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I - SHOCK DIFFUSER WITH TRIPLE-SHOCK PROJECTING CONE

By J. F. Connors and A. H. Schroeder

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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SUMMARY

A preliminary investigation was conducted in the NACA Cleveland 20-inch supersonic tunnel at a Mach number of 1.92 with a 3.6-inch-diameter ram jet to determine the effects of combustion on the performance of a shock diffuser with a triple-shock projecting cone. Results are presented for a range of outlet areas and fuel flows with both single- and split-fuel-injection systems.

The peak total-pressure recovery obtained by varying the outlet area decreased from 0.91 of the free-stream total pressure for a fuel flow of 40 pounds per hour (fuel-air ratio, approximately 0.02) to 0.67 for a fuel flow of 100 pounds per hour (fuel-air ratio, approximately 0.05) compared with a peak of 0.92 without combustion. For a given outlet-inlet area ratio, the same peak total-pressure recovery was obtained for both single- and split-fuel-injection systems.

The phenomenon of decreasing peak total-pressure recoveries is attributed to an oscillation of the diffuser normal shock, initiated by pressure pulsations from the combustion process. Observations of the flame in the combustion chamber and the shock pattern at the diffuser inlet indicated an unsteady flow condition when the fuel flow was increased or the outlet area was decreased from the values at the peak total-pressure recovery. With the outlet area adjusted to maintain a constant total-pressure recovery, combustion produced little or no effect on the Mach number distribution at the diffuser outlet.

INTRODUCTION

The efficient conversion of the kinetic energy of a supersonic air stream into pressure at the combustion chamber of ram jets has been the objective of many comprehensive investigations (references 1 to 9). At the NACA Cleveland laboratory, extensive studies have been conducted in the 18- by 18-inch supersonic tunnel at a Mach number of 1.85 with three types of supersonic diffuser: (1) the convergent-divergent diffuser (reference 1), (2) the shock diffuser (references 2 to 5), and (3) the perforated diffuser (reference 6). These investigations, conducted as cold runs at one Mach number, utilized a movable conical damper at the end of a simulated combustion chamber to vary the back pressure on the diffuser and thereby vary the location of the normal shock in a manner similar to that expected with combustion. No experimental evidence is available, however, that shows how an actual combustion process in a ram jet influences the operation of a supersonic diffuser.

A study was therefore conducted with a 3.6-inch-diameter ram jet in the NACA Cleveland 20-inch supersonic tunnel to determine the effects of combustion on the total-pressure recovery and the Mach number distribution of a shock diffuser. No attempt was made to evaluate the combustion performance of the engine.

APPARATUS AND PROCEDURE

The supersonic flow was produced in the 20-inch supersonic tunnel, a circular single-pass suction wind tunnel. The inlet air passed through an air-drier bed of activated alumina and over a series of electric heater elements. A test-section calibration survey at the inlet of the 3.6-inch-diameter ram-jet model showed that the tunnel operated at a Mach number of 1.92 ± 0.04. Throughout the investigation dry heated air was maintained at a dew point of $-15^\circ \pm 10^\circ$ F and a total temperature of $220^\circ \pm 5^\circ$ F.

A schematic diagram of the experimental model is shown in figure 1(a). The diffuser combination, which was the same as that reported in reference 4 (configuration A; tip projection, 1.50 in.), consisted of a triple-shock cone (30° -50° -60°) with a curved inlet and a 5° subsonic diffuser (inlet area without cone, 3.14 sq in.).

The combustion chamber was a straight pipe section 3.6 inches in diameter and 24.5 inches long. A spark plug ignited the acetylene pilot in the small solid cone at the center of a perforated conical flame holder (fig. 1(b)). This acetylene-gas pilot system was necessary to initiate and maintain combustion. The main fuel was unleaded 62-octane gasoline.

A single- and a split-fuel-injection system were used. In the first system, the fuel was injected upstream from a 12-gallon-per-hour diffusing spray nozzle (rated at 100 lb/sq in. gage) in the subsonic diffuser. In the second system, fuel supplied from a common manifold was injected both upstream from a 10.5-gallon-per-hour diffusing spray nozzle (rated at 100 lb/sq in. gage) in the subsonic diffuser and downstream through four 0.013-inch-diameter orifices on a circular fuel-spray bar at the flame holder. The split-fuel-injection system was designed to increase the range of fuel flows. Cold pressure measurements showed a static-pressure drop across the flame holder of approximately 0.6 the combustion-chamber dynamic pressure.

A variable-outlet-area nozzle (fig. 1 (c)) was located at the end of the combustion chamber. This device consisted of two spherical flaps that pivoted on a common axis. The projected area was measured for various positions of the flaps to estimate the values of outlet area.

A rake of 20 pitot-static tubes (fig. 1(d)) was used to obtain the pressure measurements at the combustion-chamber inlet from which values of total-pressure recovery and Mach number were calculated. All pressures were photographically recorded on a multiple-tube manometer board using tetrabromoethane as the working fluid.

A shadowgraph was installed in the tunnel to allow observation of the shock pattern at the diffuser inlet.

Runs without combustion were conducted as in references 1 to 6; that is, the total-pressure recovery was determined as a function of outlet-inlet area ratio.

Combustion studies were conducted: (1) with a constant outlet area to determine the effects of a variable fuel flow on the diffuser performance, and (2) with a variable outlet area to evaluate the diffuser performance with a constant fuel flow (that is, a constant fuel-air ratio with supersonic flow into the inlet). The air flow with the normal shock inside the diffuser was approximately 2090 pounds per hour.

RESULTS AND DISCUSSION

Symbols

The following symbols are used in this discussion:

A_i diffuser-inlet area with cone removed

A_4 projected ram-jet-outlet nozzle area normal to free stream

M_3 Mach number at diffuser outlet (combustion-chamber inlet)

P_0 free-stream total pressure

P_3 total pressure at diffuser outlet (combustion-chamber inlet)

W_f fuel flow, pounds per hour

Diffuser Performance without Combustion

The variation of total-pressure recovery P_3/P_0 with outlet-inlet area ratio A_4/A_1 for a shock diffuser with a triple-shock projecting cone at a Mach number of 1.92 is shown in figure 2. A peak P_3/P_0 of 0.92 was obtained. A similar curve is presented in reference 4 for the same diffuser combination at a Mach number of 1.85. At a Mach number of 1.85, a peak P_3/P_0 of 0.95 was obtained. The lower P_3/P_0 at a Mach number of 1.92 is attributed to the increased shock losses at the higher Mach number. This diffuser performance curve obtained without combustion is compared with the results obtained with combustion.

In order to determine the effect of fuel injection on the diffuser total-pressure recovery, cold runs were also conducted in which fuel was injected at varying flow rates in the subsonic part of the diffuser. No noticeable change in total-pressure recovery resulted.

Combustion with Constant Outlet-Inlet Area Ratio

In order to simulate a ram jet with a fixed-outlet-area nozzle, the effect of varying the fuel flow (or fuel-air ratio when supersonic flow is established in the inlet) on the total-pressure recovery of the diffuser was investigated for several values of outlet area. One-dimensional analysis indicates that if the normal shock is located in the subsonic diffuser, addition of heat to the combustion chamber moves the shock toward the throat and increases the total-pressure recovery. With increased heating, the peak cold total-pressure recovery is reached and then decreases as the shock is forced ahead of the inlet.

The experimentally determined variation of total-pressure recovery as a function of fuel flow is presented in figure 3 for several outlet-inlet area ratios and for the two systems of fuel injection. The trends of the curves for both the single- and split-fuel-injection systems are similar. For each outlet-inlet area ratio, a peak total-pressure recovery with respect to fuel flow occurs. This peak decreases with increasing outlet-inlet area ratio. The peak cold total-pressure recovery was not realized with combustion.

This phenomenon of decreasing peak total-pressure recovery with increasing outlet-inlet area ratio cannot be attributed to an insufficient heat release because of two observations: (a) The peak total-pressure recovery occurs at different fuel flows (and hence at different fuel-air ratios) for each of the outlet-inlet area ratios; and (b) the peak total-pressure recoveries for each fuel-injection system occur at about the same fuel flow for a given outlet-inlet area ratio. Shadowgraph observations showed that the air flow through the inlet was oscillatory for fuel flows greater than the peak values.

For a given outlet-inlet area ratio the small rise in total-pressure recovery above the cold-run value shown in figure 3 indicates very little heat addition from the combustion process. An estimated maximum value of 1.5 was obtained for the total-temperature ratio across the combustion chamber.

Combustion with Constant Fuel Flow

The diffuser performance of a ram jet with a variable-outlet-area nozzle was investigated at five constant fuel flows over the range of outlet-inlet area ratios. The results and the reference curve (without combustion) are shown in figure 4. The trends of the curves for both single- and split-fuel-injection systems are similar. At each fuel flow, P_3/P_0 increased to a peak value as A_4/A_1 decreased from the maximum position for which combustion could be maintained. With further decrease in A_4/A_1, P_3/P_0 decreased and dropped below the reference curve. Combustion was rough and unstable when A_4/A_1 was less than the value at the peak P_3/P_0. At increasing values of fuel flow, the curves of total-pressure recovery (fig. 4) are shifted vertically upward for a given A_4/A_1, as might be theoretically expected with the increased temperature rise from the combustion process. Contrary to theoretical predictions, the peak total-pressure recovery obtained with combustion at constant fuel flow did not remain constant, but decreased with increasing values of fuel flow. The peak total-pressure recoveries varied from 0.91 of the free-stream total-pressure at a fuel flow of 40 pounds per hour (fuel-air ratio, approximately 0.02) to 0.67 at a fuel flow of 100 pounds per hour (fuel-air ratio, approximately 0.05).

Diffuser Performance with Combustion

A summary of the peak total-pressure recoveries shown in figures 3 and 4 is given in figure 5 as a function of outlet-inlet area ratio. The peak total-pressure recoveries form one curve for both single- and split-fuel-injection systems operating under conditions of either constant outlet area or constant fuel flow. The peak total-pressure recoveries decreased rapidly with increasing outlet-inlet area ratios rather than remaining constant. This phenomenon is believed caused by a high-frequency oscillation of the normal shock initiated by pressure pulsations that result from a coupled unsteady combustion process. Transient explosions might force the normal shock ahead of the inlet with a resulting decrease in the mass-flow rate into the engine. The fuel-air ratio would thereby increase and momentary blow-out might result until the shock reenters.

Any oscillation or movement of the shock from its optimum steady-state position lowers the mean total-pressure recovery. During the oscillatory cycle, the recorded maximum total-pressure recovery may be expected to lie somewhere between the optimum cold value and the cold value for the given outlet-area setting. Under such conditions, increasing the outlet area would lower the cold total-pressure recovery for the given outlet setting and hence would result in a lowered peak recovery with combustion in accordance with figure 5.

Rough and unstable combustion was observed when the fuel flow was increased or the outlet area was decreased from peak values of figures 3 and 4. A simple shadowgraph simultaneously indicated a vibratory shock pattern at the inlet.

Mach Number Distribution at Diffuser Outlet

The effect of combustion on the Mach number distribution at the diffuser outlet with and without combustion is shown in figure 6 under conditions of constant P_3/P_0 and constant A_4/A_1. The variation of combustion-chamber Mach number M_3 with and without combustion is presented in figure 6(a) for a P_3/P_0 of 0.91 for the single-fuel-injection system and in figure 6(b) for a P_3/P_0 of 0.79 for the split-fuel-injection system. The curves indicate that combustion had very little effect on the Mach number distribution when a constant total-pressure recovery was maintained in the diffuser.

The effect of combustion on Mach number distributions is shown in figure 6(c) for an A_4/A_1 of 0.49 for the single-fuel-injection system and in figure 6(d) for an A_4/A_1 of 0.71 for the split-fuel-injection system. At constant values of A_4/A_1 and with values of P_3/P_0 in the supercritical region the curves obtained with combustion indicate a more uniform Mach number distribution than that obtained without combustion. This more uniform Mach number distribution is accompanied by a reduction in the average M_3 and a corresponding increase in P_3/P_0. These results indicate that, with a fixed-outlet-area nozzle, combustion changes the Mach number distribution through its effect on total-pressure recovery.

SUMMARY OF RESULTS

From an investigation to determine the effects on combustion in a 3.6-inch-diameter ram jet on the performance of a shock diffuser with a triple-shock projecting cone at a Mach number of 1.92, the following results were obtained:

1. Contrary to theoretical expectations, the peak total-pressure recoveries obtained with combustion by varying the outlet area decreased from 0.91 of the free-stream total pressure at a fuel flow of 40 pounds per hour (fuel-air ratio, approximately 0.02) to 0.67 at a fuel flow of 100 pounds per hour (fuel-air ratio, approximately 0.05), as compared with a peak of 0.92 without combustion.

2. At a given outlet-inlet area ratio, the same peak total-pressure recovery was obtained for both single- and split-fuel-injection systems.

3. The phenomenon of decreasing peak total-pressure recoveries is attributed to an oscillation of the normal shock, initiated by pressure pulsations from the combustion process. Observations of the flame in the combustion chamber and the shock pattern at the diffuser inlet indicated an unsteady flow condition when the fuel flow was increased or the outlet area was decreased from the values at the peak total-pressure recovery.

4. With the outlet area adjusted to maintain a constant total-pressure recovery, combustion produced little or no effect on the Mach number distribution at the diffuser outlet.

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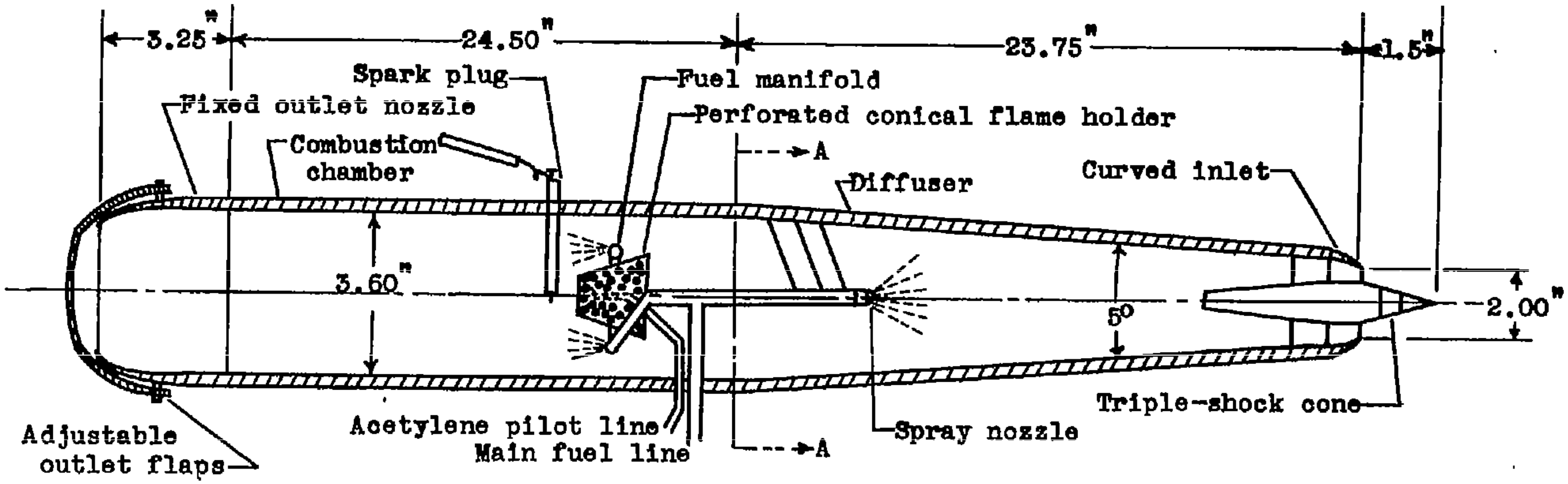
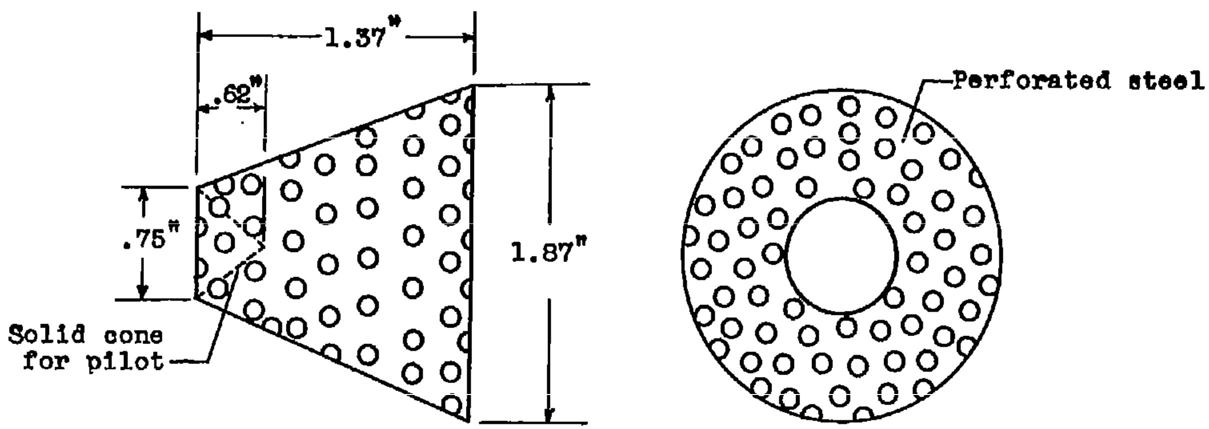
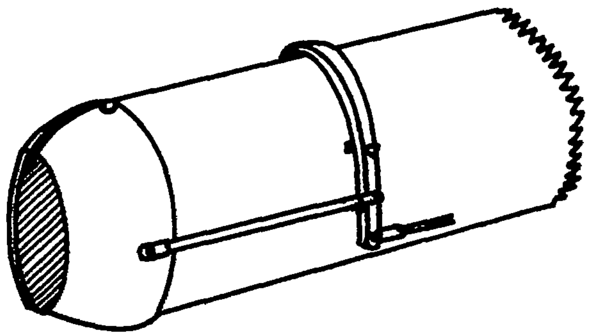


(a) Schematic diagram showing component parts.

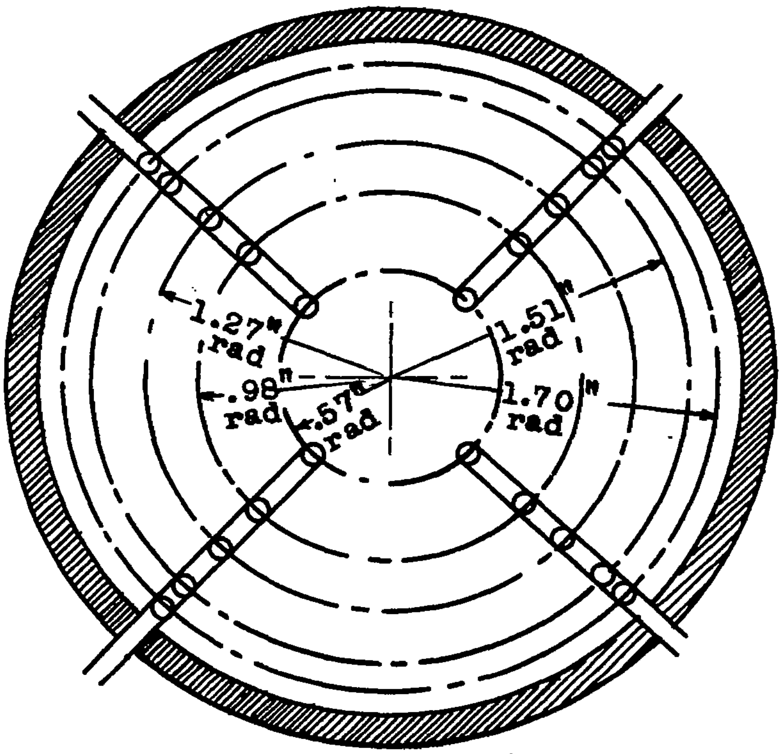


(b) Flame-holder details.

Figure 1. - Experimental ram-jet model.



(c) Variable-outlet-area nozzle.



(d) Pitot-static survey rake located at cross-section A-A (fig. 1(a)).

Figure 1. - Concluded. Experimental ram-jet model.

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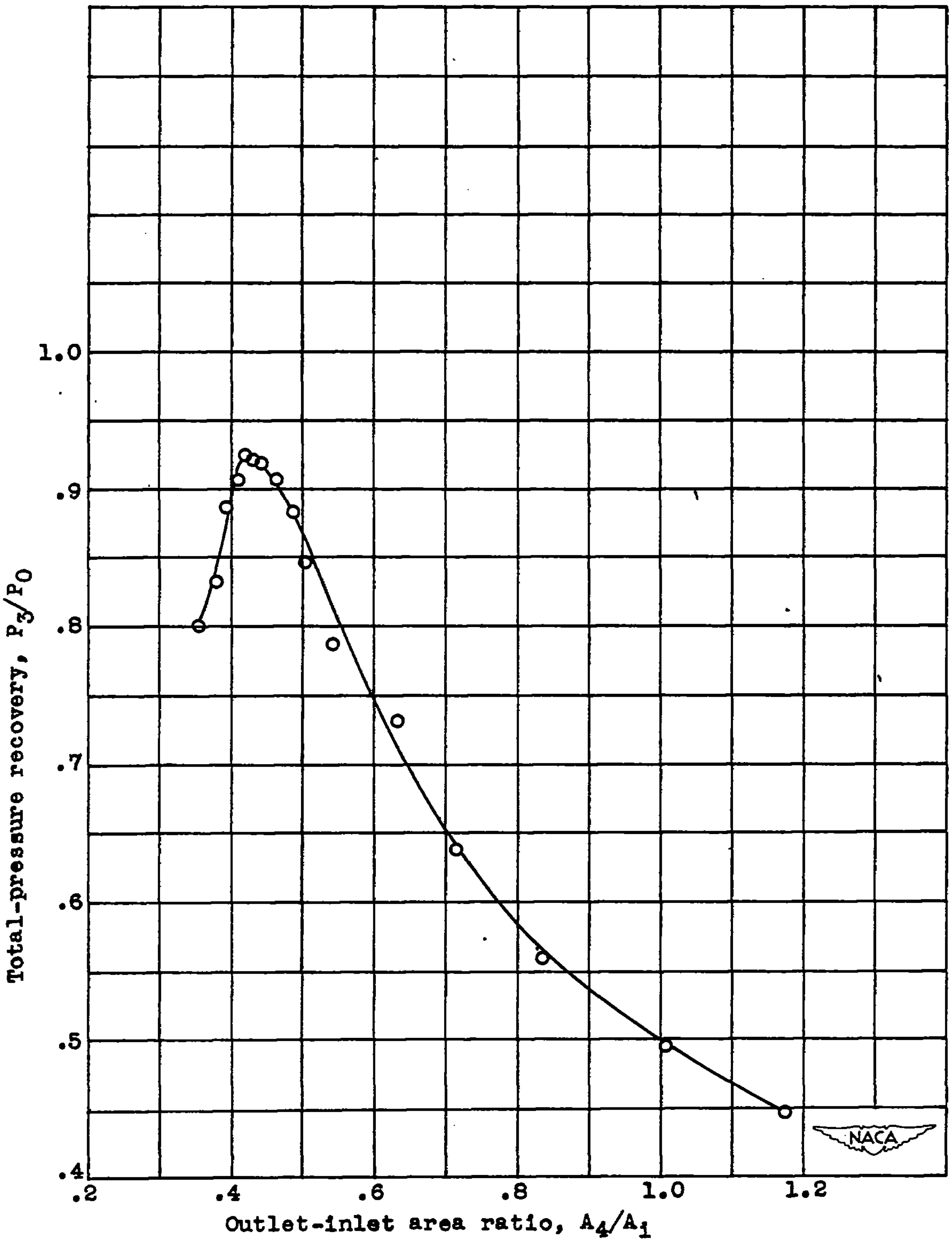
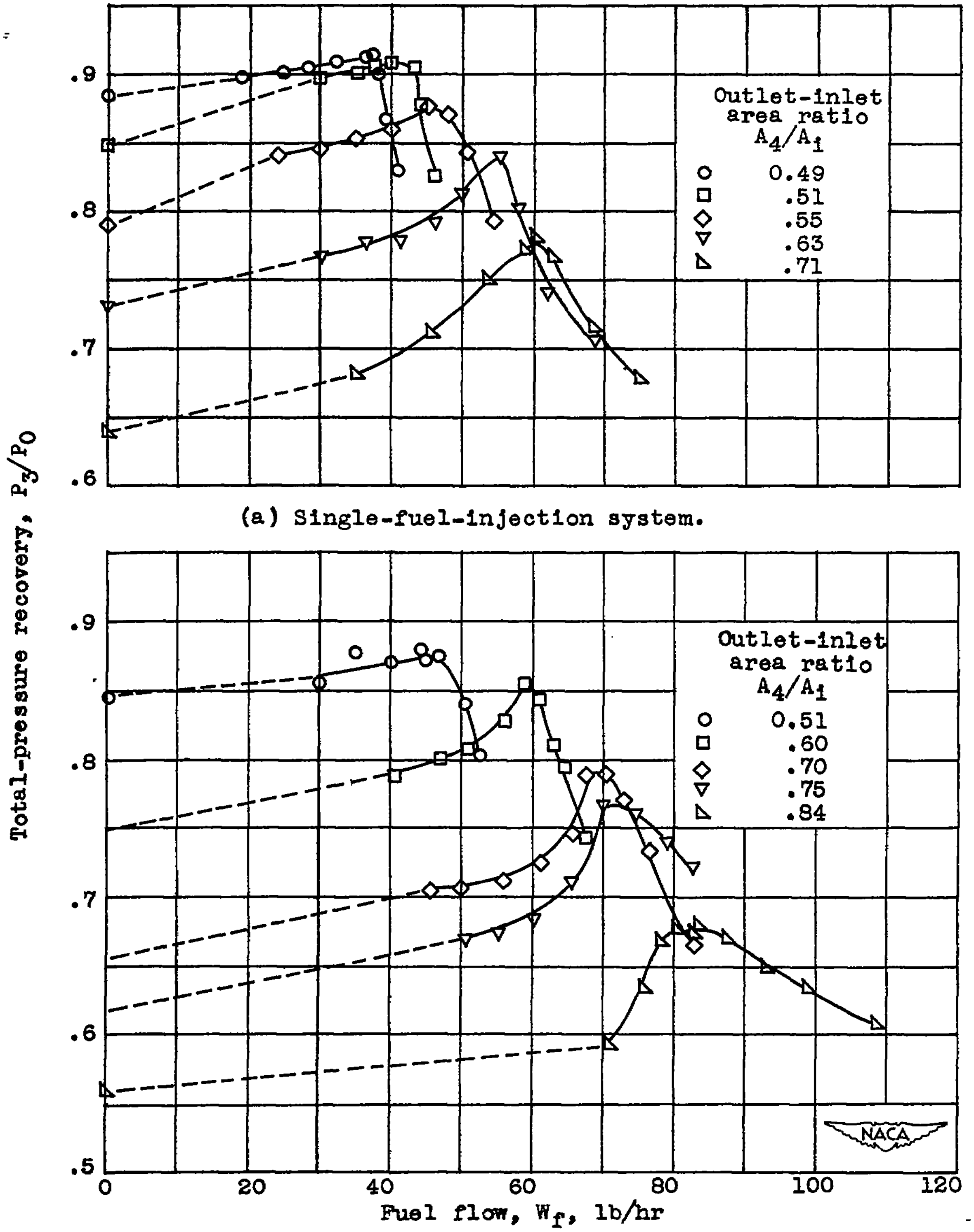


Figure 2. - Variation of total-pressure recovery with outlet-inlet area ratio without combustion.



(a) Single-fuel-injection system.

(b) Split-fuel-injection system.

Figure 3. - Effect of fuel flow on total-pressure recovery at constant outlet-inlet area ratios.

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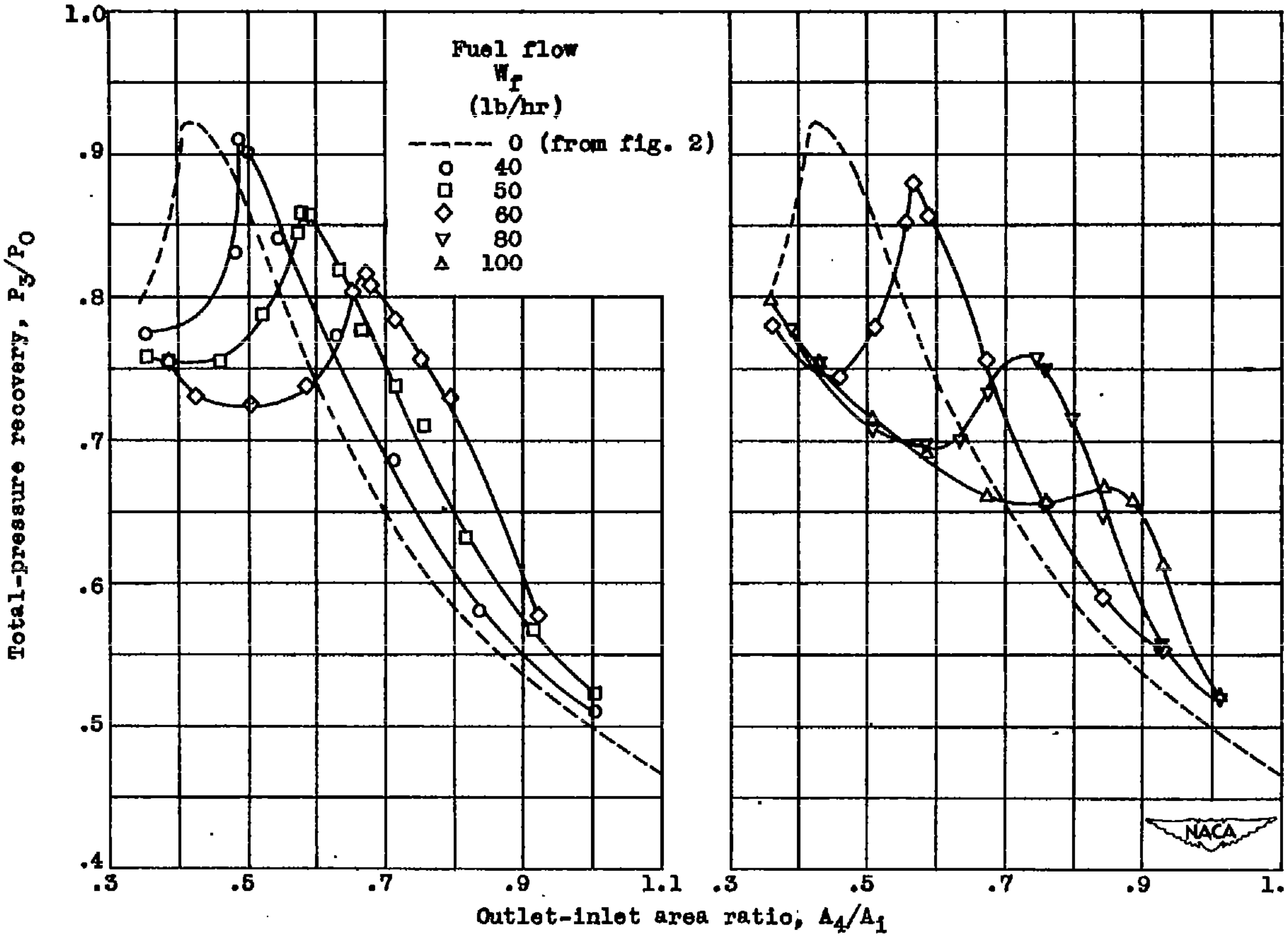

(a) Single-fuel-injection system. (b) Split-fuel-injection system.

Figure 4. - Variation of total-pressure recovery with outlet-inlet area ratio for constant fuel flows.

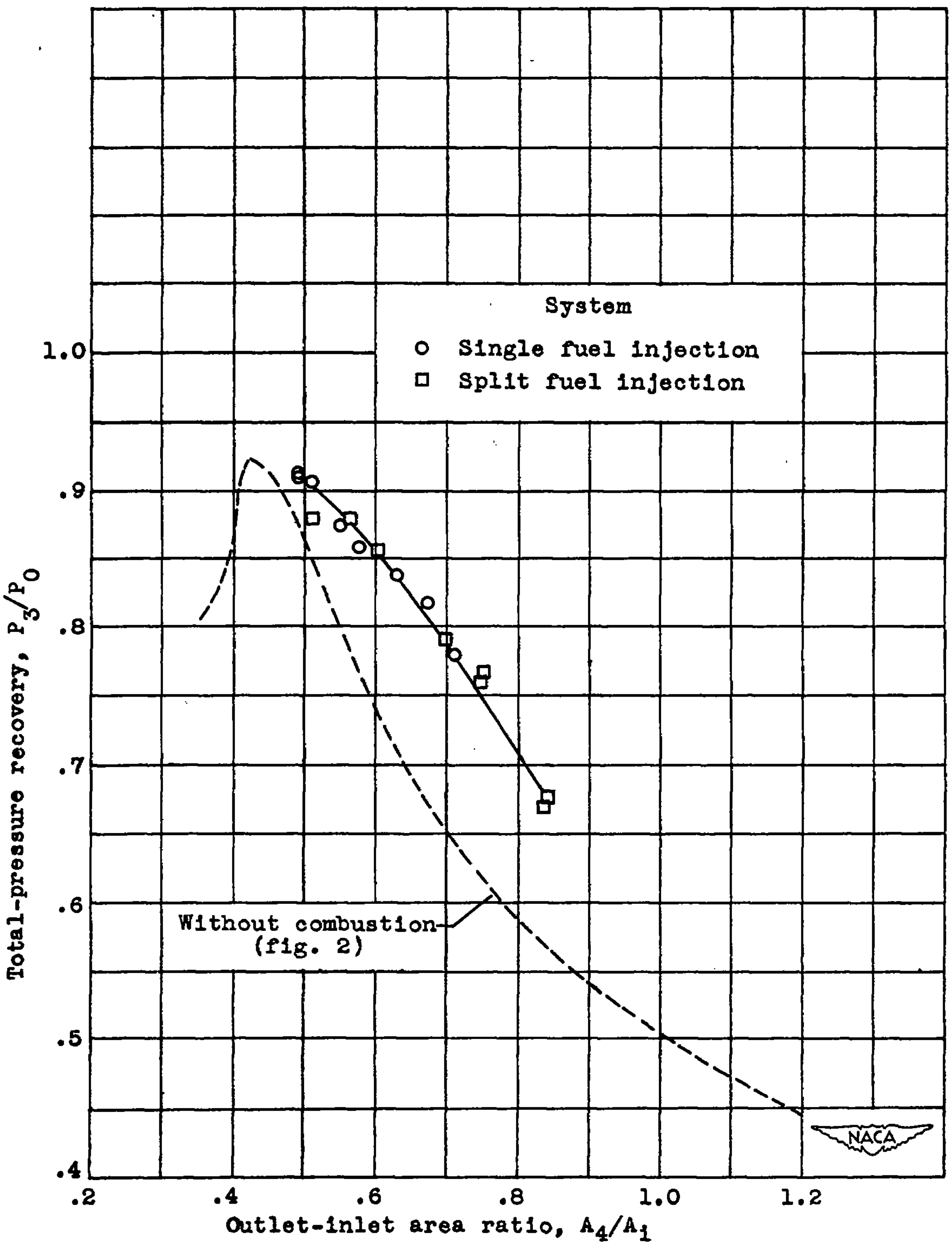

Figure 5. - Variation of peak total-pressure recoveries obtained with single- and split-fuel-injection systems over range of outlet-inlet area ratios.

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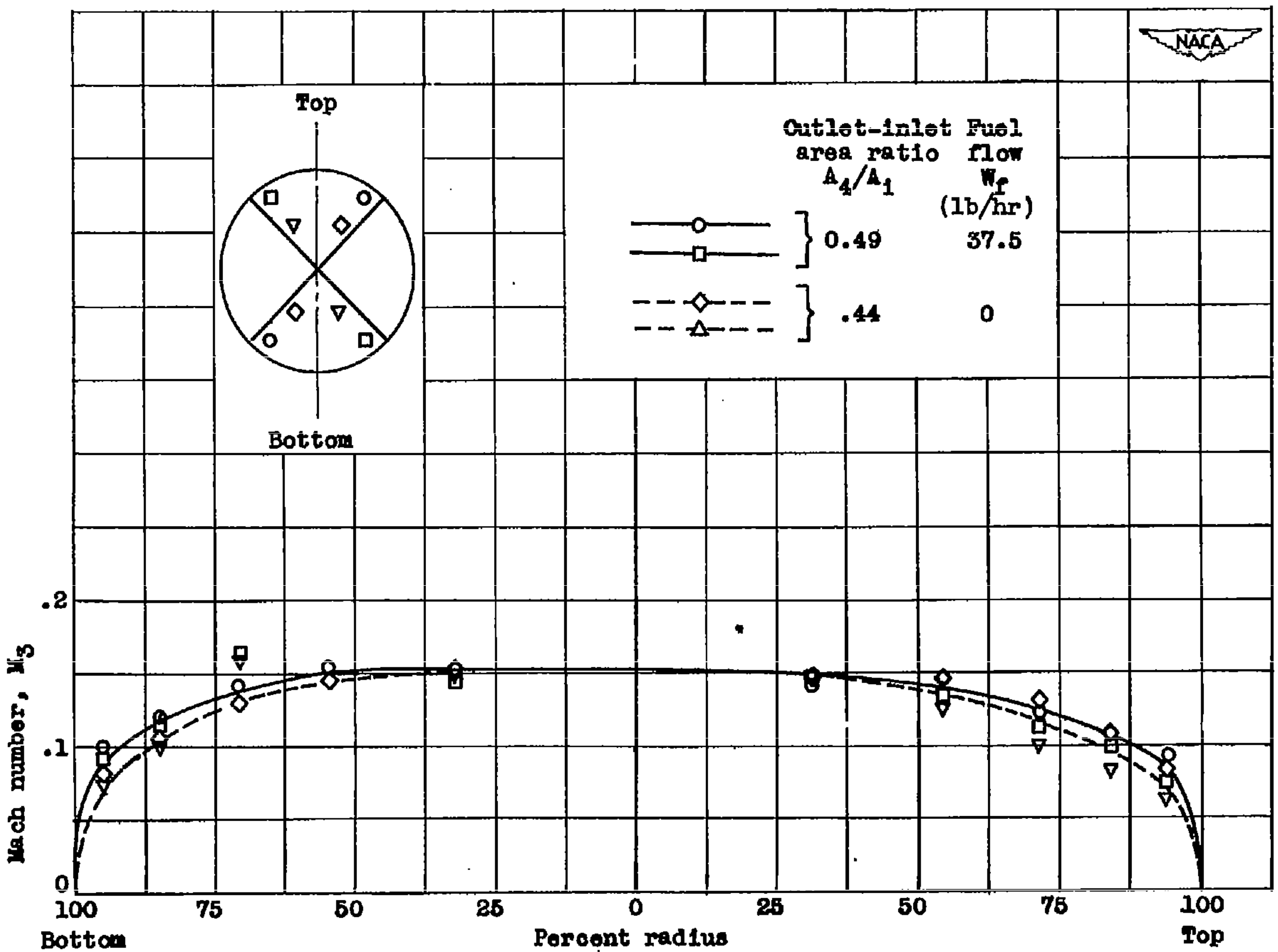
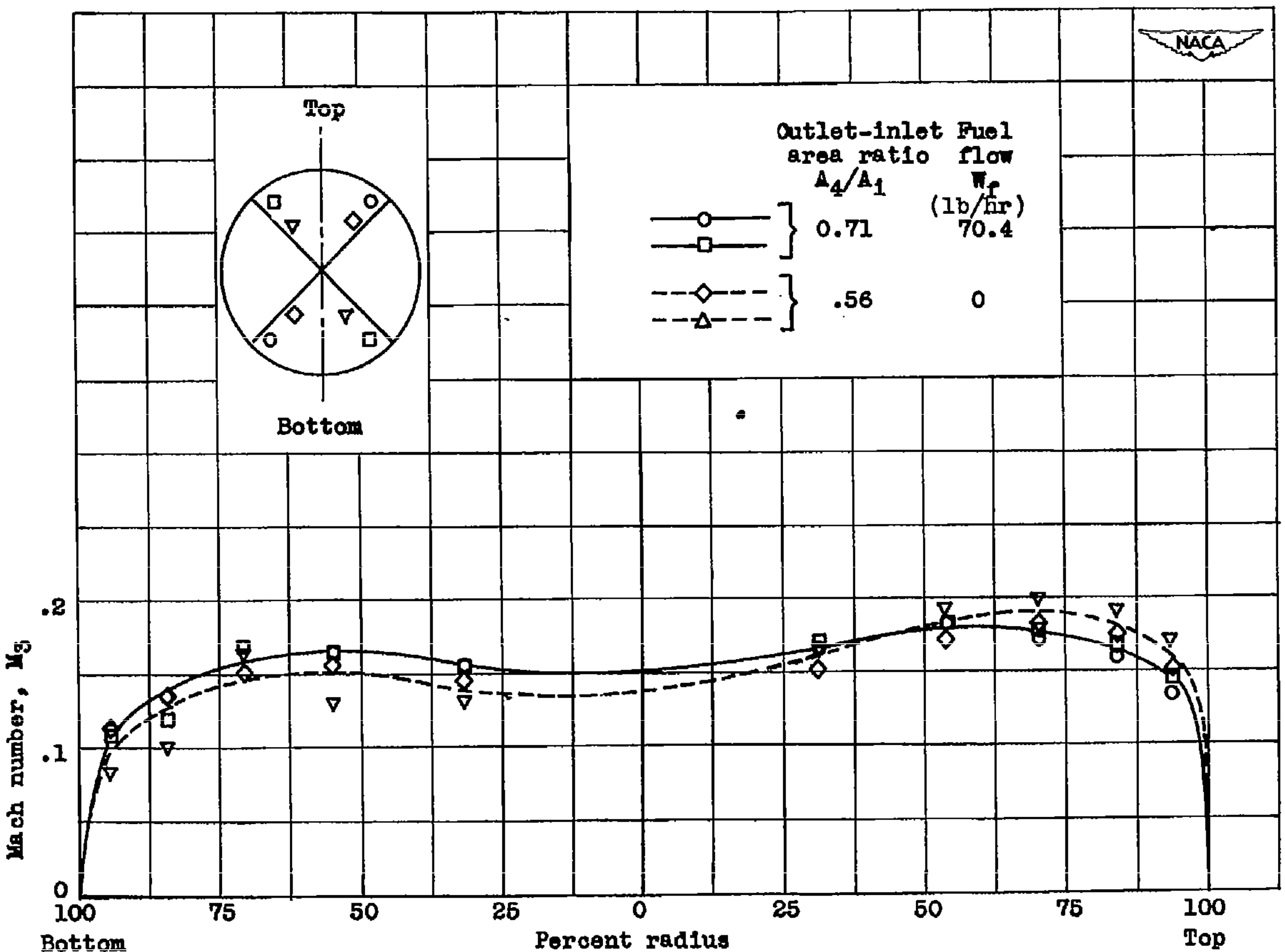


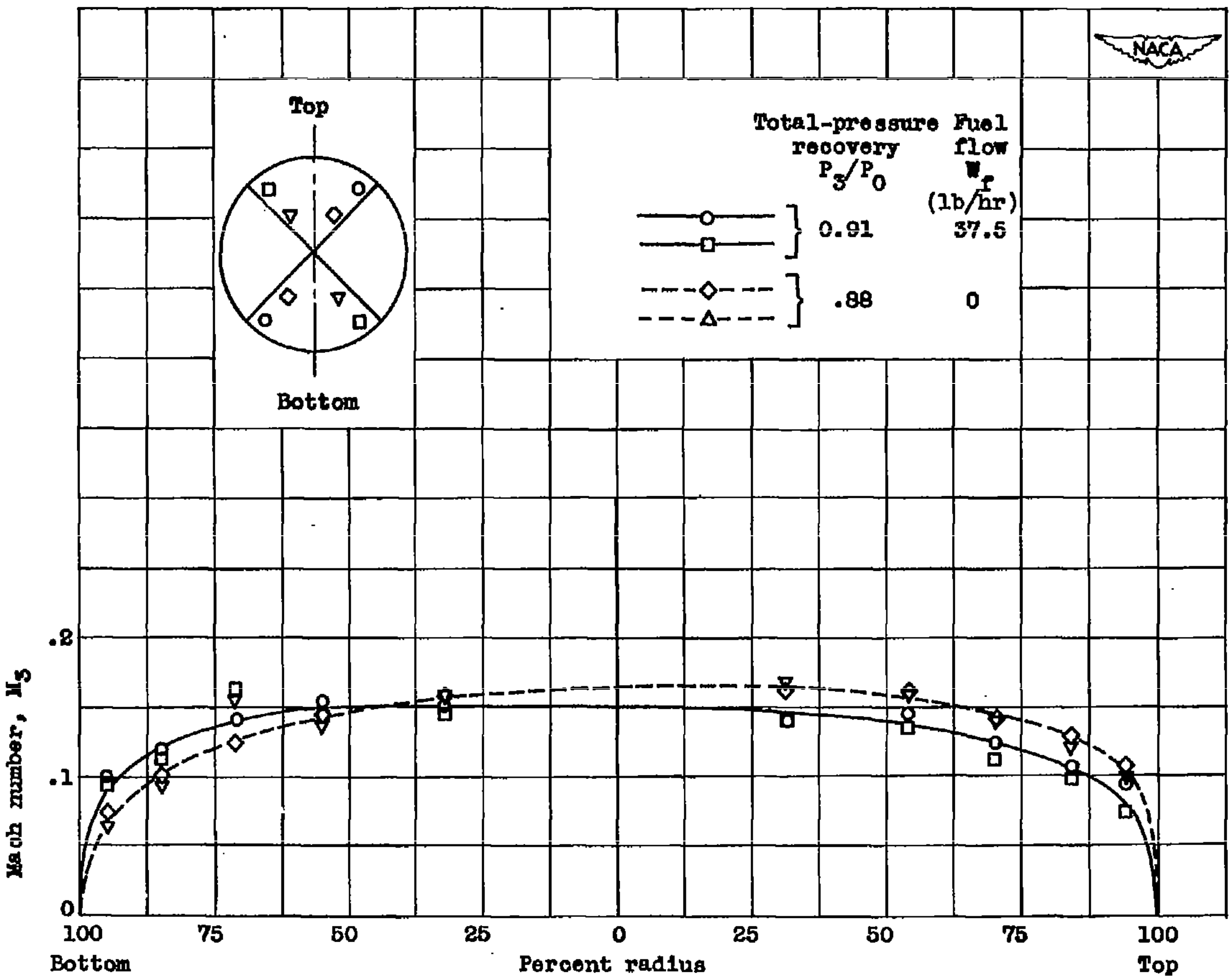
(a) Constant total-pressure recovery P_3/P_0, 0.91; single-fuel-injection system.

Figure 6. - Effect of combustion on Mach number distribution at diffuser outlet.



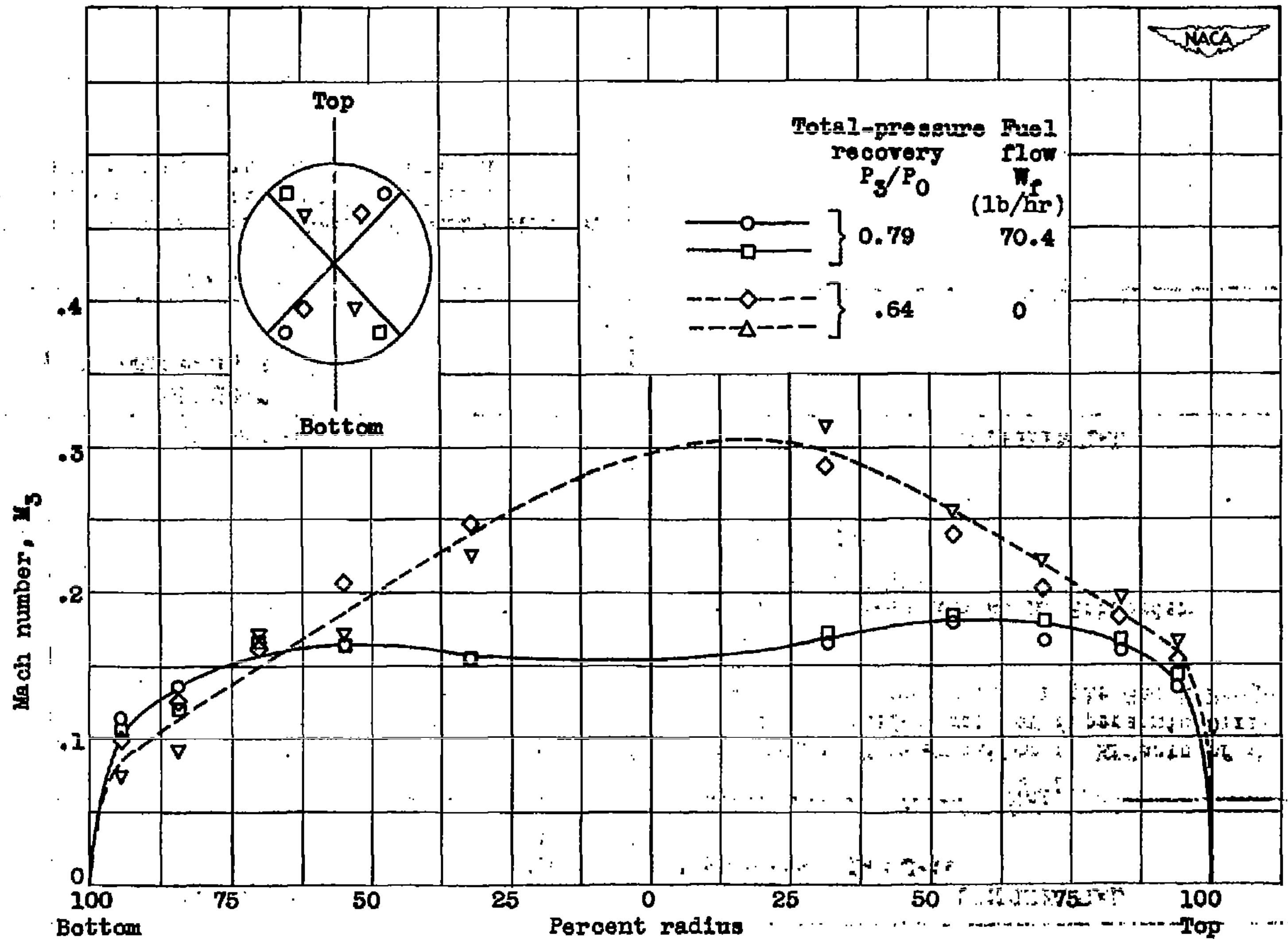
(b) Constant total-pressure recovery P_3/P_0, 0.79; split-fuel-injection system.

Figure 6. - Continued. Effect of combustion on Mach number distribution at diffuser outlet.



(c) Constant outlet-inlet area ratio A_4/A_1, 0.49; single-fuel-injection system.

Figure 6. - Continued. Effect of combustion on Mach number distribution at diffuser outlet.



(d) Constant outlet-inlet area ratio A_4/A_i, 0.71; split-fuel-injection system.

Figure 6. - Concluded. Effect of combustion on Mach number distribution at diffuser outlet.