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EFFECT OF CASING TREATMENT ON OVERALL PERFORMANCE OF AXIAL-FLOW TRANSONIC FAN STAGE WITH PRESSURE RATIO OF 1.75 AND TIP SOLIDITY OF 1.5

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16. Abstract

The effect of a number of casing treatments on the overall performance of a 1.75-pressure-ratio, 423-m/sec-tip-speed fan stage was evaluated. The skewed slot configuration with short-open slots over the midportion of the rotor had a stall margin of 23.5 percent, while the solid casing had a stall margin of 15.0 percent. The skewed slot configuration with long open slots extending ahead of and over front portion of rotor displaced the stall line to the lowest flow at all speeds tested. At design speed, the peak efficiency for the long, forward open slots was 1 point less than that for the short midopen slots and 3 points less than that for the solid casing.

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EFFECT OF CASING TREATMENT ON OVERALL PERFORMANCE OF AXIAL-FLOW TRANSONIC FAN STAGE WITH PRESSURE RATIO OF 1.75 AND TIP SOLIDITY OF 1.5

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SUMMARY

A series of tests were conducted to determine the effects of a number of casing treatments on the overall performance of an axial flow transonic fan stage. The stage was designed for a pressure ratio of 1.75 at a tip speed of 423 meters per second. A solid casing, a teardrop casing insert and eight variations of a skewed slot casing insert were evaluated. The skewed slot configuration with long, opened slots extending ahead of and over the front portion of the rotor blade displaced the stall line to the lowest flow at all speeds. At design speed the skewed slot casing with short, open slots over the midportion of the rotor was equally as effective. The peak efficiency for the long, forward, open slots was 1 percentage point less than that for the short, mid, open slots and 3 percentage points less than that for the solid casing. The stall margin for the short, mid, open slot configuration was 23.5 percent and 15.0 percent for the solid casing.

INTRODUCTION

Modern aircraft may be required to operate over a wide range of flight speeds with conditions of varying inlet flow distortions and time-unsteady flow into the engine. Thus, the fan and compressor must be capable of stable operation with these adverse inlet conditions. Multistage fans may also encounter matching difficulties at part-speed operation because of stall in the front stages and choke in the rear stages. Improving the flow margin between the fan operating point and the stall-limit point will, in general, improve the useful operating range of the engine. Under many conditions the unstable flow conditions are initiated in the tip region of the fan rotor. Thus if stall in the tip region can be delayed, the flow range of the fan may be increased.

One way of delaying stall in the tip region has been to use casing treatment across the rotor tip (ref. 1 to 6). References 1 and 2 show that several different casing treatment designs improved the flow range (delayed stall) over that for a solid casing. To further study the effects of casing treatment on fan performance, an investigation was conducted at the NASA Lewis Research Center to evaluate additional types of casing treatments. A solid casing, a teardrop configuration, and eight variations of a skewed slot configuration were tested. This report presents the overall performance results obtained using fixed instrumentation. The test stage used in this investigation was designed for an overall pressure ratio of 1.75 at a flow of 29.5 kilograms per second (200.6 $(kg/sec)/m^2$ of annulus area). The design tip of speed of this 51-centimeter rotor was 423 meters per second. This stage has a tip solidity of 1.5 and is the same as that used in the solidity investigation of reference 8.

APPARATUS AND PROCEDURE

Compressor Test Facility

The compressor stage was tested in the Lewis single-stage compressor facility which is described in detail in reference 7. A schematic diagram of the facility is shown in figure 1. Atmospheric air enters the test facility at an inlet located on the roof of the building and flows through the flow measuring orifice and into the plenum chamber upstream of the test stage. The air then passes through the experimental compressor stage, into the collector, and through the exhaust duct to the atmosphere.

Test Stage

The test stage was described in detail in reference 8 and is only briefly described herein. The overall design parameters for stage 8-8 are listed in reference 8, and the flow path geometry is shown in figure 2. This stage was designed for an overall pressure ratio 1.75 at a flow of 29.5 kilograms per second (200.6 $(kg/sec)/m^2$ of annulus area). The design tip speed was 423 meters per second. The stage was designed for a tip solidity of 1.5 for the rotor and 1.5 for the stator. This resulted in 49 rotor blades with an aspect ratio of 2.4 and 54 stator blades with an aspect ratio of 2.0.

Photographs of the rotor and stator are shown in figures 3 and 4. Each rotor blade has a vibration damper located at about 48 percent span from the outlet rotor tip. The maximum thickness of the damper was 0.214 centimeter. The axial spacing between the rotor hub trailing edge and the stator hub leading edge was 3.33 centimeters. The nominal nonrotating tip clearance of the rotor blade was 0.061 centimeter.

Casing Treatment Inserts

Solid insert. - The performance of the stage was first obtained with a solid insert to serve as a reference for comparison with that obtained with the various casing treatments.

Skewed slot insert. - The eight skewed slot casing treatment configurations were made with one basic insert. The variations were obtained by adding or removing a backing plate, by partially filling the slots with wood plugs to vary the axial length of the slots, and by varying the axial location of the insert in relation to the rotor blade.

The basic skewed slot insert is presented in figure 5. The slots were alined with the axial plane but are skewed at a 60° angle to the radial plane in the direction of rotation. The apparent slight angle of the slot to the axial plane shown in figure 5 results from the changing inner radius of the insert. There are 260 slots, with the slot width being twice the land width. The insert can be tested with the backing plate (as shown in fig. 5); or the backing plate can be removed and the insert tested "opened". The axial length of the slots is 2.66 centimeters.

The axial location of the insert with respect to the rotor and the axial length of the slots also varied. This is illustrated in figure 6. The short slot configuration over the midportion of the rotor blade (fig. 6(a)) is described in reference 6. The same short slots were also tested ahead of and over the front portion of the rotor blades (fig. 6(b)). The rear wood plugs were removed to obtain the medium length slots (fig. 6(c)) and both sets of plugs were removed to form the long slots (fig. 6(d)). All four configurations were tested both opened (backing plate removed) and closed as shown in figure 5.

Teardrop insert. - A sketch and photograph of the teardrop insert are shown in figure 7. From the side the shape of the circumferential groove is a teardrop. The groove is located ahead of and over the front portion of the blade.

Instrumentation

Two chromel-constantan thermocouples were located in the plenum tank for sensing inlet total temperature. Inlet total pressure was assumed to be equal to plenum static pressure and was determined from four manifolded wall static taps located approximately 90° apart in the plenum tank. The stage outlet conditions were determined from measurements obtained from four rakes located approximately 90° apart and 4 centimeters downstream of the stator trailing edge. A photograph of one of the rakes is shown in figure 8. Each rake had five total-pressure - total-temperature elements located at 11.0, 30.5, 50.0, 69.5, and 89.0 percent of the passage height from the outer casing. The thermocouple material for the rakes was Chromel-Alumel. Outlet static pressure at the various rake positions was determined by assuming a linear variation between the outer and inner wall static-pressure measurements. A calibrated orifice was used to determine airflow. Rotor speed was determined by using a magnetic pickup in conjunction with a electronic counter.

The estimated errors of the data, based on inherent accuracies of the instruments and recording systems, are as follows:

Airflow, kg/sec	±0.3
Temperature, K	±0.6
Inlet total pressure, N/cm^2	±0.01
Outlet total pressure, N/cm^2	±0.10
Outlet wall static pressure, N/cm^2	±0.10
Rotor speed, rpm	±30

Test Procedure

Data were recorded at 50, 60, 70, 80, 90, and 100 percent of design speed for each configuration. For each speed the data were taken over a range of flows from maximum flow to stall conditions. The stall points were established by increasing the back pressure until stall occurred. This was indicated by a drop in outlet pressure and an increase in audible noise level.

Calculation Procedure

The overall stage performance is based on average conditions in the plenum tank and mass-averaged values of total pressure and total temperature at the stator outlet. The rake temperatures were corrected for Mach number. All performance parameters were corrected to standard-day conditions based on plenum measurements.

The percent stall margin is based on the pressure ratio and flow at stall and those values at a reference point on the speed line corresponding to an operating line passing through peak efficiency for the solid casing.

RESULTS AND DISCUSSION

The overall performances for stage 8-8 with several casing treatments are presented in tabular form in table I. Only 70 and 100 percent of design speed and stall line data will be presented for each configuration. The results will be presented in four sections. First, the fan performance for the reference solid casing will be presented. Then the effect of the opened and closed slots will be presented for each type of insert and compared with reference. The performance with the teardrop configuration will be followed by an evaluation of the various casing treatments.

Fan Performance with Solid Casing

The overall fan performance for the reference solid casing is presented in figure 9(a). Total-pressure ratio and adiabatic efficiency are presented as a function of airflow. Based on the fixed instrumentation, a peak efficiency of 0.803 was obtained at a pressure ratio of 1.711 and a flow of 29.23 kilograms per second at design speed.

Fan Performance with Skewed Slot Inserts

The fan performance for the various skewed slot configurations are presented in figures 9(b) to (e). In each figure the opened and closed configurations are compared with each other and with the solid reference casing.

At design speed the open slotted configurations moved the stall flow to lower flows than did the closed, slotted configurations. However, the difference was small when the slots were located over the midportion of the rotor tip (fig. 9(b)). Also, all of the open slotted configurations moved the stall flow to lower flows than the solid casing, whereas the closed slotted configurations did not always do so (figs. 9(c) and (d)). Thus, it appears that the open slots perform better than do the closed slots. The maximum efficiency for all of the slotted configurations was slightly lower than that obtained for the solid casing. The maximum pressure ratio for the slotted configurations was also lower than that obtained for the solid casing when the slots were located over the forward portion of the rotor tip (figs. 9(c) to (e)).

At 70 percent of design speed the difference in performance with open or closed slots was small. All of the slotted configurations moved the stall flow to lower flows than those obtained with the solid casing with minimal losses in efficiency and little or no effect on pressure ratio.

Fan Performance with Teardrop Insert

The overall performance with the teardrop casing is presented in figure 9(f). At 70 percent of design speed the casing treatment has little effect. But at design speed the pressure ratio and efficiency are greatly reduced, and the stall line moved to a slightly higher flow. Also, the pressure ratio was the highest at the peak efficiency flow condition and then decreased as the flow was decreased. Apparently the teardrop configuration would not let the forward portion of the blade load up as the flow decreased. Since this configuration showed essentially no benefit and is not in the same family as the slots, no further comparisons of this treatment will be made.

Comparison of Casing Treatments

The effectiveness of casing treatments may be judged by several factors. A casing treatment that improves stall margin at design speed without severely affecting efficiency would be chosen if flow distortions at cruise were a problem. If startup problems are encountered in a multistage fan, a casing treatment that would substantially improve part-speed stall margin would be considered effective. An ideal casing treatment would be one that insures adequate stall margin at all speeds without reducing efficiency.

A comparison of the stall margin and peak efficiency for each of the slotted configurations at design speed is shown in table II. The stall margin is based on flow and pressure ratio at stall and those values on an operating line passing through the peak efficiency operating point for the reference solid casing.

The skewed, short slots over the midportion of the blade gave the largest stall margin, but this configuration has about 2-percentage-point loss in efficiency over the solid casing.

To obtain a comparison of the part-speed performance, the stall lines for the various opened slotted configurations are presented in figure 10. The opened skewed slots were shown to be better than the closed slots in figures 9(b) to (e). At all part-speed conditions each slotted configuration improved the stall margin over that for the solid casing. The lowest-flow stall line was obtained for the long, forward, opened skewed slot configuration. At design speed the short, mid, opened skewed slots and the long, forward, opened slots were equally effective in moving the stall line to lower flows. However, the peak efficiency for the long, forward, opened skewed slot configuration was 1 percentage point less than the short, mid, slotted configuration, and 3 percentage points less than the solid casing reference.

SUMMARY OF RESULTS

A series of tests were conducted to determine the effects of a number of casing treatments on the overall performance of an axial-flow fan stage. The effectiveness was based on the increase in stall margin and on the ability to displace the stall line to lower flows. A solid casing, a teardrop casing, and eight variations of a skewed slot casing were evaluated. The following principal results were obtained:

1. The skewed slot casing with long, opened slots ahead of and over the front portion of the rotor blade displaced the stall line to the lowest flow at all speeds. At design speed the skewed slot casing with short, opened slots over the midportion of the rotor was equally as effective. The peak efficiency for the long, forward slots was 1 percentage point less than the short, midportion slots and 3 percentage points less than the solid reference casing.

2. For each skewed slot configuration, opened slots displaced the stall line to a lower flow than did the closed slots.

3. The stall margin for the opened, forward, long, skewed slot casing was 21.0 percent, while the solid casing had a stall margin of 15.0 percent. The opened, mid, short slots had the best stall margin of 23.5 percent.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, November 3, 1976,
505-04.

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TABLE I. - OVERALL PERFORMANCE FOR STAGE 8-8

(a) Casing treatment, solid

Reading	Percent speed	Flow, kg/sec	Pressure ratio	Temperature ratio	Adiabatic efficiency
0527	90.3	27.42	1.449	1.149	0.752
0528	90.2	26.85	1.517	1.158	0.799
0529	90.3	25.97	1.558	1.167	0.808
0530	90.2	24.81	1.578	1.175	0.797
0531	90.2	23.85	1.585	1.181	0.778
0532	100.2	29.58	1.588	1.189	0.749
0533	100.1	29.23	1.711	1.207	0.803
0534	100.0	28.30	1.748	1.217	0.798
0535	100.1	27.47	1.761	1.223	0.787
0536	100.0	26.66	1.757	1.227	0.769
0537	80.1	25.19	1.289	1.107	0.705
0538	80.2	24.24	1.364	1.117	0.794
0539	80.0	23.11	1.403	1.126	0.810
0540	80.1	21.53	1.421	1.134	0.788
0541	80.0	19.97	1.417	1.141	0.743
0542	70.0	22.88	1.174	1.073	0.641
0543	70.1	21.74	1.244	1.082	0.783
0544	70.1	20.36	1.280	1.091	0.800
0545	70.1	18.87	1.299	1.099	0.783
0546	70.0	17.37	1.303	1.105	0.749
0547	60.3	20.51	1.115	1.050	0.628
0548	60.2	19.21	1.161	1.057	0.762
0549	60.3	17.75	1.194	1.065	0.797
0550	60.2	16.16	1.213	1.072	0.785
0551	60.3	14.75	1.219	1.078	0.747
0552	50.0	17.63	1.070	1.033	0.601
0553	50.1	16.34	1.103	1.038	0.741
0554	50.1	15.15	1.123	1.043	0.782
0555	50.0	13.52	1.141	1.049	0.784
0556	50.0	12.08	1.148	1.054	0.743

(b) Casing treatment, short, closed, mid skewed slots

Reading	Percent speed	Flow, kg/sec	Pressure ratio	Temperature ratio	Adiabatic efficiency
0466	70.3	22.77	1.191	1.076	0.675
0467	70.4	21.78	1.251	1.085	0.780
0468	70.4	19.81	1.293	1.097	0.786
0469	70.4	17.53	1.311	1.109	0.736
0470	70.5	15.81	1.310	1.120	0.672
0471	100.1	24.96	1.761	1.248	0.707
0472	100.1	27.11	1.777	1.234	0.763
0473	100.0	28.72	1.728	1.216	0.785
0474	100.1	29.45	1.625	1.194	0.765
0475	100.2	29.55	1.538	1.188	0.698
0476	90.0	21.75	1.552	1.192	0.695
0477	90.1	23.57	1.590	1.188	0.756
0478	90.1	25.49	1.568	1.173	0.790
0479	89.9	26.79	1.498	1.156	0.782
0480	90.0	27.31	1.429	1.147	0.730
0481	79.8	24.99	1.303	1.107	0.732
0482	79.8	24.22	1.361	1.116	0.790
0483	79.8	22.66	1.408	1.129	0.795
0484	80.2	20.61	1.421	1.142	0.745
0485	80.1	18.12	1.408	1.154	0.669
0486	60.0	20.03	1.132	1.052	0.689
0487	60.1	18.73	1.172	1.060	0.775
0488	60.1	17.37	1.198	1.067	0.790
0489	60.0	15.25	1.219	1.077	0.752
0490	60.1	13.00	1.222	1.089	0.661
0491	50.0	17.35	1.079	1.034	0.641
0492	50.0	15.92	1.112	1.041	0.761
0493	49.9	14.29	1.134	1.047	0.781
0494	49.9	12.37	1.148	1.055	0.739
0495	49.9	10.55	1.151	1.062	0.657

TABLE I. - Continued.

(c) Casing treatment, short, opened, mid skewed slots

Reading	Percent speed	Flow, kg/flow	Pressure ratio	Temperature ratio	Adiabatic efficiency
0496	89.9	27.16	1.389	1.146	0.674
0497	89.9	26.51	1.516	1.159	0.793
0498	90.0	25.30	1.576	1.174	0.797
0499	90.1	23.48	1.589	1.186	0.759
0500	90.1	21.92	1.556	1.191	0.705
0501	100.1	29.46	1.541	1.188	0.699
0502	100.0	29.19	1.644	1.199	0.768
0503	99.8	28.34	1.735	1.216	0.788
0504	99.8	26.68	1.772	1.234	0.758
0506	99.6	24.70	1.748	1.245	0.706
0507	70.0	14.89	1.307	1.121	0.656
0508	70.2	17.58	1.311	1.108	0.748
0509	70.0	19.65	1.291	1.096	0.790
0510	70.1	21.50	1.251	1.085	0.777
0511	70.1	22.74	1.177	1.074	0.640
0512	80.1	17.68	1.406	1.154	0.663
0513	80.0	20.39	1.421	1.142	0.746
0514	80.3	22.61	1.420	1.132	0.797
0515	80.3	23.96	1.378	1.121	0.794
0516	80.4	25.07	1.289	1.108	0.694
0517	60.2	20.19	1.118	1.051	0.633
0518	60.0	18.53	1.172	1.061	0.767
0519	60.0	16.64	1.207	1.070	0.787
0520	59.8	14.43	1.222	1.080	0.736
0521	59.9	12.07	1.218	1.091	0.633
0522	50.0	17.45	1.073	1.034	0.597
0523	50.1	15.92	1.109	1.040	0.746
0524	50.0	14.16	1.135	1.047	0.782
0525	50.0	12.14	1.151	1.055	0.744
0526	50.1	9.80	1.150	1.065	0.627

(d) Casing treatment, short, opened, forward skewed slots

Reading	Percent speed	Flow, kg/sec	Pressure ratio	Temperature ratio	Adiabatic efficiency
0982	90.2	27.41	1.412	1.147	0.704
0983	90.2	27.09	1.492	1.154	0.785
0984	90.2	26.36	1.537	1.163	0.802
0985	90.3	25.54	1.569	1.172	0.798
0986	90.2	24.41	1.578	1.180	0.775
0987	90.2	23.78	1.573	1.182	0.759
0988	100.1	29.58	1.578	1.188	0.740
0989	100.1	29.42	1.631	1.194	0.772
0990	100.1	28.99	1.680	1.203	0.786
0991	100.0	28.41	1.711	1.211	0.787
0992	100.0	27.90	1.726	1.217	0.779
0993	100.0	27.60	1.725	1.219	0.770
0994	80.0	18.13	1.407	1.151	0.680
0995	79.8	25.04	1.282	1.107	0.692
0996	79.8	24.37	1.357	1.115	0.791
0997	79.8	23.44	1.392	1.123	0.803
0998	80.0	21.82	1.419	1.135	0.780
0999	80.0	20.07	1.418	1.142	0.738
1000	70.1	15.47	1.307	1.117	0.677
1001	70.0	22.91	1.173	1.073	0.638
1002	69.9	21.45	1.256	1.084	0.795
1003	70.0	19.60	1.295	1.097	0.792
1004	70.0	17.61	1.308	1.106	0.752
1005	59.8	12.61	1.219	1.088	0.662
1006	59.8	20.37	1.111	1.049	0.620
1007	59.8	18.76	1.170	1.058	0.786
1008	59.9	16.93	1.203	1.068	0.799
1009	59.9	14.99	1.219	1.077	0.756
1010	49.9	10.04	1.150	1.063	0.649
1011	49.9	17.62	1.071	1.033	0.607
1012	50.0	15.99	1.110	1.039	0.773
1013	50.0	14.26	1.135	1.046	0.801
1014	50.0	12.21	1.149	1.054	0.752

TABLE I. - *Continued.*

(e) Casing treatment, short, closed, forward skewed slots

Reading	Percent speed	Flow, kg/sec	Pressure ratio	Temperature ratio	Adiabatic efficiency
0948	89.8	27.35	1.387	1.146	0.671
0949	89.7	26.56	1.517	1.157	0.805
0950	89.7	25.53	1.560	1.168	0.808
0951	89.8	24.58	1.581	1.176	0.796
0952	89.8	23.63	1.586	1.182	0.775
0953	89.7	22.37	1.566	1.185	0.739
0954	89.7	21.07	1.543	1.189	0.698
0955	89.8	21.05	1.541	1.190	0.692
0956	100.0	29.58	1.550	1.187	0.712
0957	100.0	29.12	1.679	1.201	0.795
0958	99.9	28.30	1.725	1.212	0.796
0959	99.9	27.43	1.744	1.219	0.787
0960	99.6	26.57	1.737	1.221	0.772
0961	80.0	25.04	1.279	1.108	0.676
0962	80.1	23.87	1.385	1.121	0.810
0963	80.1	22.40	1.425	1.132	0.806
0964	80.0	20.73	1.428	1.140	0.768
0965	80.1	19.23	1.423	1.147	0.721
0966	79.8	17.75	1.405	1.153	0.667
0967	70.1	22.92	1.165	1.073	0.608
0968	70.0	21.34	1.259	1.086	0.795
0969	70.0	19.65	1.296	1.096	0.801
0970	70.0	17.44	1.312	1.107	0.753
0971	69.9	15.08	1.306	1.120	0.664
0972	59.9	20.29	1.119	1.050	0.651
0973	59.9	18.58	1.171	1.059	0.784
0974	60.0	16.85	1.205	1.069	0.797
0975	60.0	14.62	1.223	1.079	0.748
0976	60.0	12.28	1.221	1.090	0.652
0977	50.3	17.70	1.074	1.033	0.621
0978	50.2	15.90	1.111	1.040	0.772
0979	50.3	14.11	1.138	1.047	0.796
0980	50.3	12.16	1.152	1.055	0.753
0981	50.3	9.83	1.152	1.065	0.637

(f) Casing treatment, medium, opened, forward skewed slots

Reading	Percent speed	Flow, kg/sec	Pressure ratio	Temperature ratio	Adiabatic efficiency
1080	90.4	23.53	1.560	1.183	0.741
1081	90.5	24.63	1.573	1.178	0.778
1082	90.4	25.85	1.541	1.168	0.785
1083	90.5	26.91	1.474	1.153	0.764
1084	90.5	27.30	1.344	1.147	0.599
1085	80.0	17.15	1.406	1.163	0.627
1086	79.8	19.35	1.425	1.150	0.712
1087	79.9	21.57	1.425	1.137	0.776
1088	79.9	23.86	1.369	1.119	0.787
1089	79.9	25.00	1.242	1.106	0.604
1090	70.2	14.21	1.306	1.132	0.603
1091	70.3	17.26	1.316	1.112	0.728
1092	70.3	19.40	1.301	1.100	0.778
1093	70.3	21.43	1.257	1.087	0.776
1094	70.4	23.00	1.167	1.074	0.614
1095	60.0	11.26	1.217	1.099	0.581
1096	59.9	14.33	1.225	1.083	0.720
1097	59.8	16.76	1.203	1.070	0.775
1098	60.0	18.65	1.171	1.060	0.770
1099	59.7	20.23	1.111	1.049	0.624
1100	49.9	8.89	1.146	1.071	0.558
1101	49.7	12.00	1.150	1.056	0.730
1102	49.9	14.37	1.132	1.046	0.778
1103	49.8	16.12	1.104	1.038	0.748
1104	49.9	17.53	1.069	1.032	0.593
1105	100.1	26.82	1.720	1.221	0.758
1106	100.2	27.83	1.700	1.211	0.776
1107	100.2	28.62	1.651	1.199	0.775
1108	100.4	29.25	1.566	1.186	0.733
1109	100.4	29.31	1.390	1.184	0.538

TABLE I. - Continued.

(g) Casing treatment, medium, closed, forward skewed slots

Reading	Percent speed	Flow, kg/sec	Pressure ratio	Temperature ratio	Adiabatic efficiency
1050	90.3	27.20	1.336	1.146	0.591
1051	89.8	25.70	1.528	1.165	0.783
1052	89.9	24.09	1.561	1.177	0.766
1053	89.9	22.38	1.555	1.187	0.721
1054	90.0	20.02	1.529	1.199	0.648
1055	79.9	24.97	1.258	1.106	0.638
1056	79.8	23.30	1.385	1.123	0.790
1057	79.9	21.43	1.419	1.136	0.772
1058	79.8	19.30	1.414	1.146	0.713
1059	79.8	16.57	1.395	1.161	0.618
1060	70.0	22.78	1.159	1.072	0.595
1061	70.0	20.95	1.264	1.088	0.791
1062	70.2	19.00	1.300	1.100	0.775
1063	70.1	16.73	1.308	1.111	0.720
1064	70.0	14.51	1.302	1.124	0.632
1065	59.5	20.13	1.109	1.048	0.619
1066	59.5	18.31	1.171	1.059	0.781
1067	59.3	16.38	1.202	1.069	0.781
1068	59.4	14.02	1.217	1.080	0.720
1069	59.4	11.60	1.213	1.093	0.614
1070	50.2	17.59	1.070	1.033	0.598
1071	50.1	15.85	1.112	1.040	0.770
1072	50.0	13.99	1.137	1.048	0.786
1073	50.1	12.12	1.150	1.055	0.735
1074	50.2	9.99	1.151	1.065	0.633
1075	99.5	29.10	1.353	1.179	0.504
1076	99.5	28.23	1.654	1.201	0.768
1077	99.6	27.24	1.696	1.214	0.761
1078	99.6	25.99	1.712	1.222	0.747
1079	99.7	24.99	1.728	1.234	0.724

(h) Casing treatment, long, opened, forward skewed slots

Reading	Percent speed	Flow, kg/sec	Pressure ratio	Temperature ratio	Adiabatic efficiency
1146	50.0	17.58	1.067	1.032	0.581
1147	50.1	15.87	1.109	1.040	0.755
1148	50.0	13.88	1.137	1.049	0.763
1149	49.9	11.29	1.153	1.060	0.694
1150	50.0	8.57	1.144	1.074	0.529
1151	60.1	20.32	1.112	1.049	0.622
1152	60.1	18.50	1.169	1.059	0.766
1153	60.1	16.75	1.206	1.071	0.777
1154	60.2	13.84	1.229	1.087	0.692
1155	60.1	11.22	1.219	1.103	0.563
1156	70.1	22.79	1.168	1.073	0.625
1157	70.1	21.61	1.241	1.083	0.766
1158	70.1	20.28	1.283	1.094	0.787
1159	70.1	18.30	1.313	1.106	0.761
1160	70.3	15.73	1.318	1.122	0.669
1161	70.2	13.55	1.304	1.138	0.570
1162	80.2	25.04	1.235	1.106	0.584
1163	80.2	23.83	1.371	1.120	0.789
1164	80.3	22.32	1.422	1.134	0.792
1165	80.3	20.45	1.437	1.146	0.748
1166	80.3	18.75	1.429	1.157	0.685
1167	80.2	16.93	1.411	1.168	0.616
1168	90.0	27.09	1.339	1.144	0.604
1169	90.1	26.78	1.464	1.151	0.763
1170	90.0	25.82	1.530	1.164	0.788
1171	90.1	24.43	1.568	1.177	0.776
1172	90.1	23.14	1.581	1.185	0.755
1173	90.1	22.18	1.569	1.193	0.713
1174	100.1	29.25	1.388	1.183	0.536
1175	100.1	29.15	1.580	1.188	0.743
1176	100.0	28.28	1.670	1.204	0.775
1177	100.0	27.12	1.696	1.214	0.760
1178	100.0	26.18	1.713	1.222	0.748

TABLE I. - Concluded.

(i) Casing treatment, long, closed, forward skewed slots

Reading	Percent speed	Flow, kg/sec	Pressure ratio	Temperature ratio	Adiabatic efficiency
1110	90.5	27.21	1.359	1.145	0.632
1111	90.2	26.11	1.513	1.159	0.790
1112	90.2	25.24	1.550	1.168	0.797
1113	90.2	23.92	1.577	1.177	0.784
1114	90.2	22.39	1.577	1.188	0.740
1115	90.1	21.04	1.553	1.197	0.681
1116	90.2	19.48	1.529	1.207	0.624
1117	100.2	29.22	1.534	1.185	0.704
1118	100.2	28.35	1.666	1.202	0.777
1119	100.1	27.08	1.721	1.216	0.776
1120	100.1	25.75	1.732	1.228	0.746
1121	100.1	24.65	1.725	1.236	0.715
1122	80.2	24.96	1.245	1.106	0.611
1123	80.1	23.73	1.367	1.118	0.792
1124	80.1	22.13	1.416	1.131	0.795
1125	80.0	20.55	1.425	1.140	0.760
1126	80.3	18.85	1.422	1.151	0.701
1127	80.2	17.43	1.408	1.159	0.646
1128	80.3	15.74	1.394	1.173	0.575
1129	70.1	22.76	1.165	1.072	0.614
1130	70.1	21.25	1.249	1.085	0.776
1131	70.1	19.69	1.289	1.095	0.790
1132	70.2	17.96	1.308	1.105	0.759
1133	70.1	15.44	1.307	1.119	0.669
1134	70.1	12.95	1.295	1.138	0.553
1135	60.1	20.28	1.107	1.049	0.605
1136	60.2	18.93	1.160	1.057	0.757
1137	60.2	17.16	1.198	1.067	0.788
1138	60.1	15.08	1.220	1.077	0.756
1139	60.1	13.07	1.223	1.088	0.672
1140	60.2	10.73	1.213	1.103	0.548
1141	49.9	17.49	1.066	1.032	0.571
1142	50.0	15.87	1.105	1.039	0.747
1143	49.9	13.79	1.135	1.047	0.778
1144	50.0	11.51	1.150	1.057	0.719
1145	49.8	8.78	1.144	1.071	0.555

(j) Casing treatment, teardrop

Reading	Percent speed	Flow, kg/sec	Pressure ratio	Temperature ratio	Adiabatic efficiency
1179	90.0	27.10	1.406	1.143	0.713
1180	89.9	25.96	1.494	1.155	0.785
1181	90.0	24.75	1.508	1.161	0.774
1182	89.9	23.57	1.509	1.165	0.755
1183	90.0	22.43	1.501	1.170	0.726
1184	100.2	29.32	1.546	1.184	0.720
1185	100.0	28.42	1.639	1.197	0.770
1186	100.1	27.29	1.634	1.201	0.750
1187	100.2	26.25	1.636	1.206	0.731
1188	100.2	24.99	1.626	1.212	0.704
1189	79.9	24.94	1.264	1.105	0.662
1190	80.0	23.84	1.360	1.116	0.792
1191	79.9	22.54	1.389	1.124	0.794
1192	79.9	21.09	1.395	1.130	0.768
1193	79.9	19.44	1.389	1.135	0.727
1194	69.9	22.74	1.171	1.072	0.640
1195	70.1	21.26	1.250	1.084	0.785
1196	70.0	19.67	1.282	1.093	0.793
1197	69.9	18.01	1.292	1.099	0.764
1198	70.0	16.45	1.289	1.105	0.717
1199	60.0	20.26	1.114	1.049	0.635
1200	59.9	18.89	1.160	1.057	0.765
1201	59.8	17.53	1.189	1.064	0.797
1202	59.8	15.68	1.207	1.071	0.778
1203	59.8	13.71	1.208	1.077	0.717
1204	49.9	17.39	1.072	1.032	0.618
1205	49.9	16.15	1.103	1.038	0.755
1206	50.0	14.74	1.125	1.043	0.791
1207	49.9	13.29	1.139	1.048	0.781
1208	49.8	11.53	1.143	1.053	0.731

TABLE II. - EFFICIENCY COMPARISON

Casing	Percent stall margin	Peak efficiency
Solid	15.0	0.803
Skewed, short, mid, opened	23.5	.785
Skewed, short, mid, closed	23.4	.785
Skewed, short, forward, opened	16.0	.796
Skewed, short, forward, closed	10.9	.787
Skewed, medium, forward, opened	19.9	.768
Skewed, medium, forward, closed	10.6	.776
Skewed, long, forward, opened	21.0	.777
Skewed, long, forward, closed	13.0	.775

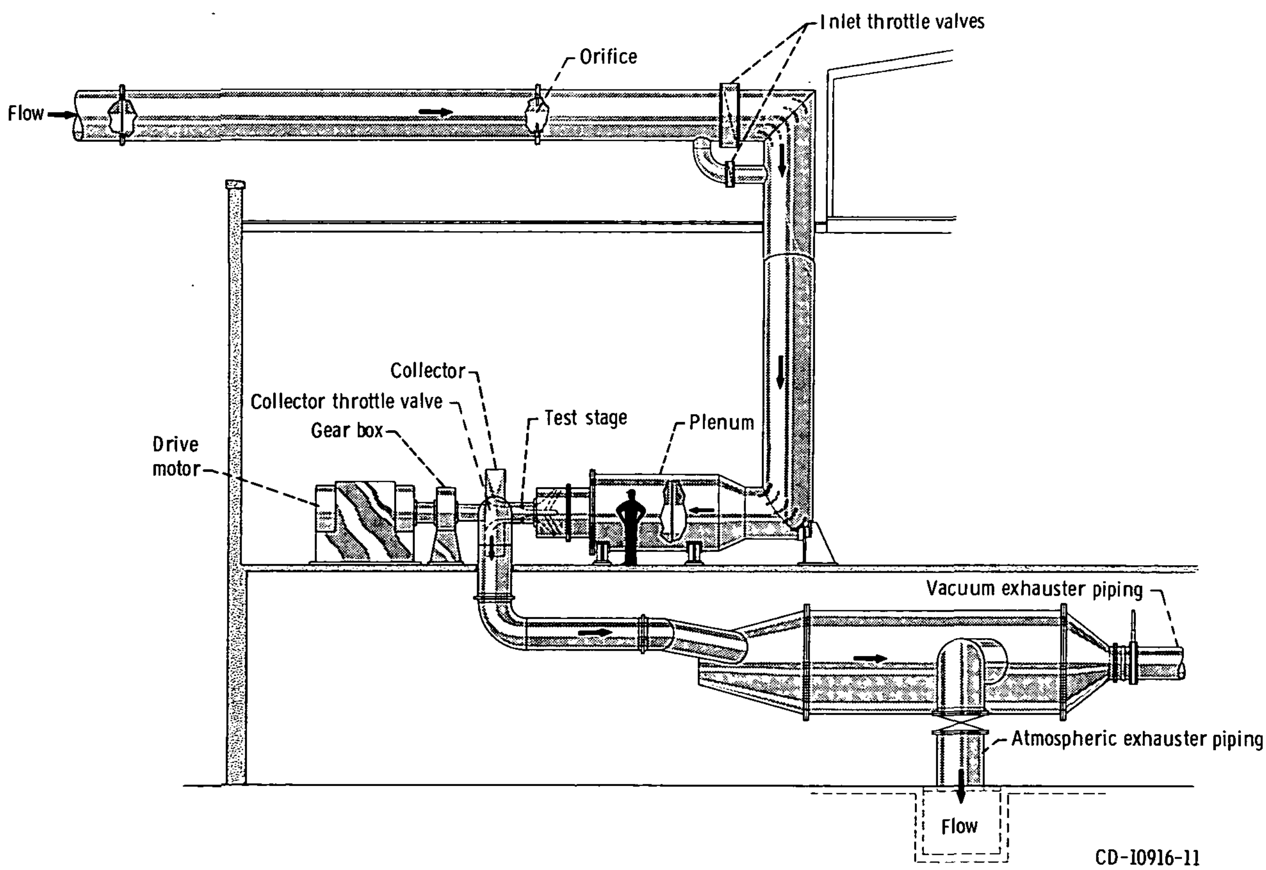
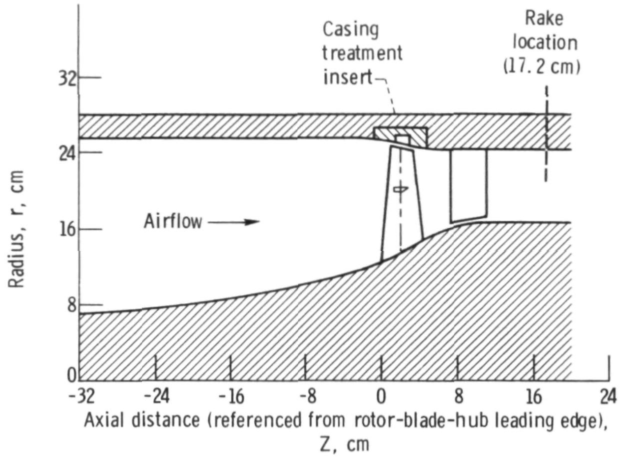


Figure 1. - Compressor test facility.



Flow path coordinates		
Axial distance, Z, cm	Radius, r, cm	
	Inner	Outer
-30.480	7.303	25.400
-25.400	7.493	↓
-22.860	7.874	
-20.320	8.255	
-15.240	9.144	
-10.160	10.097	
-5.080	10.922	
-2.540	11.659	
0	12.668	25.273
4.572	14.605	24.511
6.096	15.240	24.397
7.620	15.748	24.384
11.176	16.510	↓
13.462	↓	
15.240		
20.320		

Figure 2. - Flow path for stage 8-8.

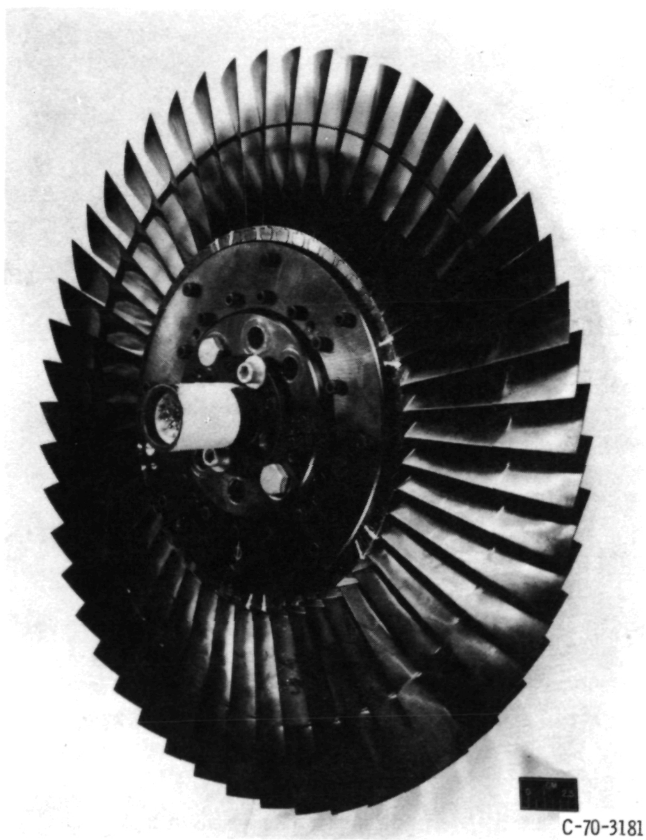


Figure 3. - Rotor 8.

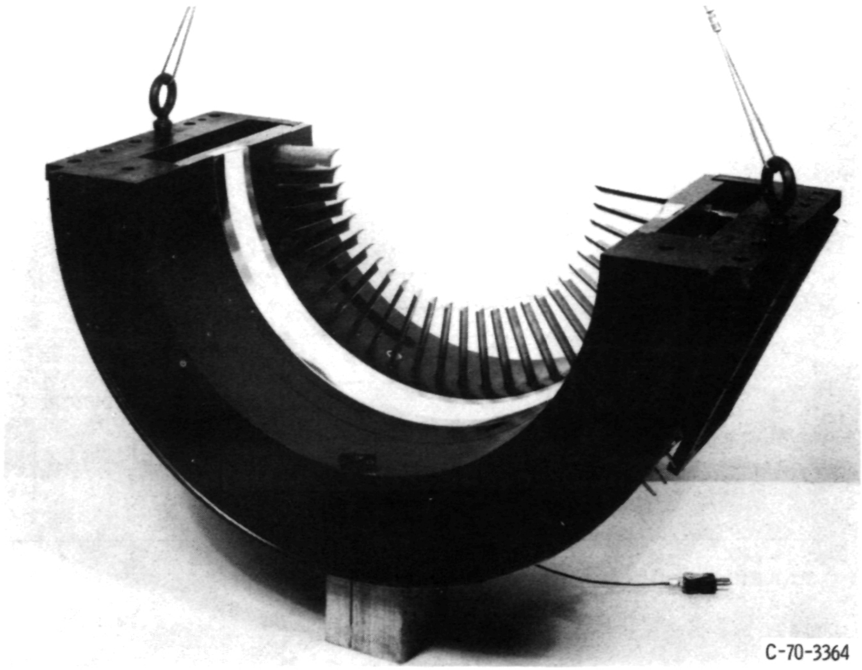


Figure 4. - Stator 8.

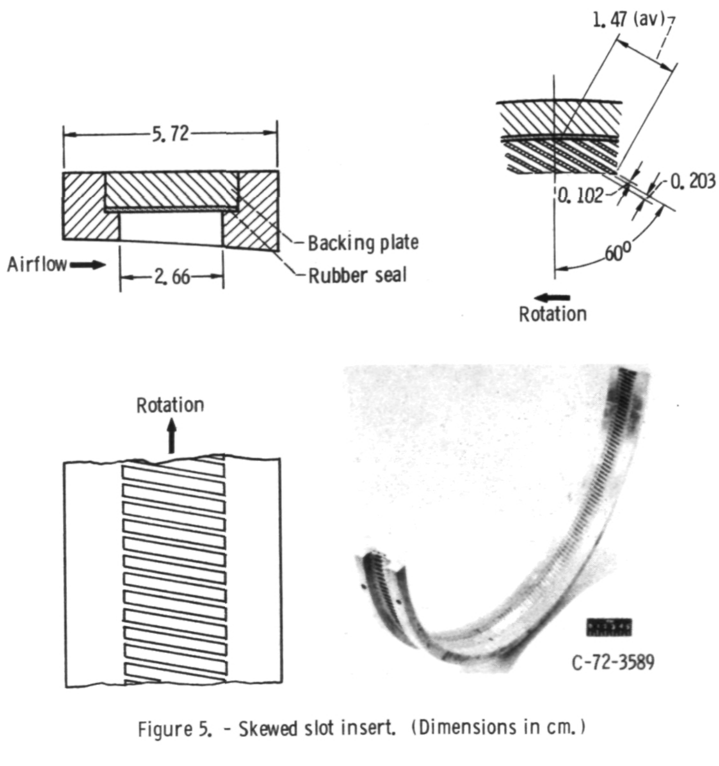


Figure 5. - Skewed slot insert. (Dimensions in cm.)

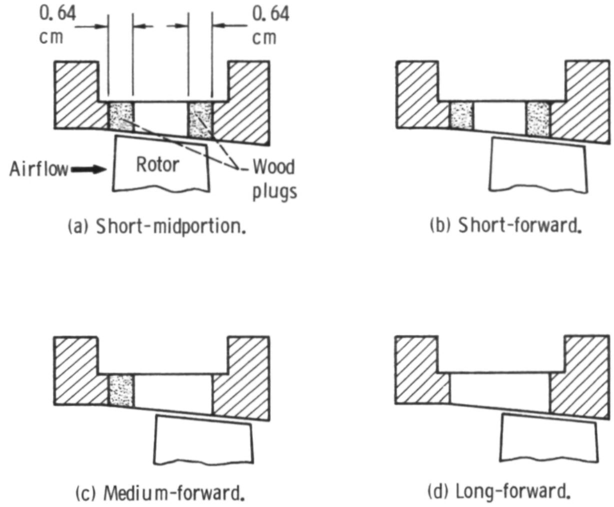


Figure 6. - Skewed slot insert configurations (also tested with backing plate).

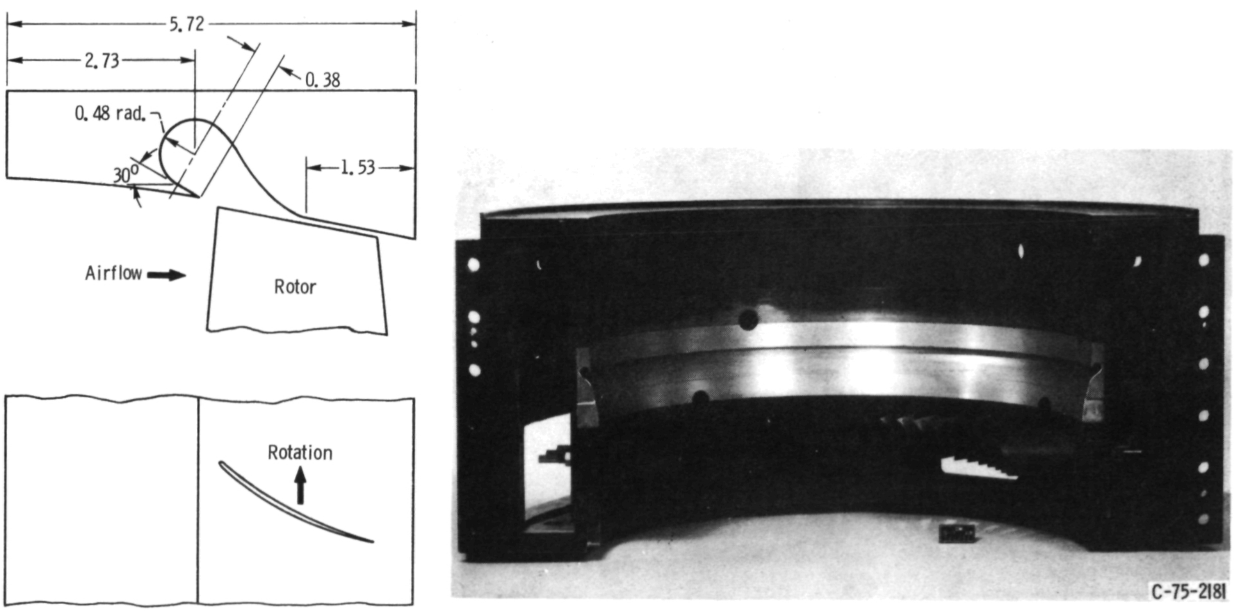


Figure 7. - Teardrop insert. (All linear dimensions are in cm.)

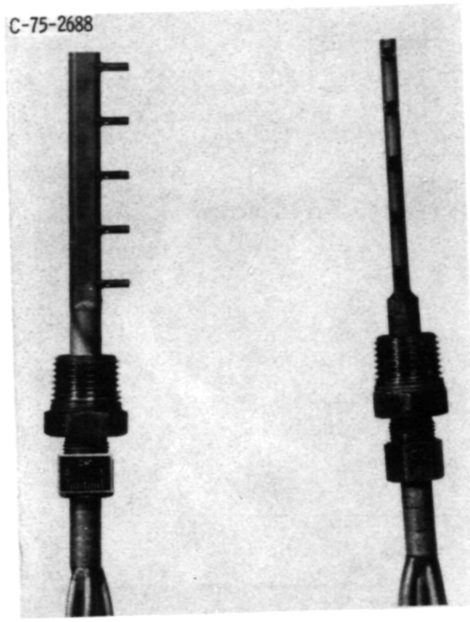
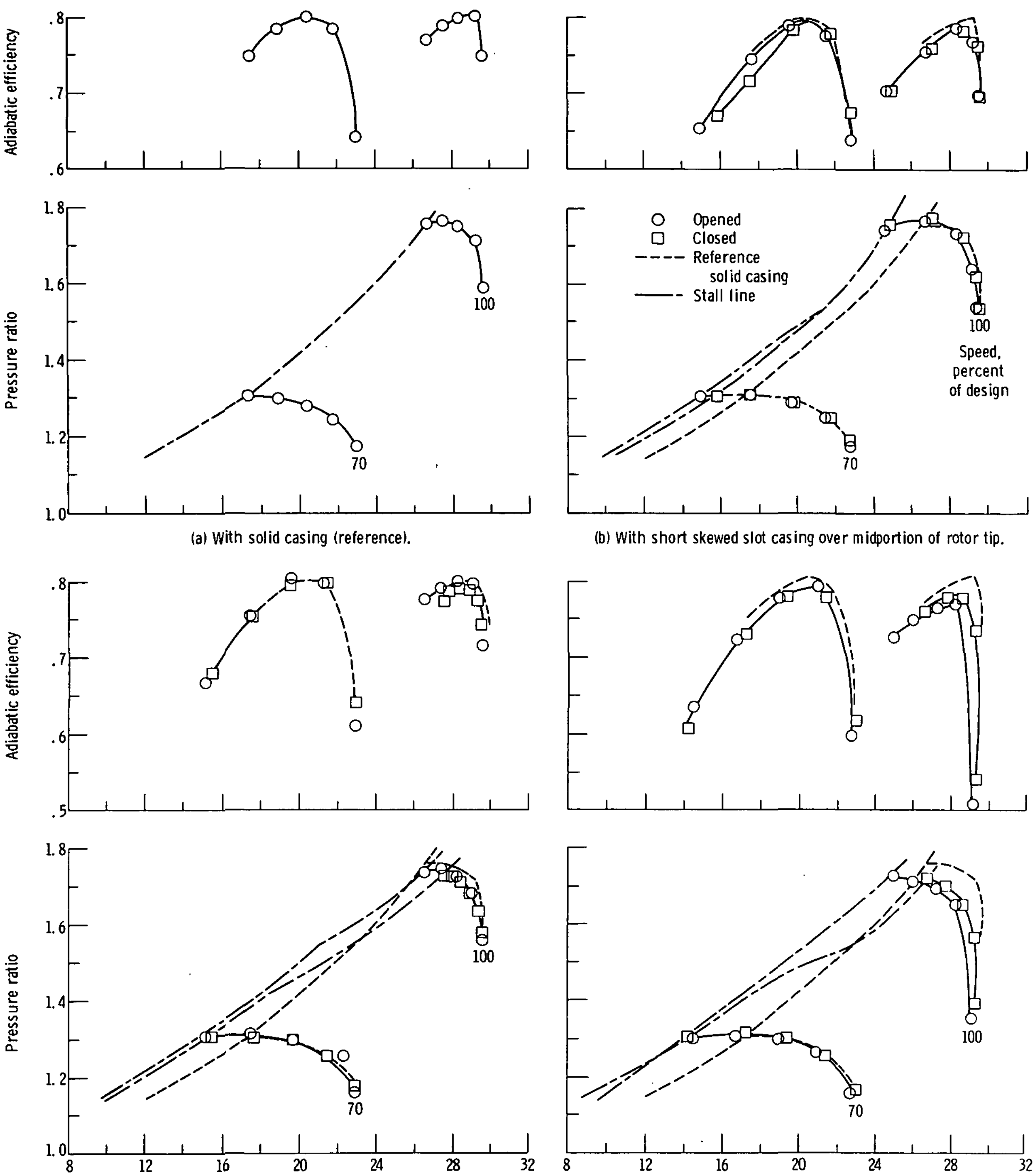


Figure 8. - Total-pressure - total-temperature rake.



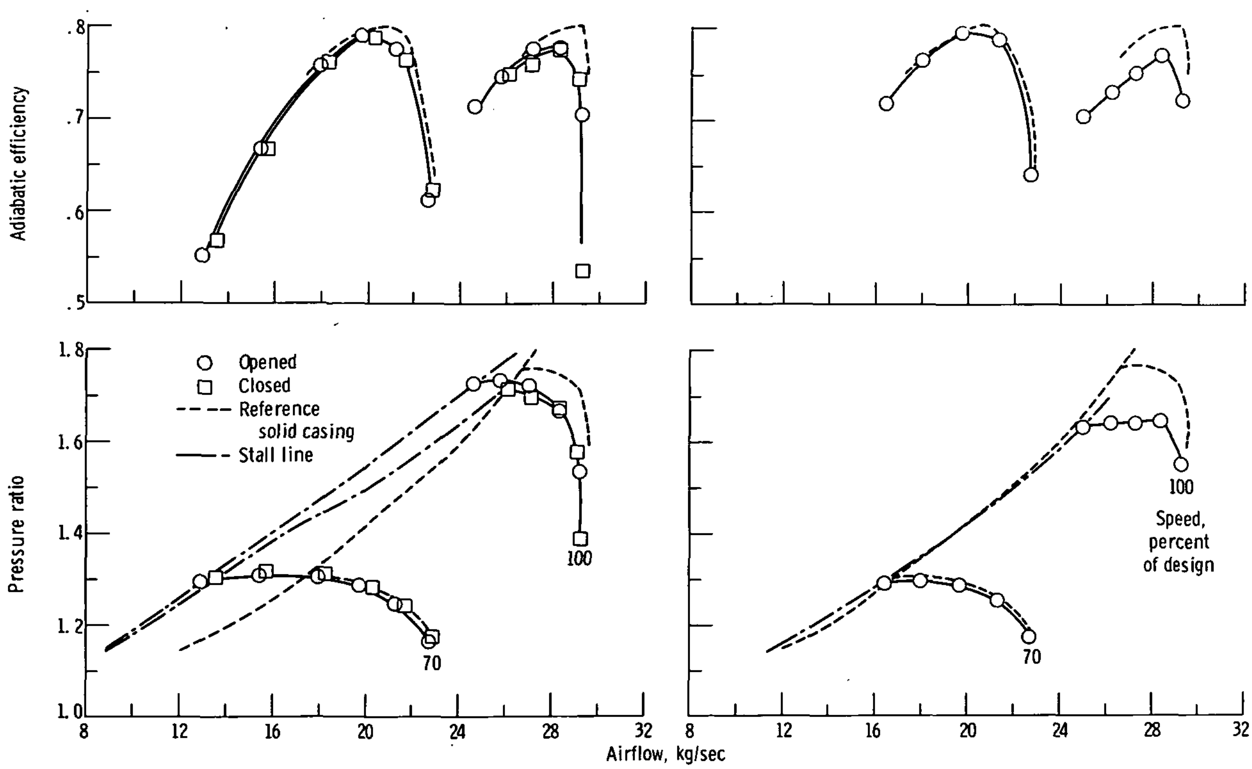
(a) With solid casing (reference).

(b) With short skewed slot casing over midportion of rotor tip.

(c) With short skewed slot casing over forward portion of rotor tip.

(d) With medium skewed slot casing over forward portion of rotor tip.

Figure 9. - Overall performance for stage 8-8.



(e) With long skewed slot casing over forward portion of rotor tip.

(f) With teardrop casing.

Figure 9. - Concluded.

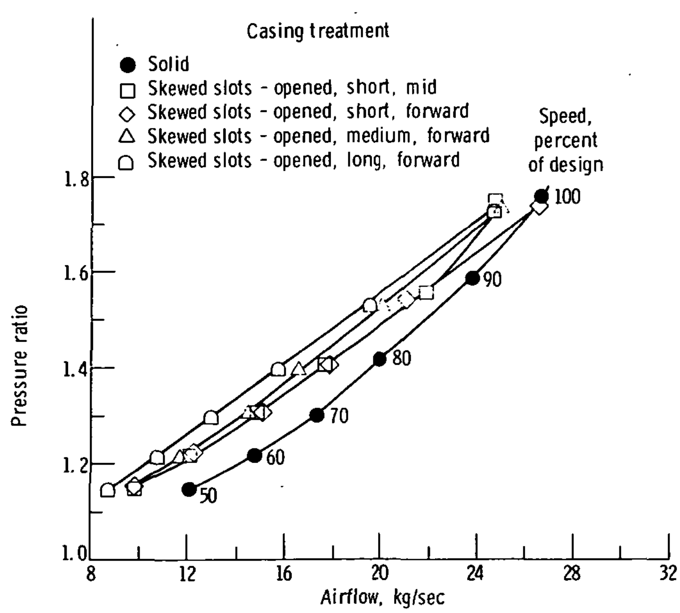


Figure 10. - Effect of casing treatment on stall line for stage 8-8.

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