NASA Technical Paper 1452

Performance of a Vortex-Controlled Diffuser in an Annular Swirl-Can Combustor at Inlet Mach Numbers up to 0.53

John M. Smith

APRIL 1979

NASA

NASA Technical Paper 1452

Performance of a Vortex-Controlled Diffuser in an Annular Swirl-Can Combustor at Inlet Mach Numbers up to 0.53

John M. Smith
Lewis Research Center
Cleveland, Ohio

National Aeronautics
and Space Administration

**Scientific and Technical
Information Office**

1979

SUMMARY

A short, annular dump diffuser designed for improved flow expansion by means of suction-stabilized vortices on both walls in the region of an abrupt area change was tested with a full-scale swirl-can combustor over a range of inlet pressures, temperatures, and Mach numbers. Diffuser effectiveness and combustor total pressure loss were obtained for nominal inlet Mach numbers from 0.25 to 0.53 with total suction rates ranging from 0 to 20 percent of total diffuser mass flow rate. The included divergence angle of the diffuser approach section was 14°, resulting in a prediffuser area ratio of 1.4. Static pressure measurements were taken along the prediffuser and also on the inner and outer walls of the diffuser downstream of the vortex fence.

The best diffuser geometry was found to be one having inner and outer wall suction slots with radial gap and axial gap dimensions of 0.13 and 0.76 centimeter, respectively. Diffuser effectiveness, that is, diffuser static pressure recovery, increased from 47 percent without suction to 80 percent at a total suction rate of 14 percent. The combustor pressure loss for an inlet Mach number of 0.40 was reduced from 6.8 percent with no suction to 4.0 percent at a total suction rate of approximately 14 percent.

INTRODUCTION

An investigation was conducted to determine the performance of a short, annular dump diffuser with improved flow expansion using suction to provide stable vortices. The diffuser was tested with a full-annular swirl-can combustor.

Ringleb, in reference 1, first proposed using standing vortices to control flow expansion in a short diffuser. Hekstad, in reference 2, tested a two-dimensional duct with a variable-step area change on its lower wall followed by a suction slot. The results show that a smooth expansion of the flow without separation downstream of the step area change could be obtained if sufficient suction was applied. In reference 3, which used an annular step-area-change diffuser, flat walls called fences were placed downstream of the vortices which were formed and stabilized by suction. The fences formed a partially enclosed vortex chamber with the upstream walls of the diffuser.

Detailed performance data of an annular dump diffuser using these fences were obtained in a cold flow rig as described in reference 4. The included divergence angle was 14°, the prediffuser area ratio was 1.4, and the overall area ratio was 4.0.

A diffuser was designed, fabricated, and tested with the swirl-can combustor using the results of this cold flow test. The diffuser had the geometry based on the diffuser used in the cold flow test including the vortex fence dimensions and location as described in reference 4.

This report presents the results of the performance investigation of this short, annular dump diffuser with improved flow expansion and suction to provide stable vortices. The performance data of the diffuser-combustor tests are compared with the results of the cold flow tests for the same Mach numbers and total suction rates. Diffuser effectiveness (static pressure recovery), Mach number effect on diffuser performance, and combustor overall pressure loss data were obtained for nominal Mach numbers of 0.25, 0.30, 0.34, 0.41, and 0.53. Suction rates were from 0 to 20 percent of the diffuser inlet air flow. Inlet pressures and temperatures were from 0.51 to 1.0 megapascals and 589 to 896 K, respectively.

SYMBOLS

A	area
AR	diffuser area ratio
B	bleed flow fraction of total mass flow rate
C_P	static pressure recovery, percent
gc	dimensional constant
M	Mach number
m	mass flow rate
P	total pressure
p	static pressure
S	suction rate, percent
T	temperature
X	axial distance from exit of prediffuser to vortex fence
Y	radial distance from exit of prediffuser to vortex fence
γ	specific heat ratio
η	diffuser effectiveness

Subscripts:

i	inner wall of diffuser
o	outer wall of diffuser
t	total suction
w	diffuser wall static pressure
1	diffuser inlet
2	combustor exit

APPARATUS AND INSTRUMENTATION

Test Facility

The investigation was conducted in a closed-duct facility. The flow path and the arrangement of the major components of the combustion air system are shown in figure 1. The combustion air is heated to a maximum of 589 K in an outside preheater and is delivered to the cell through a 91.5-centimeter-diameter ASME orifice run. Upon reaching the test cell, the air can be delivered to the test combustor or it can be first passed through heat exchangers having the capacity to heat the air to 922 K. Fixed probes at the test combustor entrance measure the inlet temperature and pressure profiles. The combustor airflow rate and pressure are set with an inlet valve and an exhaust valve. Before the hot gas enters the exhaust valve, it is cooled to 355 K by a series of quench water sprays. Beyond the exhaust valve, the gas flows into the central atmospheric or altitude exhaust system. A more complete description of the facility is given in reference 5.

Diffusers

Diffuser geometry. - The geometry for the diffuser used in the diffuser-combustor test is listed in table I. This includes the prediffuser area ratio, half angle θ, overall area ratio, and radial and axial suction slot dimensions. Figure 2(a) shows the diffuser-combustor annular passage details. The x- and y-dimensions in figure 2(a) are the axial and radial distances from the end of the prediffuser to the vortex fence. Also shown is the location of the inner and outer module rows of the swirl-can combustor. The angle θ is one-half the included divergence angle of the prediffuser. The inner and outer wall static taps measured the wall static pressures which were than used to compute the diffuser static pressure recovery.

The diffuser evaluated in the cold flow test is described in reference 4. The values for the prediffuser area ratio, half angle θ, overall area ratio, and radial and axial suction slot dimensions are listed in table I. Figure 2(b) shows the axial and radial spacings, x and y, respectively, which are the distances from the end of the prediffuser to the vortex fence. The angle θ is one-half the included angle of the prediffuser. The wall static pressures were measured by wall static taps which were then used to compute the diffuser static pressure recovery.

Diffuser instrumentation. - For the diffuser-combustor test, inlet airflow and diffuser bleed were measured by square-edge orifice plates installed according to ASME standards. The diffuser suction rate S_t was defined as the ratio of diffuser bleed to diffuser airflow expressed as a percent. Instrumentation used with the diffuser in the cold flow test is described in reference 4.

Combustor

Combustor geometry. - Figure 2(a) shows a schematic of the swirl-can combustor with an inner and outer swirl-can module. The prediffuser, vortex fence, and dump section of the diffuser are also shown. Locations of the inner and outer combustor liners are indicated by the dashed lines.

Another schematic of the combustor used in this investigation is shown in figure 3. The large number of swirl-can modules distributes the fuel-air mixture across the annulus resulting in more uniform combustion. The individual swirl-can modules perform several functions. Each module creates some degree of premixing of the air and fuel, swirls the mixture, stabilizes combustion, and provides large mixing areas between the bypass air through the array and the hot gases in the module wake. All the combustor airflow, exclusive of liner coolant air and diffuser bleed flow, passes through the array. More detail on swirl-can combustors can be found in references 6 and 7.

Combustor instrumentation. - Chromel-Alumel thermocouples were used to measure the inlet-air temperature. The combustor liner temperatures were measured by the same type of thermocouples. Combustor overall pressure loss was determined with pressure measurements from total pressure rakes at the inlet to the diffuser and the exit of the combustor.

PROCEDURE

The overall diffuser performance was evaluated in terms of diffuser effectiveness and total pressure loss.

Diffuser effectiveness was computed from o outer wall of di

$$\eta = \frac{(p_w - p_1)}{(P_1 - p_1)\left[1 - \left(\frac{1 - B}{AR}\right)^2\right]} 100 \qquad (1)$$

Equation (1) is an approximation expressing the ratio of actual to ideal conversion of inlet dynamic pressure to exit static pressure for the case of compressible flows through a diffuser with wall bleed for $M \leq 0.5$ and $AR \geq 2$. A derivation of equation (1) and its limitation is shown in reference 8.

The total pressure loss was defined as

$$\frac{\Delta P}{P} = \frac{(P_1 - P_2)}{P_1} 100$$

The static pressure recovery in the diffuser was defined as

$$C_P = \frac{(p_w - p_1)}{(P_1 - p_1)} 100$$

The test conditions for this program are as follows:

Total pressure, MPa	0.5 to 1.0
Temperature, K	589 to 895
Mach number	0.25 to 0.53
Reference velocity, m/sec	8.5 to 31.0
Suction rate, percent of total flow	0 to 20

The U.S. Customary Systems of Units was used for primary measurements and calculations. The conversion to the International System of Units is done for reporting purposes only.

RESULTS AND DISCUSSION

A high area dump diffuser with suction-stabilized vortex control was tested with a full-scale annular swirl-can combustor. The performance of the diffuser was evaluated in terms of the diffuser effectiveness (i.e., static pressure recovery) and overall combustor pressure loss, which includes losses in the diffuser. Data were obtained for Mach numbers from 0.25 to 0.53 for a range of total suction rates from 0 to 20 percent of the diffuser inlet airflow.

Diffuser Effectiveness

Figure 4(a) is a plot of diffuser effectiveness and total suction rate S_t for inlet Mach numbers of 0.3 and 0.41. The effectiveness values ranged from 42 percent without suction to about 73 percent at a total suction rate of 14 percent. The effectiveness values were calculated using the inner wall static pressure measurements. The total suction rate of 14 percent was about equally divided between the inner and outer diffuser walls. Figure 4(b) is a plot of diffuser effectiveness based on outer wall static pressures and diffuser total suction rate for Mach numbers of 0.25 and 0.34. The effectiveness values increased from 49 percent without suction to about 76 percent at a total suction rate of 14 percent. Again the total suction rate was about equally divided between the inner and outer walls of the diffuser. The increase of approximately 29 percent in diffuser effectiveness on both inner and outer walls of the diffuser with 14 percent total suction shows that the use of diffuser bleed can improve the performance of the diffuser.

Diffuser Static Pressure Recovery

Figure 5 shows the static pressure recovery along the outer wall of the prediffuser, the dump region, and the combustor for a total suction rate of approximately 15 percent at an inlet Mach number of 0.25. The pressure recovery through the prediffuser is approximately 35 percent and the overall pressure recovery is 77 percent. There was about a 7.5 percent suction rate on both the inner and outer walls of the diffuser. Similar values of diffuser static pressure recovery were obtained using the inner wall static pressures. Results indicate that there is some pressure recovery in the prediffuser, but about 55 percent of the recovery occurs downstream of the vortex fence.

Diffuser-Combustor Pressure Loss

Figure 6 shows the combustor overall pressure loss and the diffuser effectiveness as functions of the percent of bleed on the outer wall. The percent of bleed was varied from 0 to 100 percent of the total suction rate. The highest effectiveness value and the lowest pressure loss occurred when equal amounts of suction were applied to the inner and outer wall of the diffuser. It would appear from these data that applying equal amounts of suction to both the inner and outer walls gave the greatest static pressure recovery in the diffuser and would also provide a minimum of overall pressure loss in the combustor.

The overall pressure loss for the diffuser and combustor is shown in figure 7 for a Mach number of 0.41 and a range of total suction rates from 0 to 15 percent. The pressure loss without suction was 6.8 percent. For a suction rate of approximately 14 percent, the overall pressure loss was 4.0 percent. This is a reduction of 41 percent of the pressure loss without suction.

Effect of Inlet Mach Number on Effectiveness

The effect of inlet Mach number on diffuser effectiveness is shown in figure 8 for a range of Mach numbers from 0.3 to 0.53. Static pressures along the diffuser outer wall were used to calculate diffuser effectiveness values for a total suction rate of approximately 10 percent. As can be seen in figure 8, Mach number had little or no effect on diffuser pressure recovery for a constant suction rate. Similar results were obtained with effectiveness values based on diffuser inner wall static pressures.

Comparison of Diffuser Cold Flow and Diffuser-Combustor Effectiveness Values

Figure 9 compares the cold flow diffuser effectiveness data, as reported in reference 4, with the diffuser-combustor effectiveness data. Results were obtained for a range of Mach numbers from 0.18 to 0.53 and total suction rates from 0 to 18 percent of the total airflow. Effectiveness values increased from approximately 50 percent without suction to approximately 75 percent at a 14 percent total suction rate. Effectiveness values were calculated using diffuser outer wall static pressures.

The good agreement between the cold flow data and the diffuser-combustor data is encouraging because in the cold flow tests no blockage was used to simulate the combustor. These results indicate that cold flow tests provide a good prediction of the diffuser-combustor performance and that combustor simulation in the cold flow test may not be necessary. Thus, small-scale cold flow tests can be used to predict diffuser performance with a combustor. These tests generally cost less and use less energy and time than the full-scale combustor tests.

SUMMARY OF RESULTS

The performance of a short, annular, suction-stabilized-vortex diffuser tested with a combustor was evaluated in terms of diffuser effectiveness and combustor total pressure loss for nominal inlet Mach numbers of 0.25, 0.30, 0.34, 0.41 and 0.53. The test program consisted of a detailed performance evaluation of the diffuser tested with a combustor followed by a comparison of these results with the results of a similar diffuser tested in a cold flow facility.

The results are as follows:

1. The effectiveness of the diffuser tested with the combustor gave good agreement with the effectiveness values determined from cold flow tests without a combustor.
2. Diffuser effectiveness values based on outer wall static pressures for the diffuser tested with the combustor increased from 50 percent without suction to approximately 76 percent with 14 percent suction.
3. The best effectiveness value and lowest pressure loss occurred when equal amounts of suction were applied to the inner and outer walls of the diffuser.
4. For the same total suction rate, Mach number had little or no effect on diffuser effectiveness values.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, March 6, 1979,
505-04.

REFERENCES

1. Ringleb, Friedrich Otto: Flow Control by Generation of Standing Vortices and the Cusp Effect. Rept. 317, Princeton Univ., 1955.
2. Heskestad, Gunnar: Remarks on Snow Cornice Theory and Related Experiments with Sink Flows. J. Basic Eng., vol. 88, no. 2, June 1966, pp. 539-549.
3. Hestestad, Gunnar: Further Experiments with Suction at a Sudden Enlargement in a Pipe. J. Basic Eng., vol. 92, no. 3., Sep. 1970, pp. 437-449.
4. Smith, John M.; and Juhasz, Albert J.: Performance of a Short Annular Dump Diffuser Using Suction-Stabilized Vortices at Inlet Mach Numbers to 0.41. NASA TP-1194, 1978.
5. Adam, Paul W.; and Norris, James W.: Advanced Jet Engine Combustor Test Facility. NASA TN D-6030, 1970.
6. Diehl, Larry A.; and Trout, Arthur M.: Performance and Emission Characteristics of Swirl-Can Combustors to a Near-Stoichiometric Fuel-Air Ratio. NASA TN D-8342, 1976.

7. Anderson, D. N.; Juhasz, Albert J.; and Niedzwiecki, Richard W.: Performance of a Swirl-Can Primary Combustor To Outlet Temperatures of 3600° F (2256 K). NASA TM X-52902, 1970.

8. Juhasz, Albert J.: Performance of an Asymmetric Short Annular Diffuser with a Nondiverging Inner Wall Using Suction. NASA TN D-7575, 1974.

TABLE I. - DIFFUSER GEOMETRY

Diffuser	Prediffuser		Radial gap, y, cm	Axial gap, x, cm	Overall area ratio
	Area ratio	Half-angle, θ, deg			
Cold flow test	1.4	7	0.13	0.76	4.0
Diffuser-combustor test	1.4	7	.13	.76	4.96

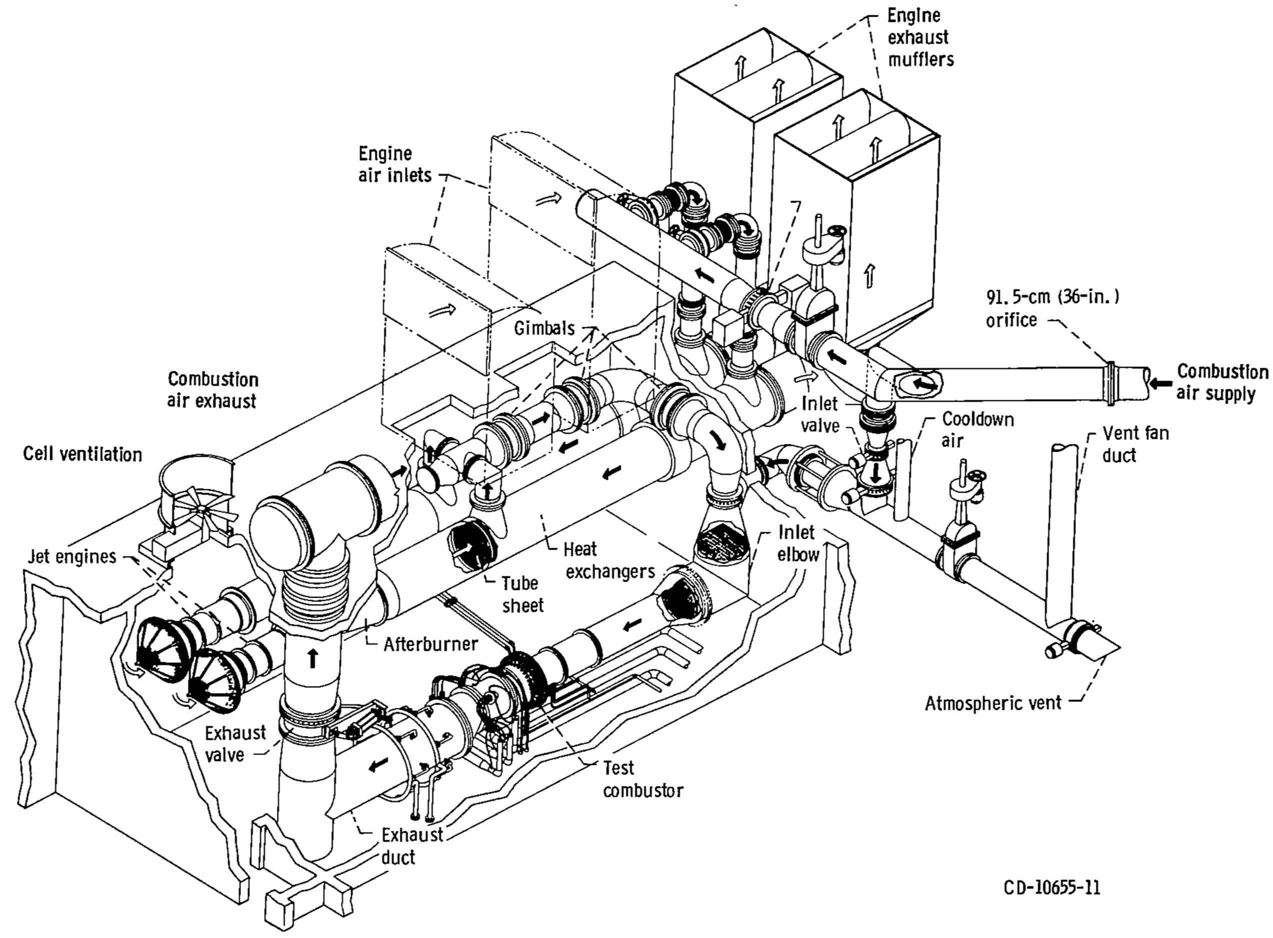
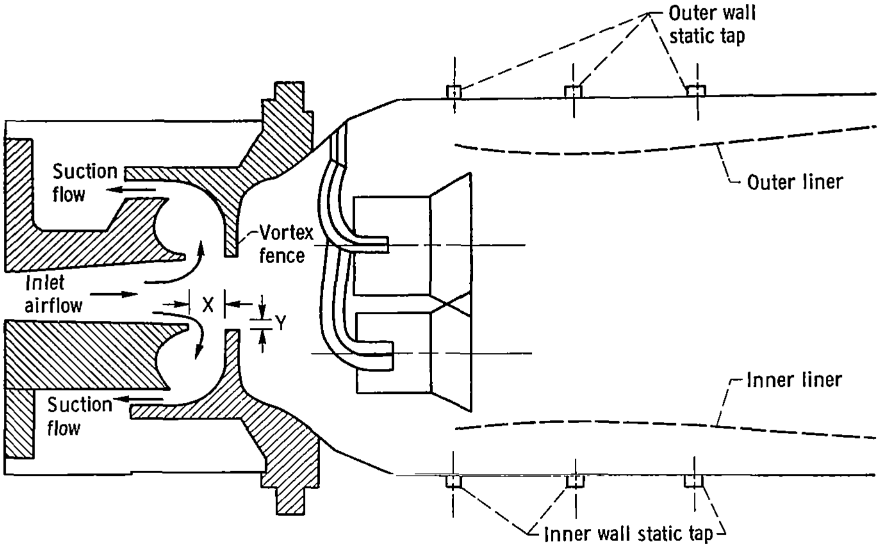
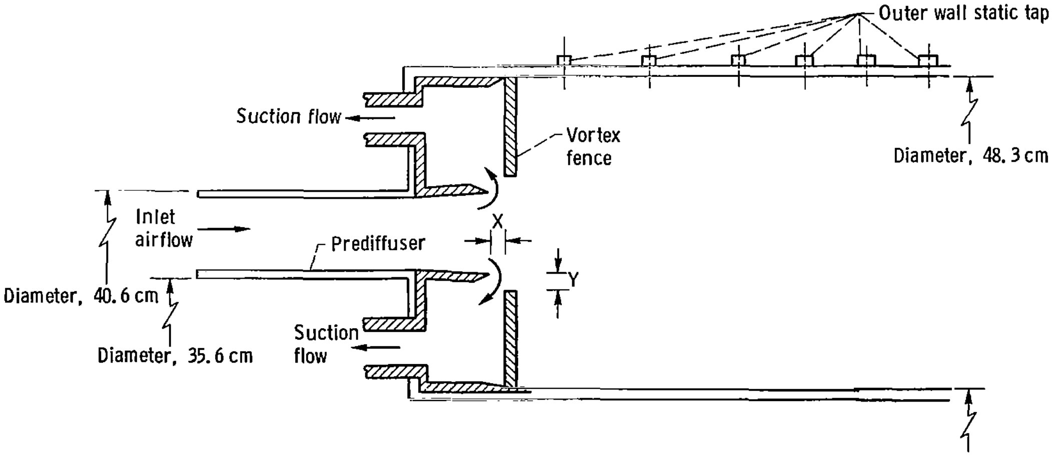


Figure 1. - ECRL-1 flow path and equipment arrangement.



(a) Diffuser-combustor annulus passage details.



(b) Diffuser annulus passage details for cold flow test.

Figure 2. - Schematic of diffuser-combustor annulus and cold flow diffuser.

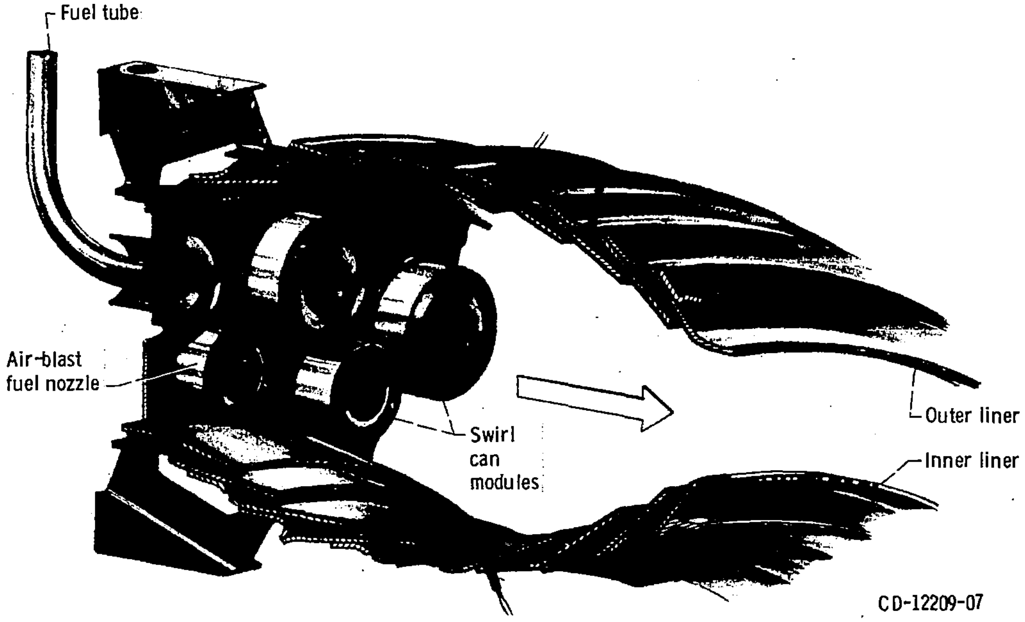
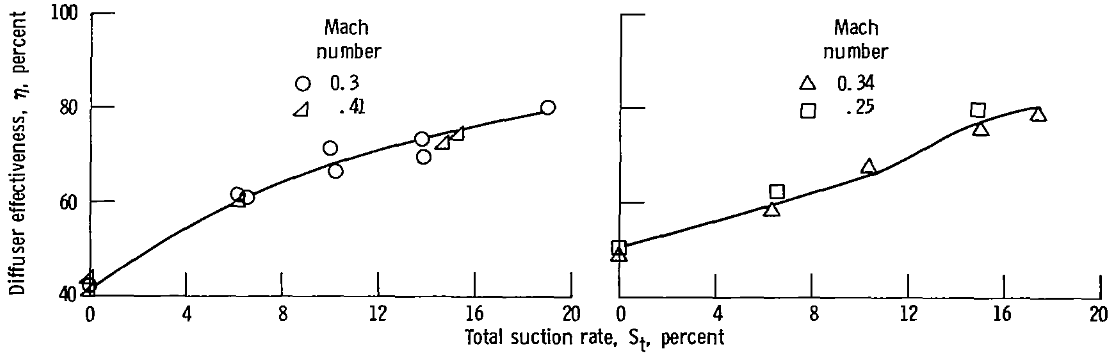


Figure 3. - Schematic illustration of combustor liner, air-blast fuel nozzles.



(a) Values based on inner wall static pressure.

(b) Values based on outer wall static pressures.

Figure 4. - Diffuser effectiveness values for diffuser tested with combustor for range of total suction rates S_t and Mach numbers.

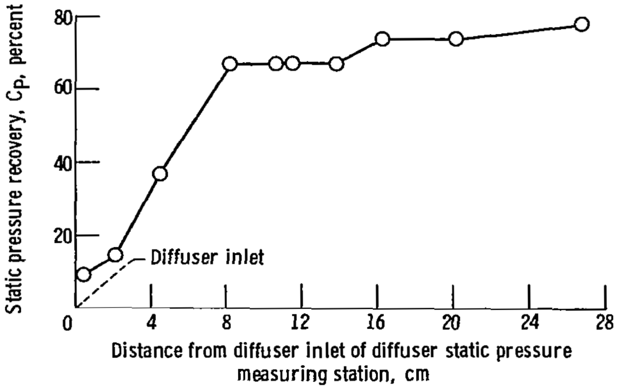


Figure 5. - Static pressure recovery in prediffuser and along outer wall of diffuser for total suction rate of approximately 15 percent and inlet Mach number of 0.26.

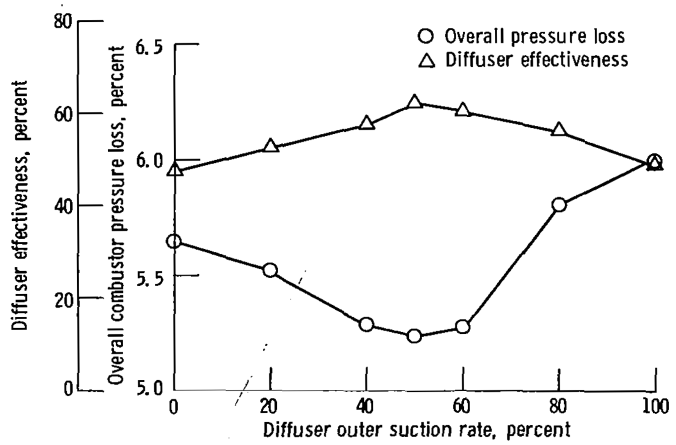


Figure 6. - Diffuser overall combustor pressure drop and effectiveness as functions of outer diffuser bleed split for total suction rate of approximately 9 percent and inlet Mach number of 0.33. Values based on diffuser outer wall static pressures.

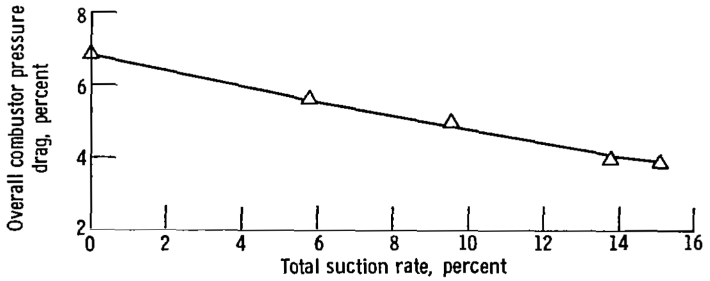


Figure 7. - Total pressure loss for diffuser for range of total suction rates and Mach number of 0.41.

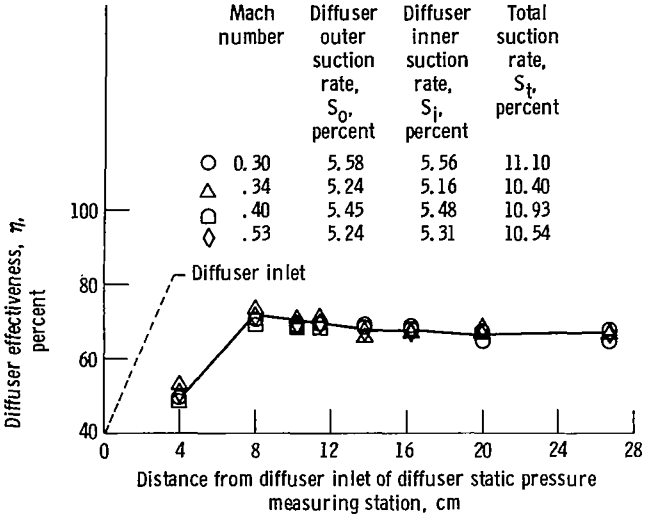


Figure 8. - Diffuser effectiveness as function of outer wall static pressures for range of inlet Mach numbers and total suction rate of approximately 11.0 percent.

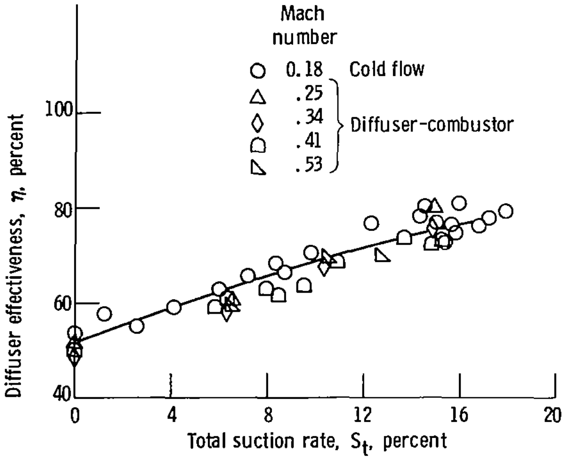


Figure 9. - Comparison of diffuser effectiveness values from cold flow data with results of diffuser - combustor test for range of total suction rates and inlet Mach numbers. Values based on outer wall static pressures. Axial distance from exit of prediffuser to vortex fence, x, 0.13 centimeter; radial distance from exit of prediffuser to vortex fence, y, 0.76 centimeter.

1. Report No. NASA TP-1452	2. Government Accession No.	3. Recipient's Catalog No
4 Title and Subtitle PERFORMANCE OF A VORTEX-CONTROLLED DIFFUSER IN AN ANNULAR SWIRL-CAN COMBUSTOR AT INLET MACH NUMBERS UP TO 0.53		5. Report Date April 1979 6. Performing Organization Code
7 Author(s) John M. Smith		8. Performing Organization Report No E-9832 10. Work Unit No.
9 Performing Organization Name and Address National Aeronautics and Space Administration Lewis Research Center Cleveland, Ohio 44135		11. Contract or Grant No 13. Type of Report and Period Covered Technical Paper
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D.C. 20546		14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

A short, annular dump diffuser with suction-stabilized vortices in the region of abrupt area change was tested with a full-scale, annular swirl-can combustor. The prediffuser area ratio was 1.4. Performance data were obtained for both isothermal and burning conditions at inlet temperatures of 589 to 895 K and pressures of 0.5 to 1.0 MPa for a range of diffuser inlet Mach numbers from 0.25 to 0.53. Suction rates were 0 to 20 percent of the total diffuser mass flow rate. Diffuser effectiveness increased from 47 percent without suction to approximately 80 percent for a total suction rate of 14 percent. Combustor total pressure loss for the same total suction rate was reduced from 6.8 percent without suction to 4.0 percent at an inlet Mach number of 0.40.

17. Key Words (Suggested by Author(s)) Vortex diffuser Swirl-can combustor	18. Distribution Statement Unclassified - unlimited STAR Category 07

19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 15	22 Price* A02

* For sale by the National Technical Information Service, Springfield Virginia 22161

NASA-Langley, 1979