzle exit should not greatly exceed the "matched" pressure one would have without a diffuser.

4) The beginning of the pressure rise in the diffuser should be located as far downstream as possible.

5) Some applications may not permit a transient increase of p_o/p_E for starting.

Theoretically, and usually for large Re in practice, requirements 1-3 are satisfied simultaneously. Our experiments have shown that this is no longer true for small and moderate Re because the shocks in the diffuser generally influence the flow and the pressure at the upstream nozzle exit via the boundary layer.

Including the results obtained with configurations I, III, and IV, we have also found that the best type and position of the inserts with respect to any of the above requirements changed with Re_e and the geometry of the diffuser. This explains why different investigators have found contradicting results. For example, according to Weizmann[18] who also used a series of short wedges, the wedges performed best in the downstream position while in the present experiments the center position yielded the best results. It follows that in order to realize diffuser performances substantially better than predicted by Eq. (7) for the "medium-quality" diffuser, the optimum type and position of the inserts will have to be sought by experiment for each nozzle-diffuser geometry and each Re_e.

The remaining geometries of Fig. 7 are all of less significance. The diffusers with less than five wedges in a row (Nos. 11, 12-14 in Fig. 7) and those with all five wedges arranged in a stepwise symmetrical manner (Nos. 8-10 and others not shown) proved to be good with respect to only one of the above requirements at most, but they were always inferior to the better diffusers discussed above. The same applies to the diffusers using blocks ("ramps") at the shorter walls only (Nos. 13, 27, 29-33). These wall blocks performed particularly badly when placed far upstream (Nos. 27, 32) because then the superposition of the ramp angle with the configuration's own corner at the nozzle-diffuser junction concentrated the pressure increase in particularly strong shocks. Because of the shock/boundary-layer interaction, these have a tendency to move upstream into the nozzle in the vicinity of the small walls. Diffuser No. 13 developed deteriorative asymmetric boundary-layer separations even before breakdown of the flow at the nozzle exit. Only the wall blocks of No. 30 permitted results comparable to the better diffusers discussed above for the small $Re_e \approx 5350$. Perhaps further studies would be desirable of diffusers using artificially created "dead water" regions as proposed by Petty[19] or as partially present in our diffuser No. 30.

Very poor performances were achieved by diffusers with blunt bodies for inserts (No. 15) because of the strong shocks, and those with a single big central body (No. 28). The latter is in accordance with Moore[20] for axisymmetric diffusers and with Clawson[4] for a slender rectangular cross section. With two additional blunt bodies placed in parallel with the central one, the diffuser of No. 15 would not even start, although the geometrical area contraction does not exceed the theoretical limit of the one-dimensional theory.

Combinations of different types of inserts such as wedges plus profiles (Nos. 18, 21-24, and others not shown), or short wedges in front of long wedges (some forming additonal throats), were always less effective than applications of one type of inserts only. Also, with large blockage (No. 23 and others not shown), such diffusers could not be started. The best diffuser in this series was No. 24.

An attempt to remove the boundary-layer flow at the small walls from the core flow (No. 26) also gave disappointing results. Supposedly, downstream disturbances uninhibited by the supersonic core could move upstream more freely in the separated channels.

A row of short wedges with rounded leading edges (No. 36) behaved very much like its counterpart with pointed wedges in the same position (No. 3).

Conclusions

The "performance" of supersonic diffusers is largely independent of the Mach number, the isentropic exponent, and the aspect ratio of the flow cross section of the nozzle exit if $M>2.5$. It strongly depends, however, on the Reynolds number. An empirical formula is given for this dependence which may be used to predict the performance of medium-quality diffusers. The performance may be larger or smaller than the predicted value by a factor of up to 1.4, depending on the internal geometry of the diffuser.

Below a certain limiting Reynolds number depending on the Mach number, supersonic diffusers no longer act as diffusers even though the flow at the nozzle exit may not break down.

Constant-area diffusers may start as theory predicts for diffusers with area contractions and vice versa. The starting behavior is determined by a critical Reynolds number which was in the vicinity of 15,000 or smaller in the tested geometries.

Area contractions seem to improve the performance down to surprisingly small Reynolds numbers. Irregularities in the nozzle-diffuser walls including "open-wall diffusers" were found to be detrimental to the performance.

A study of a great variety of inserts for area contractions in the diffusers showed that the optimum type and position of the inserts depend on the Reynolds number, the nozzle-diffuser geometry, and the criterion with respect to which the diffuser is to be optimized.

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