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PRELIMINARY INVESTIGATION OF DIFFUSER WALL BLEED TO CONTROL COMBUSTOR INLET AIRFLOW DISTRIBUTION

by Albert J. Juhasz and James D. Holdeman

Lewis Research Center
Cleveland, Ohio 44135

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16. Abstract

Velocity profile control tests were conducted with a short annular diffuser equipped with wall bleed capability. The diffuser area ratio was 4, and the length to inlet height ratio was 1.5. Results show that the diffuser radial exit velocity profile may be shifted towards either the inner or outer diffuser wall by, respectively, bleeding off a small fraction of the total flow through the inner or outer wall. Based on these results, application of the diffuser bleed technique to a gas turbine combustor should be considered. The advantages of such a combustor could be shorter length, reduced idle exhaust emissions, and improved altitude relight capability.

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SUMMARY

Velocity profile control experiments were conducted with a short annular diffuser equipped with wall bleed (suction) capability. The diffuser had an area ratio of 4, a length to inlet height ratio of 1.5, and walls of quarter circle cross section. Preliminary tests have demonstrated that the diffuser radial exit velocity profile may be shifted toward either the hub or tip of the annulus by bleeding off a small fraction of the total flow through the inner or outer diffuser wall, respectively. The capability to alter the radial exit velocity profile suggests that the diffuser bleed technique could be effectively utilized in controlling the airflow distribution in gas turbine combustors. The potential advantages of a combustor equipped with diffuser bleed capability over conventional designs would be threefold: (1) a significant reduction in diffuser length would be possible since the short diffuser flow separation problem could be controlled; (2) combustor exhaust emissions during engine idle operation could be reduced by adjusting airflow to the primary zone; and (3) combustor altitude relight capability could be improved, again by altering flow through the primary zone.

In addition to controlling combustor airflow distribution, diffuser bleed air could be used to satisfy turbine cooling requirements. The potential advantages of a diffuser bleed combustor could then be realized without sacrificing engine cycle efficiency.

INTRODUCTION

The ability to control combustor inlet airflow distribution may result in several design improvements in advanced aircraft engines. These include the use of shorter diffusers, a significant reduction in idle exhaust emissions, and improved altitude relight capability.

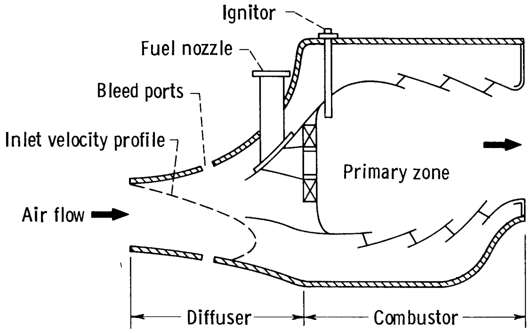
The advantages of short combustion chambers for advanced aircraft engines are pointed out in reference 1. Since the diffusing section between the compressor exit and the fuel injection stations represents a considerable fraction of total combustor length in conventional engines, a significant length reduction would be realized if a very short diffuser could be used. Reference 2 shows that if the annular diffuser length for a given area ratio is reduced beyond a certain minimum, the pressure recovery and hence the diffuser effectiveness decrease rapidly because of diffuser flow separation. A separated flow may also adversely affect the airflow through the combustor and impair the exit temperature profile. Thus, a method of flow control is required for satisfactory performance with a diffuser that is shorter than the minimum length referred to above. The use of guide vanes in the diffusing passage (ref. 3) represents one technique of flow control. However, the complexity of these vanes in annular diffusers and their associated pressure loss are severe drawbacks.

Reduction of gas turbine exhaust emissions during engine idle operation would also be possible if combustor airflow distribution could be controlled, as shown in reference 4. Combustion efficiency would be improved by altering combustor airflow distribution, so that less air is introduced into the primary zone. This results in an increase in local fuel-air ratio to near stoichiometric values and a decrease in primary-zone velocity. These changes in the primary-zone conditions would result in a significant decrease in emissions of hydrocarbons and carbon monoxide. Controlling combustor velocity distribution by mechanically operated vanes or variable area air entry ports would be undesirable because of the large number of mechanical linkages that would have to operate in a high-temperature environment.

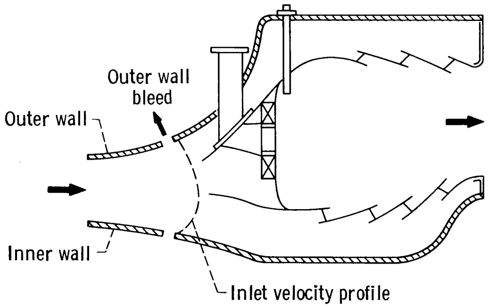
Altitude relight performance of an engine would also be improved by effective control of combustor airflow distribution. This is because a low-velocity recirculation zone could be established around the fuel nozzles and ignitors, instead of the high-velocity flow occurring in conventional combustors during engine windmilling conditions. The objections to the use of mechanically operated vanes to cause the flow to bypass the primary zone were mentioned previously.

Reference 4 shows the improvement in exit velocity profile and pressure recovery obtained with a short, high area ratio, two-dimensional diffuser when a small fraction of the flow is bled away through the walls.

This suggests that combustor inlet flow distribution may be controlled without the need of either fixed or mechanical devices by use of a diffuser equipped with wall bleed capability. Moreover the air bled off through the diffuser walls could be used to satisfy turbine cooling requirements, thus preserving engine cycle efficiency. A short annular combustor designed to operate with this diffuser concept (henceforth referred to as a controlled separation combustor) is shown schematically in figure 1. The diffuser geometry is asymmetric, with a rapidly diverging outer wall and a gradually diverging inner



(a) Idle or altitude relight operation.



(b) Cruise or takeoff operation.

Figure 1. - Application of diffuser bleed in short annular controlled separation combustor.

wall. Bleed ports (or slots) permit a small fraction of the diffuser inlet air flow to be ducted through the walls at certain operating conditions.

The use of bleed flow would depend on the desired combustor inlet velocity distribution at a given operating condition. When no wall bleed is used, the asymmetric diffuser geometry causes the flow to adhere to the inner wall but to separate from the outer wall. The resulting combustor inlet velocity distribution would allow most of the flow to bypass the primary zone of the combustor as required for engine idle and altitude relight conditions. Hence, the desired velocity distribution could be obtained at these conditions without applying diffuser bleed as indicated in figure 1(a). Should some turbine cooling air be necessary at the idling condition, the application of inner wall bleed to meet this cooling air requirement would have no detrimental effect on the desired combustor inlet velocity distribution.

Figure 1(b) shows the proposed bleed combustor during takeoff or cruise operation. Since now there is sufficient static pressure differential between the diffuser and turbine inlet stations, a certain percentage of the airflow may be bled off through the bleed ports in the outer wall of the diffuser and used for turbine cooling. The effect of bleed on diffuser flow would be to cause attachment to the outer wall thereby flattening the velocity profile. A small amount of bleed on the inner wall could also be applied to trim the profile, if necessary. The uniform airflow distribution would provide sufficient cooling air for inner and outer combustor liners and also improve the pattern factor at the turbine inlet. Moreover, the high diffuser effectiveness obtainable with an unseparated flow would aid cycle efficiency by keeping combustor pressure loss to the lowest values obtainable at a given heat release rate.

An annular diffuser test facility and test apparatus were constructed to experimentally verify the feasibility of controlling the exit velocity distribution by diffuser bleed. Since the purpose of this facility was to provide a flow system for the evaluation of a variety of scaled-down annular diffuser designs at ambient flow conditions, the following capabilities were necessary:

(1) Independent control of inner and outer diffuser wall suction rates

(2) Vacuum systems for diffuser bleed sinks since diffuser inlet total pressure was limited to near atmospheric pressure

(3) Removeable diffuser walls provided with suction plenum chambers which could be readily connected to the facility vacuum systems.

SYMBOLS

AR	diffuser area ratio
H	inlet passage height
L	diffuser length
P_{s1}	average static pressure at diffuser inlet
P_{s2}	average static pressure at diffuser exit
P_T	average total pressure at diffuser inlet
ΔP_T	diffuser total pressure loss
R	wall contour radius
V	diffuser exit velocity at a radial position
$\overline{V}$	average diffuser exit velocity
V_1	average velocity at diffuser inlet
x	downstream distance
η	diffuser effectiveness defined by eq. (1)
ρ_1	air density at diffuser inlet

APPARATUS AND INSTRUMENTATION

Flow System

A schematic of the flow system is shown in figure 2. Air at a pressure of approximately 10 atmospheres (145 psia) and at ambient temperature is supplied to the facility by a remotely located compressor station. This air feeds the three branches of the flow system.

The center branch (identified as "main air line") is the source of airflow through the test diffuser. The air flowing through this branch is metered by a sharp-edged orifice installed according to ASME standards. The air is then throttled to near atmospheric pressure by a flow control valve before entering a mixing chamber whence it flows through the test diffuser. The air discharging from the diffuser is exhausted to atmosphere through a noise absorbing duct.

The two other branches of the flow system supply the two air ejectors which produce the required vacuum for the inner and outer wall diffuser bleed flows. The ejectors are designed for a supply air pressure of 6.8 atmospheres (100 psia) and are capable of producing up to 560 torr (22 in. Hg) vacuum.

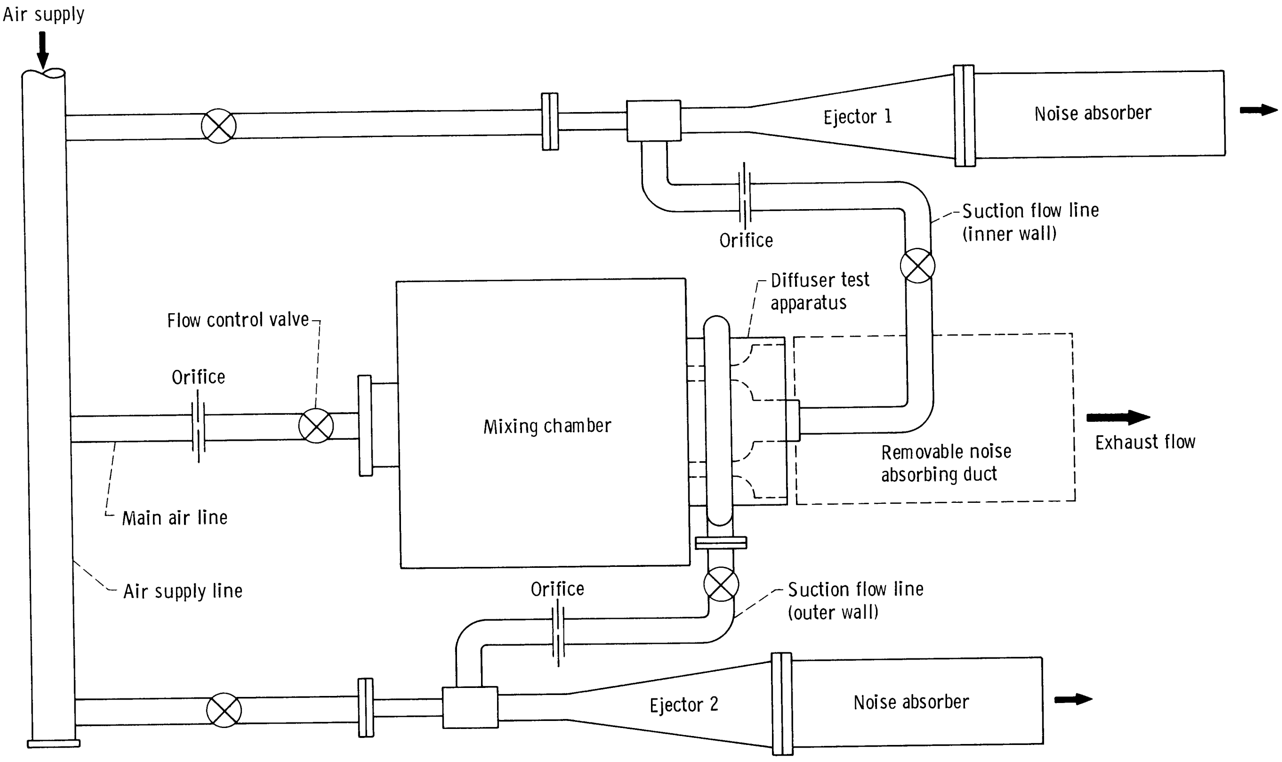


Figure 2. - Flow system.

The inner and outer diffuser wall bleed flows are also metered by sharp-edged orifices. These orifices are installed according to ASME specifications in the suction flow lines which connect the inner and outer diffuser wall bleed chambers to their respective ejector vacuum sinks.

Diffuser Test Apparatus

A cross-sectional sketch of the annular diffuser test apparatus is shown in figure 3, along with a few descriptive dimensions. The component parts are assembled onto a 91-centimeter (36-in.) mounting flange. The apparatus can thus be bolted as a unit onto the downstream flange of the mixing chamber in the main airflow line. The centerbody, which represents the inner annular surface is cantilevered from support struts located 30 centimeters (12 in.) from the diffuser inlet passage. This construction allowed eval-

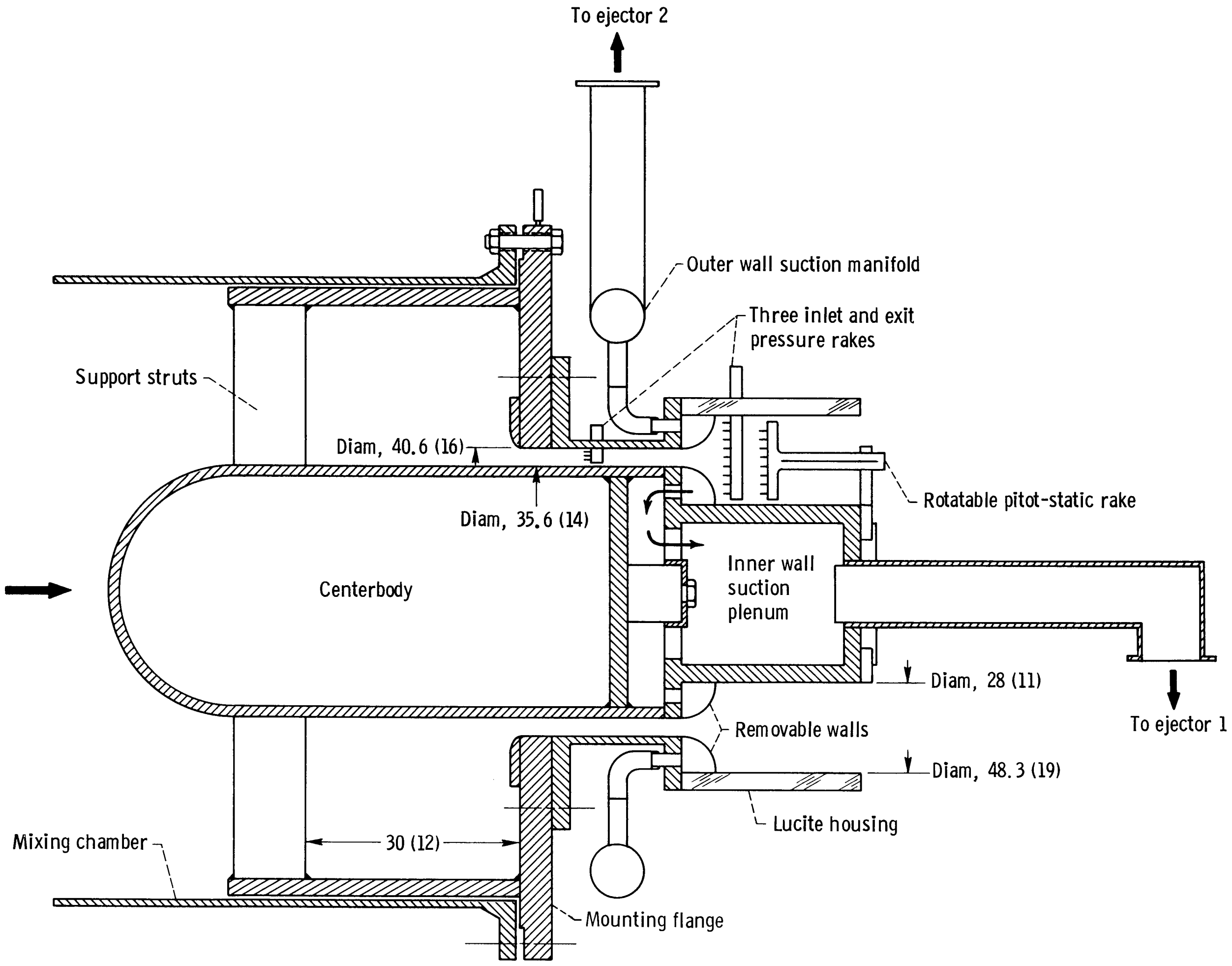


Figure 3. - Cross section of annular diffuser test apparatus. (Dimensions are in centimeters (in.).)

uation of the effect of bleed on diffuser exit velocity distribution without possible strut separation affecting the results.

Contour Diffuser Walls

The removeable contour walls are shown positioned in the apparatus (fig. 3) at the juncture of inlet and exit passages. The wall contours used for the preliminary tests had a quarter circle cross-section as indicated in figure 4. The diffuser area ratio is 4, and the length to inlet height ratio is 1.5. The suction chambers are integral with the removeable walls, and they are held in place by 12 equally spaced pipe nipples which also serve to duct the bleed flow into the inner suction plenum and the outer suction manifold. The bleed flows are drawn off the contour walls through two 0.051-centimeter (0.020-in.) slots milled into the contour surfaces at 20° and 40° of arc measured from the inlet of the diverging passage. A flat flow splitter ring, shown dashed, was placed in the stream for part of the tests.

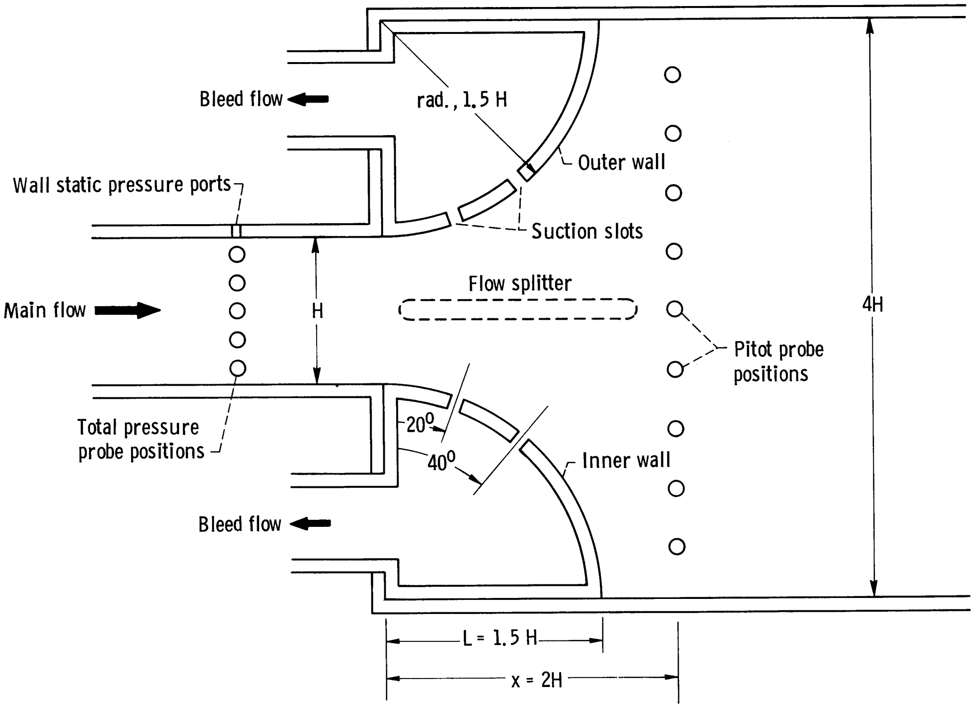


Figure 4. - Diffuser contour wall detail. Inlet passage height, H, 2.54 centimeters (1 in.).

Diffuser Instrumentation and Test Procedure

Diffuser inlet total pressure was obtained from three five-point total-pressure rakes equally spaced around the circumference. Inlet static pressure was measured using wall taps in the vicinity of the rakes.

Diffuser exit total and static pressures were measured using three equally spaced nine-point pitot-static rakes. These rakes were located downstream of the start of the diffusing section at a distance equal to twice the inlet passage height. In addition to the fixed rakes, two nine-point pitot-static rakes were available which could be rotated in a circumferential direction.

All rake pressures were read on common well manometers using dibutyl phthalate fluid (specific gravity, 1.04). Temperatures of the main and bleed flows were measured with copper-constantan thermocouples.

The main-air orifice pressure was measured with a high accuracy Bourdon gage; orifice pressure drop was determined by use of a strain gage transducer. The subatmospheric bleed-air orifice pressures were read on a mercury U-tube manometer; the orifice pressure drops, on dibutyl phthalate U-tube manometers.

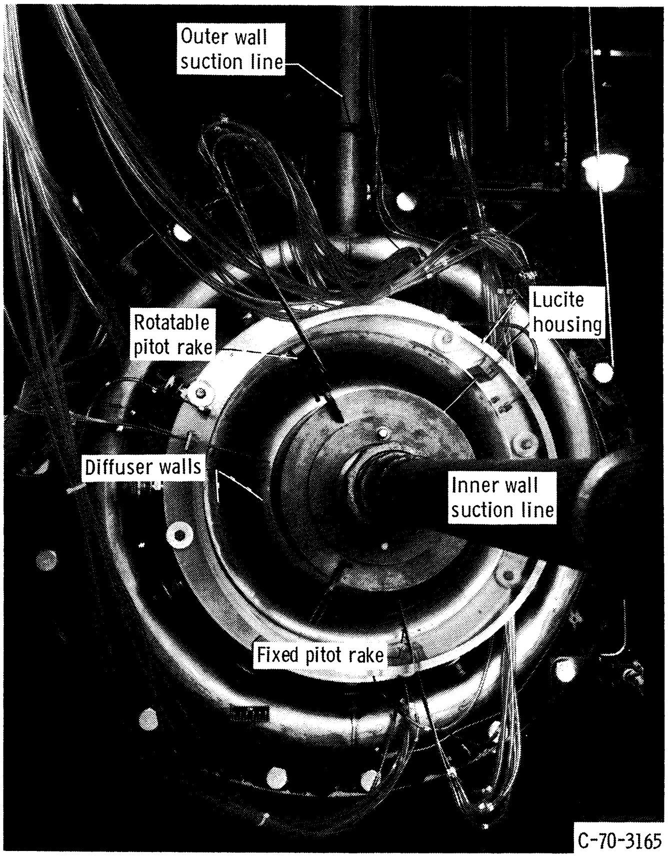


Figure 5. - Annular diffuser test apparatus. (View looking upstream).

Figure 5 is a photograph of an upstream view of the test apparatus showing the major components and pressure rakes.

Performance Paramenters

Velocities at each radial position were computed by using the compressible flow relation with the rake total and static pressures and stream temperature as input.

Diffuser and bleed flow rates were computed from the respective air orifice pressures and temperatures.

Diffuser effectiveness was computed from the relation

$$\eta = \frac{P_{s1} - P_{s2}}{\frac{1}{2}\rho_1 V_1^2 \left(1 - \frac{1}{AR^2}\right)} \tag{1}$$

Test Conditions

Typical diffuser inlet conditions were:

Pressure, atm (psia)	1 (14. 5)
Temperature, $^{\circ}C$ ($^{\circ}F$)	20 (70)
Mach number	0. 17 to 0. 265
Velocity, m/sec (ft/sec)	55 to 93 (185 to 310)
Reynolds number	1.9×10^5 to 3.3×10^5
Bleed rate, percent of total flow	2 to 12

RESULTS AND DISCUSSION

A short annular diffuser equipped with wall bleed capability was tested at several inlet velocities and bleed rates to determine to what degree diffuser bleed could be used to control combustor inlet velocity profile. The velocity profiles obtained for several typical tests are presented in figures 6 to 10. In these figures the ratio of radial to average diffuser exit velocity is plotted as a function of annulus height. The plotted values of velocity ratio were obtained by averaging the values obtained for three circumferential stations. Values for diffuser effectiveness η and for total pressure loss

$\Delta P_T/P_T$ referred to an inlet Mach number of 0.265, are also indicated on each figure. Although inlet Mach numbers were not constant for all tests, the velocity profiles were found to be independent of Mach number.

The jet flow type velocity profile obtained for tests without bleed is shown in figure 6. The symbols indicate results of two separate tests. It is interesting to note that the peak of the profile is not along the annulus centerline but is displaced toward the inner wall. This is because the outer wall, having a higher surface area, exerts a greater retarding shear force on the flow than does the inner wall. Thus flow separation from the outer wall will precede inner wall separation, thereby causing the velocity profile to be skewed towards the hub of the annulus.

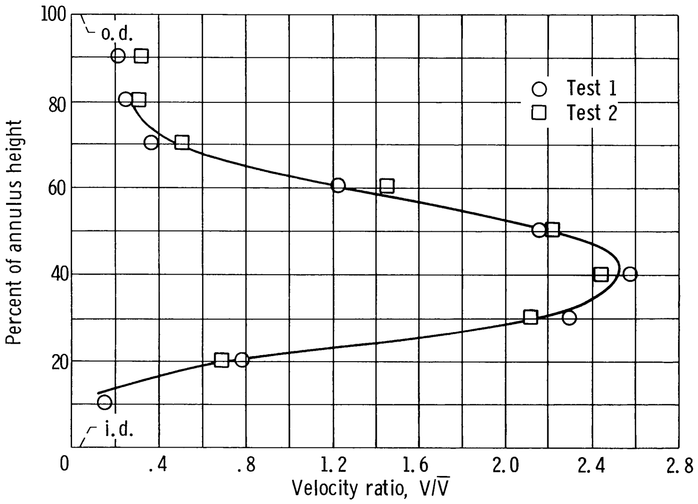


Figure 6. - Diffuser exit velocity profile with no bleed. Diffuser effectiveness, 0.25; total pressure loss, 2.8 percent.

Figure 7 shows the shift in velocity profile toward the inner wall when approximately 2 percent of the total flow is bled away through the slots in this wall. The dashed curve, representing the velocity profile without bleed, is also shown for comparison. The value of effectiveness η is shown to have increased from 0.25 to 0.42.

Figure 8 shows a comparable shift in velocity profile ($\eta = 0.41$) toward the outer wall. Note that more than twice as much bleed was required to achieve this profile shift than for the case shown in figure 7. Probable reasons for this are the increasing surface area and higher effective area ratio that the flow encounters in passing over the outer wall.

With balanced bleed applied to both walls the velocity profile was unstable, peaking towards the inner or the outer wall at the slightest unbalance of suction rate. This problem was partially attributed to suction slot width not being sufficiently uniform in a cir-

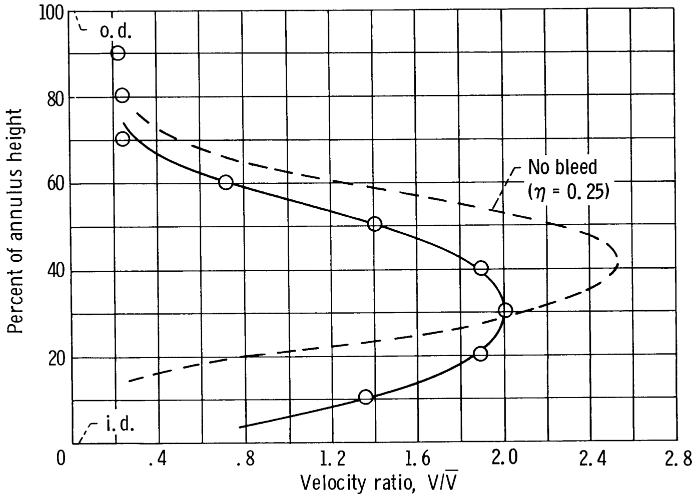


Figure 7. - Diffuser exit velocity profile with inner wall bleed of 2.1 percent. Diffuser effectiveness, 0.42; total pressure loss, 2.25 percent.

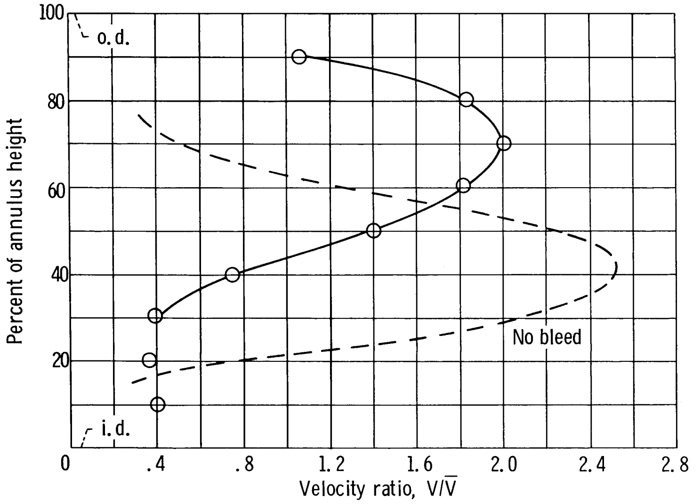


Figure 8. - Diffuser exit velocity profile with outer wall bleed of 4.6 percent. Diffuser effectiveness, 0.42; total pressure loss, 2.5 percent.

cumferential direction. Hence, a flat flow splitter was placed into the annulus as shown by the dashed lines of figure 4. This splitter divided the diffuser exit region into two nonsymmetric half annuli, each having one flat nondiverging wall and a rapidly diverging opposite wall.

A diffuser geometry similar to the inner half annulus, namely, a straight outer wall and a rapidly diverging inner wall, was tested with boundary-layer suction in references 5 and 6. Although effective control over the velocity distribution was obtained (ref. 5), diffuser effectiveness was low. The reason for this was attributed to inadequate contour design upstream of the suction slot. Reference 6 employed suction through several rows of holes in the diverging inner wall. This resulted in a significant improvement in diffuser effectiveness especially if the entrance edges of suction holes were rounded.

The outer half annulus is similar to the diffuser geometry of the controlled separation combustor proposed in the INTRODUCTION. Hence, the velocity profile control obtainable in this passage with outer wall bleed would be indicative of that expected in the controlled separation combustor.

The velocity profiles obtained with the flow splitter are shown in figure 9. The dashed curve represents the profile without bleed. The flow is separated from the inner and outer diffuser walls and attached to the flow splitter surface. Because of the flow splitter frictional loss, the diffuser effectiveness was only 0.15, even lower than for the open diffuser without bleed. The solid curve shows the profile obtained with approximately 3.5 percent bleed on each wall. The elimination of previously separated regions is shown by the relatively high values of velocity ratio at the 10- and 90-percent span locations. The control over the original separated velocity profile was so effective that an increase in bleed rate, beyond the values shown, actually resulted in separation from

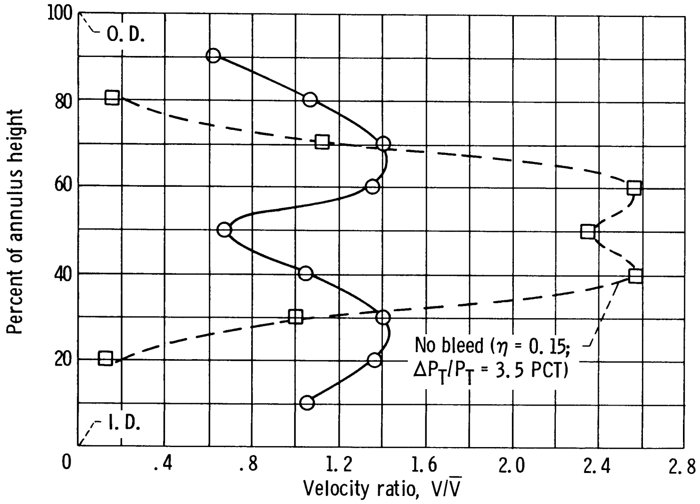


Figure 9. - Diffuser with flat flow splitter exit velocity profile with inner wall bleed of 3.7 percent and outer wall bleed of 3.4 percent. Diffuser effectiveness, 0.60; total pressure loss, 1.9 percent.

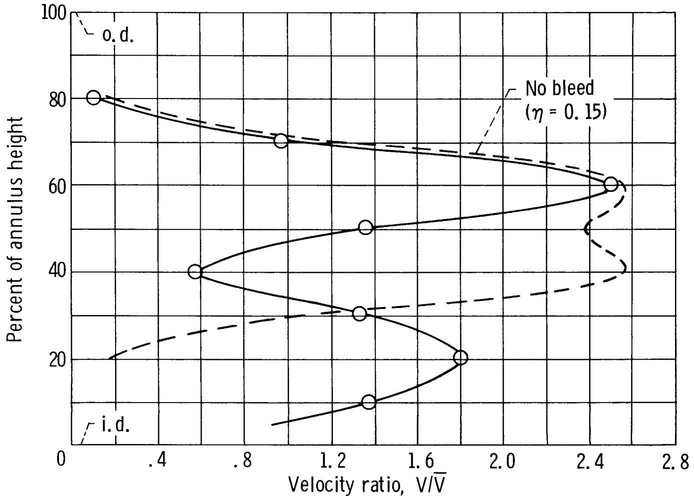


Figure 10. - Diffuser with flat flow splitter. Exit velocity profile with inner wall bleed of 1.8 percent. Diffuser effectiveness, 0.25; total pressure loss, 3.3 percent.

the flow splitter. Diffuser effectiveness increased to 0.60, a fourfold increase over the no-bleed case.

Figure 10 shows the velocity profile obtained with the same geometry when only inner wall bleed was applied, again compared with the no-bleed case (dashed curve). The profile indicates that, although only a small amount of inner wall bleed is needed to control the profile in the inner half annulus, inner wall bleed has no effect on the profile in the outer half annulus because of the obstruction presented by the flow splitter. Thus, a combustor snout would have to be positioned downstream of diffuser bleed ports for effective profile control over the full annulus height if bleed on only one wall is used.

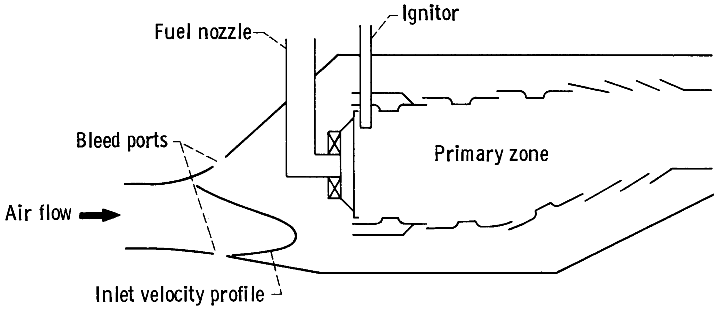
APPLICATION OF TECHNIQUE TO CONVENTIONAL GAS TURBINE COMBUSTORS

In addition to the proposed application in a short controlled separation combustor, the results of this study suggest a method for reducing idle exhaust emissions in conventional engine combustors. The particular approach used to implement the diffuser bleed technique in conventional combustors would depend on existing engine design characteristics.

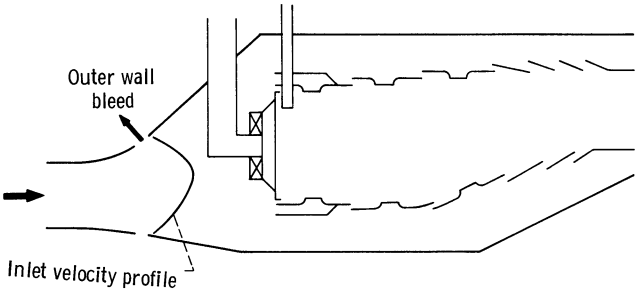
If the combustor inlet velocity distribution were flat at idle operation, application of inner wall diffuser bleed could cause a hub peaked profile. Consequently, the primary-zone velocity would be reduced and the local fuel-air ratio increased, leading to a reduction of exhaust emissions. On certain bypass type engines, outer wall diffuser bleed into the bypass stream could also lead to a reduction of primary-zone velocity and increase in the local fuel-air ratio.

Improved combustor performance at all operating conditions, rather than just at idle, could be realized if the conventional combustor had a diffuser with a gradually diverging inner wall and a rapidly diverging outer wall (fig. 11). The combustor inlet velocity profile without bleed (fig. 11(a)) would be similar to that of the controlled separation combustor (fig. 1(a)), with most of the airflow bypassing the primary zone as desired for idle and altitude relight operation. At takeoff and cruise operation (fig. 11(b)) the combustor inlet velocity profile would be straightened by application of outer wall bleed, resulting in the same performance improvements discussed for the controlled separation combustor in the INTRODUCTION.

Full-scale testing on diffuser combustor systems is needed to provide quantitative answers on the actual performance of both the proposed controlled separation combustor as well as the conventional engine with diffuser bleed capability.



(a) Idle or altitude relight operation.



(b) Cruise or takeoff operation.

Figure 11. - Application of diffuser bleed in conventional annular combustor.

SUMMARY OF RESULTS

Velocity profile control experiments were conducted on a short annular diffuser equipped with wall bleed capability. The results were as follows:

1. Flow that initially separated from both inner and outer walls could be shifted to either wall by bleeding off part of the flow through ports in the diffuser wall. The required bleed rate was less than 5 percent of total airflow.
2. More bleed was required to shift the peak of the velocity profile towards the outer wall than to accomplish a similar shift towards the inner wall.
3. Applying bleed to both walls resulted in unstable velocity profiles, with a slight unbalance in bleed rates causing drastic changes of profile shape.
4. The shape of the velocity profiles with and without bleed was independent of inlet Mach number.
5. With bleed on both walls, velocity profiles could be stabilized by placing a flat flow splitter in the diffuser.
6. Diffuser effectiveness (ratio of actual pressure recovery to ideal pressure recovery) with the flow splitter installed could be improved from a minimum value of 0.15 for no bleed to a maximum of 0.60 for approximately 3.5 percent bleed from both walls.
7. Corresponding values of diffuser total pressure loss, referred to an inlet Mach number of 0.265, decreased from 3.5 percent for no bleed to 1.9 percent with bleed.

The results could be applied to the design of a controlled separation combustor discussed in the INTRODUCTION section of this report.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, April 28, 1971,
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