INVESTIGATION OF THRUST AUGMENTATION OF A
1600-POUND THRUST CENTRIFUGAL-FLOW-TYPE
TURBOJET ENGINE BY INJECTION OF
REFRIGERANTS AT COMPRESSOR INLETS

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SUMMARY

The performance of a centrifugal-flow-type turbojet engine (having a normal military rating of 1600-lb thrust at a rotor speed of 16,500 rpm), has been investigated at zero flight speed with injection of refrigerants at the compressor inlets. The largest part of these investigations was devoted to the injection of water and water-alcohol mixtures; brief investigations were also conducted with the injection of kerosene and carbon dioxide.

The engine performance with the injection of water was investigated over a range of rotor speeds. Three different exhaust-nozzle sizes were used in order to evaluate the thrust augmentation possible when an adjustable-area exhaust nozzle is used. Various mixtures of water and alcohol were injected for a range of total flows up to 2.2 pounds per second. The runs with kerosene injected into the compressor inlets covered a range of injected flows up to approximately 30 percent of the normal engine fuel flow and were conducted over a range of rotor speeds. The carbon dioxide was injected in snow form from standard 75-pound fire-extinguisher bottles and its use was investigated both alone and with the injection of water and alcohol.

The injection of 2.0 pounds per second of water alone would provide a thrust augmentation of 35.8 percent at rated engine conditions for operation with an adjustable-area exhaust nozzle. A maximum thrust augmentation at zero flight speed of 40 percent was indicated at rated engine conditions for operation with an adjustable-area exhaust nozzle by injection of 1.6 pounds per second of water and 0.4 pound of alcohol per second. The injection of kerosene produced a negligible increase in thrust. A thrust augmentation of 23.5 percent was obtained with the injection
of 4.6 pounds per second of carbon dioxide alone. The injection of 3.5 pounds per second of carbon dioxide with a mixture of water and alcohol provided a thrust augmentation of 36 percent, 16 percent of which was contributed by the carbon dioxide.

INTRODUCTION

Thrust augmentation of turbojet engines to provide improved take-off, climb, and high-speed flight characteristics is of importance in increasing the effectiveness of the application of turbojet engines to both civilian and military aircraft. One of the methods of increasing the thrust of the turbojet engine is by the injection of refrigerants at the compressor inlets. This method increases the density of the air and the compressor Mach number. The increased density gives a higher mass flow through the engine and the increased compressor Mach number yields a higher pressure ratio across the compressor. Both of these factors increase the thrust of the engine.

As part of a general research program being conducted at the NACA Cleveland laboratory to investigate various methods of thrust augmentation, the performance of a centrifugal-flow-type turbojet engine at zero flight speed and sea-level conditions with injection of water and water-alcohol mixtures has been determined. For the investigation reported, which was conducted during the fall of 1944, various mixtures of water and alcohol were used over a range of injected liquid flows. The engine performance with injection of water was determined over a range of rotor speeds; the use of water-alcohol mixtures was investigated at two rotor speeds. Three different exhaust-nozzle sizes were used in order to evaluate the thrust augmentation possible if an adjustable-area exhaust nozzle were used.

The investigation with injection of water-alcohol mixtures was of importance because of: (a) the provision in the injected mixture of the extra fuel that is required for operation with water injection; (b) the possibility of choosing a mixture that would eliminate the need for adjustment of the fuel throttle during injection; and (c) the low freezing temperature of water-alcohol mixtures.

In addition to the investigation of engine performance with water and alcohol injection, brief investigations were also conducted with the injection of kerosene and carbon dioxide. The investigations
with kerosene injection covered a range of injected flows up to approximately 30 percent of the normal fuel flow and were conducted over a range of rotor speeds. The carbon dioxide was injected in snow form from standard 75-pound fire-extinguisher bottles and its use was investigated both alone and in conjunction with the injection of water and alcohol.

APPARATUS

General Setup

The general arrangement of the test setup is shown in figure 1. The investigations were conducted on an I-16 turbojet engine (normal rating, 1600-lb thrust) that was rigidly mounted on a framework suspended from the ceiling of the test cell by four rods supported by ball-bearing pivots. The tail pipe of the engine extended through an air seal in the outside wall of the test chamber. All supply lines to the engine were of flexible hose in order that restraining forces would be at a minimum. Lateral movement of the engine and the frame was prevented by means of ball-bearing guide rollers. The thrust exerted by the suspended engine was transmitted by a cranklever arrangement to the diaphragm of a calibrated balanced pressure cell. Measurement of the balancing pressure provided an indication of the engine thrust. The fuel flow (kerosene) to the engine was measured by calibrated rotameters. A chronometric tachometer was used to measure the rotor speed. The air supply to the engine entered the nearly airtight test chamber through an 18-inch throat-diameter A.S.M.E. standard air-measuring nozzle. A diffuser, which had an area ratio of 4, was connected to the nozzle in order to convert the velocity pressure at the nozzle throat to static pressure in the test cell. The cell leakage, which was found by calibration to be less than 0.3 percent of the total air flow, was added to the measured air flow.

An aluminum cowl and a wooden inlet-air nozzle were installed on the engine to restrict the inlet-air flow to an area in which the temperature could be accurately measured.

Injection Equipment

Water and alcohol injection. - Water and alcohol mixtures were injected through twenty 37.5-gallon-per-hour spray nozzles connected to a common manifold, as shown in figure 2. Ten nozzles were equally
spaced around each compressor-inlet screen. Water and alcohol flows were measured by calibrated orifices. The alcohol used in these investigations was approximately 50-percent methyl and 50-percent ethyl by weight.

**Kerosene injection.** - For the injection of kerosene, the engine fuel system was so revised that both the fuel injected into the compressor and the fuel supplied to the engine burner nozzles passed through the overspeed governor. Separate throttles were provided for each fuel line. The kerosene was injected into the compressor inlets through twenty 6.5-gallon-per-hour spray nozzles installed in the same manner as the water-alcohol injection nozzles. The total flow of kerosene to the engine was measured by a calibrated rotameter. The injected kerosene flows at the compressor inlets were determined by a flow calibration of the injection nozzles.

**Carbon-dioxide injection.** - The additional equipment required for the injection of carbon dioxide is shown in the foreground of the photograph presented in figure 3. (The injection manifold shown mounted on the inlet nozzle was not used during these runs.) Carbon dioxide from 75-pound-capacity fire extinguishers was injected into the inlet-air stream in snow form.

Several bottles of carbon dioxide were discharged to obtain weight-flow calibrations. The results of five such calibrations are presented in figure 4 from which carbon-dioxide flows have been determined for these investigations. Although the data for these curves scatter somewhat, the trends indicate that the flow rate of carbon dioxide is dependent on its initial temperature with the greatest flow rates occurring at the highest temperature.

**Pressure and Temperature Instrumentation**

The stations at which the engine was instrumented for temperature and pressure measurements are shown in figure 2. The variables measured and the number, type, and location of instruments are:

(a) Cowl-inlet total temperature $T_0$, average of six unshielded thermocouples in inlet-air nozzle

(b) Cowl-inlet total pressure $P_0$, one open-end tube in test cell

(c) Compressor-outlet total temperature (inlet of burner 10) $T_2$, one unshielded thermocouple
(d) Compressor-outlet total temperature (inlet of burner 5) 
\( T_2 \), one stagnation-type thermocouple

(e) Compressor-outlet static pressure (inlet of burner 9) 
\( P_2 \), four static wall taps connected to a piezometer ring

(f) Compressor-outlet total pressure (inlet of burner 9) 
\( P_2 \), one five-tube total pressure rake with all tubes connected to a common line

(g) Tail-pipe gas temperature \( T_7 \), six aspirating-type thermocouples connected in parallel

These measurements were read on potentiometers and manometers.

PROCEDURE

Water and Water-Alcohol Injection

Five separate series of runs were conducted, three with water injection and two with water-alcohol injection. The conditions for the five runs are presented in the following table:

<table>
<thead>
<tr>
<th>Run</th>
<th>Injected liquid</th>
<th>Exhaust nozzle diameter (in.)</th>
<th>Injected water flow ( W_W ) (lb/sec)</th>
<th>Injected alcohol flow ( W_{al} ) (lb/sec)</th>
<th>Total injected liquid flow ( W_W + W_{al} ) (lb/sec)</th>
<th>Rotor speed ( N ) (rpm)</th>
<th>Cowl inlet-air temperature range (°R)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Water</td>
<td>12.5</td>
<td>0-1.9</td>
<td>0</td>
<td>0-1.9</td>
<td>11,000-16,500</td>
<td>526 - 540</td>
</tr>
<tr>
<td>B</td>
<td>Water</td>
<td>12.0</td>
<td>0-1.9</td>
<td>0</td>
<td>0-1.9</td>
<td>11,000-16,500</td>
<td>529 - 540</td>
</tr>
<tr>
<td>C</td>
<td>Water</td>
<td>11.5</td>
<td>0-1.9</td>
<td>0</td>
<td>0-1.9</td>
<td>11,000-16,000</td>
<td>533 - 555</td>
</tr>
<tr>
<td>D</td>
<td>Water-alcohol</td>
<td>12.0</td>
<td>0.5-0</td>
<td>0-0.5</td>
<td>0.5</td>
<td>16,000</td>
<td>537 - 543</td>
</tr>
<tr>
<td>E</td>
<td>Water-alcohol</td>
<td>12.0</td>
<td>1.5</td>
<td>0-0.6</td>
<td>1.5-2.1</td>
<td>16,000, 16,500</td>
<td>541 - 547</td>
</tr>
</tbody>
</table>

<sup>a</sup>Top speed limited by allowable tail-pipe gas temperature.
Water-injection runs A, B, and C differed only in the size of the exhaust nozzle used on the engine. Water-alcohol injection runs D and E were run with a 12-inch-diameter exhaust nozzle and differed in the manner in which the proportion of water and alcohol were varied. In run D, the total injected flow of water and alcohol was held constant at approximately 0.5 pound per second and the proportions of each were varied. In run E, the injected water flow was held constant at 1.5 pounds per second and the alcohol rate was progressively increased from 0 to 0.6 pound per second.

Prior to each run, engine performance was determined without injection in order to provide a basis for evaluating the thrust augmentation.

**Kerosene and Carbon-Dioxide Injection**

The investigation of the performance of a centrifugal-flow-type turbojet engine, which had a 12-inch-diameter exhaust nozzle, during injection of kerosene, carbon dioxide, and carbon dioxide with a water-alcohol mixture was conducted according to the following procedure:

**Kerosene injection.** - The normal performance of the engine was determined prior to the injection of kerosene. Kerosene was injected into the compressor inlets of the turbojet engine in the same manner as the water and alcohol and the injected flows were varied from 0 to 603 pounds per hour. The rotor speed was varied from 14,000 rpm to 16,500 rpm; the inlet-air temperature was approximately 535°F.

**Carbon-dioxide injection.** - The normal performance of the engine without injection was first established. The injection of carbon dioxide into the compressor inlets was then accomplished by simultaneously opening the valves on four 75-pound capacity carbon-dioxide bottles. The injected flow of carbon dioxide varied from 4.6 pounds per second at the beginning of the run to almost zero at the end of the run. The engine was first operated at 16,500 rpm but the speed abruptly decreased when the injection valves were opened. When the rotor speed was stabilized at 16,100 rpm, data were taken in quick succession until the contents of the bottles were depleted. The ambient cell temperature varied from 526°F to 530°F.

**Carbon-dioxide injection with water-alcohol mixture.** - The normal engine performance was first established. This determination was followed by an investigation of engine performance for the injection of a 9:8 mixture of water and alcohol. Then, while the
water and alcohol mixture was being injected at a rotor speed of approximately 16,500 rpm, the valves on three 75-pound capacity carbon-dioxide bottles were simultaneously opened. Readings were started 6 seconds after opening of the valves and were taken at 12-second intervals until the contents of the bottles were depleted. The variation in rotor speed was about 60 rpm for the run and the ambient cell temperature varied from 507° to 514° R.

SYMBOLS

The following symbols are used in this report:

- **F** thrust, (lb)
- **h** lower heating value of fuel, (Btu)/(lb)
- **K** fuel-flow correction factor
- **N** rotor speed, (rpm)
- **P** total pressure, (lb)/(sq in. absolute)
- **p** static pressure, (lb)/(sq in. absolute)
- **T** indicated temperature, (°R)
- **t** time, (sec)
- **W_a** air flow, (lb)/(sec)
- **W_al** injected alcohol flow, (lb)/(sec)
- **W_c** injected carbon-dioxide flow, (lb)/(sec)
- **W_f** fuel flow, (lb)/(hr)
- **W_k** injected kerosene flow, (lb)/(hr)
- **W_w** injected water flow, (lb)/(sec)
- **W_t** total liquid consumption, (lb of fuel, water, alcohol, and carbon dioxide)/(sec) or (lb)/(hr)
METHODS OF CORRECTION

All performance data from water and water-alcohol injection runs were corrected to standard conditions at the cowl inlet by the following equations (the values without the subscript corr are observed data):

\[ F_{\text{corr}} = \frac{F}{8} \]  
\[ N_{\text{corr}} = \frac{N}{\sqrt{\theta}} \]  
\[ P_{\text{corr}} = \frac{P}{8} \]  
\[ P_{\text{corr}} = \frac{P}{8} \]  
\[ T_{\text{corr}} = \frac{T}{8} \]  
\[ W_a_{\text{corr}} = \frac{W_a \sqrt{\theta}}{8} \]  
\[ W_{al\text{corr}} = \frac{W_{al \sqrt{\theta}}}{8} \]  
\[ W_w_{\text{corr}} = \frac{W_w \sqrt{\theta}}{8} \]
\[ W_t \text{ corr} = \frac{W_{al}\sqrt{\theta}}{\delta} + \frac{W_{w}\sqrt{\theta}}{\delta} + \frac{W_{f}K}{\delta \sqrt{\theta} \times 3600} \]  

\[ W_f \text{ corr} = \frac{W_{f}K}{\delta \sqrt{\theta}} \]  

where the correction factors

- \( \delta = \frac{\text{cowl-inlet total pressure} \ P_0}{\text{pressure of NACA standard atmosphere at sea level}} \)
- \( \vartheta = \frac{\text{cowl-inlet total temperature} \ T_0}{\text{temperature of NACA standard atmosphere at sea level}} \)

\[ K = 1 + (3600 \times 0.4 \frac{W_{al}}{W_{f}})(1 - \theta) \]

The accuracy of the correction of engine performance data with liquid injection to standard inlet conditions is somewhat questionable because of unknown effects of inlet-air temperature on the vaporization of the injected liquid. The corrections applied are therefore only approximate and probably limited to small ranges of inlet temperature such as contained in the present data.

The correction equations are all valid if the corrected pressures and temperatures throughout the engine are related to the corresponding uncorrected values by the factors \( \delta \) and \( \vartheta \). A theoretical analysis of the wet compression process indicates that if liquid-air ratio and compressor Mach number are held constant, the corrected pressures and temperatures will be related to the uncorrected values by the factors \( \delta \) and \( \vartheta \), provided that: (1) the liquid is completely vaporized in the compressor, and (2) the variations in inlet conditions are small.

The corrections are based on maintaining corrected values of water-air and alcohol-air ratios and Mach numbers the same as the uncorrected values. The water-air and alcohol-air ratios are maintained constant by correcting water and alcohol flows in the same manner as the air flow. Corrected and uncorrected Mach numbers of the flow through the engine are the same except for variations in the thermodynamic properties of the gases arising from
small changes (with correction) in fuel-air ratio (and, hence fuel-water and fuel-alcohol ratios), and (2) small changes in the vaporization processes in the compressor (with inlet conditions).

The total liquid consumption of the engine consists of fuel (kerosene), water, and alcohol, which provide or absorb heat in the engine combustion process. Because both the engine fuel and the injected alcohol provide heat during combustion, the resultant fuel flow must be corrected in a manner that accounts for the changes in alcohol flows arising from correction. The correction factor \( K \), which takes into consideration the action of fuel and injected alcohol, is derived from a simple heat-balance equation. The value 0.4 in definition of \( K \) is an approximate ratio of the effective heating value of alcohol to the effective heating value of kerosene based on data from the water-alcohol injection runs.

The performance data from runs with kerosene and carbon-dioxide injection are presented directly as read without correction for inlet conditions.

**RESULTS AND DISCUSSION**

**Water and Water-Alcohol Injection**

The greater part of the investigation of engine performance was conducted with injection of the refrigerants that were considered of primary importance, namely, water and water-alcohol mixture.

**Water injection.** - The observed and the corrected data of water-injection runs A, B, and C are presented in table I. The curves presented in figure 5 show the variation in engine performance with injected water flow at a corrected rotor speed of 16,500 rpm and a cowl-inlet air temperature of from 534° to 540° R for 12.0- and 12.5-inch-diameter exhaust nozzles. (Data for 11.5-in.-diameter exhaust nozzle, run C, was not obtained at 16,500 rpm because of excessive tail-pipe gas temperature.) These curves were obtained by cross-plotting curves of engine performance against rotor speed from the data in table I. Figure 5(a) shows a graph of thrust plotted against injected water flow. For an injected water flow of 2.0 pounds per second, a thrust of 1755 pounds, or an increase of 330 pounds, was obtained using the 12.5-inch-diameter exhaust nozzle; and a thrust of 1935 pounds, or an increase of 345 pounds, was obtained with the 12.0-inch-diameter exhaust nozzle. These values represent a 23.2-percent thrust increase for the 12.5-inch-diameter exhaust nozzle and a 21.7-percent increase for the 12.0-inch-diameter
exhaust nozzle. The dashed line in figure 5(a) represents the thrust with an adjustable-area exhaust nozzle and will be discussed in the following paragraph.

The tail-pipe gas temperatures decreased appreciably with injection of water for both exhaust nozzle sizes (fig. 5(b)). The excessive tail-pipe gas temperatures obtained with the 12.0-inch-diameter exhaust nozzle at points of low injection are reduced to the rated value of 1640° R by the injection of 2.0 pounds per second of water. The reduction in temperature with injection together with the higher thrust provided by the use of the smaller exhaust nozzle (fig. 5(a)), indicates that in order to realize fully the benefits of water injection the engine should be equipped with a variable-area exhaust nozzle. The thrust available when the exhaust-nozzle area is reduced sufficiently during injection to maintain the rated tail-pipe gas temperature, as shown by the dashed line in figure 5(a), was obtained by cross-plotting curves of thrust and tail-pipe gas temperature against exhaust-nozzle size. This curve for constant tail-pipe gas temperature shows that the thrust increases from 1425 pounds for no injection to 1935 pounds for injection of 2.0 pounds per second, representing a thrust augmentation of 35.8 percent. The leveling off of the curves of figures 5(a) and 5(b) indicates that both the increase in thrust and the reduction in tail-pipe gas temperature, and hence the effectiveness of the water injection, are reduced as the injection rate is increased.

The changes in fuel flow, total liquid consumption, air flow, and compressor-outlet total pressure caused by water injection are shown in figures 5(c) to 5(f), respectively. Both the fuel flow (fig. 5(c)) and the total liquid consumption (fig. 5(d)) increase appreciably for both exhaust-nozzle sizes with injected water flow. The injection of 2.0 pounds per second of water resulted in an increase of roughly 500 pounds per hour in the fuel flow and the total liquid consumption at this injection rate was about five times as high as for no injection. The air flow (fig. 5(e)) reaches a maximum (with an increase of about 2.5 lb/sec) at an injected water flow of approximately 1.0 pound per second for both exhaust-nozzle sizes. Although the air flow reaches a maximum at an injected water flow of 1.0 pound per second, the total mass flow (air plus liquid) through the engine continues to rise with injected water flow throughout the range investigated. The compressor-outlet total pressure (fig. 5(f)) increased over a larger range of injected water flows than did the air flow, leveling off at about the same injected water flow as did the thrust and the tail-pipe gas temperature.
Water-alcohol injection. - The results of run D, in which the proportions of water and alcohol were varied while the total injection rate was held constant at 0.52 pound per second (corrected value) are presented in Figure 6. These data were obtained for inlet-air temperature from 537° to 543° R and are presented for a corrected rotor speed of 16,000 rpm. Figures 6(a) and 6(b) show that at this low total injected flow small amounts of alcohol (up to 0.15 lb/sec, or 30-percent alcohol) in the injected mixture produces about the same thrust and tail-pipe gas temperature as are produced by the injection of 0.52 pound per second of water alone. Injection of mixtures richer than 0.15 pound per second of alcohol, however, resulted in less thrust augmentation and higher tail-pipe gas temperatures than the injection of the same amount of water. Because alcohol acts as additional fuel, replacing some of the extra engine fuel required during water injection, the proportion of alcohol in the injected liquid has a marked effect on the engine fuel flow (fig. 6(c)). For injection of 0.10 pound per second of alcohol and 0.42 pound per second of water, the same fuel flow is required as with no injection, and therefore no adjustment of the fuel throttle is necessary. The composition of the injected mixture for constant throttle setting, (with constant nozzle size) from the previous observation, is approximately 20-percent alcohol by weight.

Figure 6(d) shows that total liquid consumption decreases as the proportion of alcohol is increased for a constant total injected mixture flow of 0.52 pound per second. This decrease in total liquid consumption is caused by the replacement of some of the engine fuel with alcohol as the injected mixture is enriched with alcohol.

Both the air flow (fig. 6(e)) and the compressor-outlet total pressure (fig. 6(f)) were higher for mixtures containing small amounts of alcohol than for mixtures rich in alcohol. These higher air flows and pressures indicate that the greatest cooling of the intake air occurred for mixtures containing a small amount of alcohol. The more rapid vaporization of mixtures rich in alcohol is apparently counteracted by the reduction in the heat of vaporization as the alcohol content is increased.

The results of run E, in which the injected water flow was held constant at 1.6 pounds per second (corrected value) and the injected alcohol flow was varied, are presented in figure 7. These data were obtained for inlet-air temperatures from 541° to 547° R and are presented for corrected rotor speeds of 16,000 and 16,500 rpm. Although the thrust values for no injection from figure 7(a) do not agree with those of figure 5(a) because of a change in normal engine performance, the percentage thrust increases brought about by injection of 1.6 pounds of water per second are about the same for both runs.
A comparison of the thrust augmentation in figures 5(a) and 7(a) shows that the addition of alcohol to an injected water flow of 1.6 pounds per second results in a greater increase in thrust than the injection of the same total flow of water alone. Moreover, the addition of alcohol to an injected water flow of 1.6 pounds per second produces a slightly lower tail-pipe gas temperature (approximately 300°F for 0.4 lb/sec alcohol) than was produced by the same total injected flow of water alone (fig. 7(b)).

The curve of fuel flow against injected alcohol flow (fig. 7(c)) indicates that the engine can be operated without adjustment of the fuel throttle with injection of 1.6 pounds per second of water and approximately 0.4 pound per second of alcohol for both rotor speeds. This mixture is in agreement with the constant-throttle-setting injection mixture of run D (approximately 20-percent alcohol by weight). Comparison of figures 5(d) and 7(d) show that the total liquid consumption is less for the injection of 1.6 pounds of water per second plus various amounts of alcohol than for the injection of an equal amount of water alone. A similar comparison of figures 5(e) and 5(f) with 7(e) and 7(f) shows that both the air-flow and compressor-outlet pressure increase more for the injection of mixtures containing alcohol than for the injection of water alone.

The foregoing comparison of the performance data presented in figures 5 and 7 indicated that the addition of alcohol to the injected liquid at high injected water flows (approximately 1.6 lb/sec) is more effective in increasing the thrust and reducing the tail-pipe gas temperature than the addition of more water. The maximum possible thrust augmentation with water-alcohol injection was not obtained, however, because run E was conducted with only one size exhaust nozzle, which permitted the gas temperatures to decrease as the injected flow was increased. In order to illustrate the maximum thrust augmentation that may be expected with water-alcohol injection, figure 8 is presented. The data from figure 5(a) for water injection at a constant tail-pipe gas temperature of 1640°F (at 16,500 rpm) is replotted in figure 8 as percentage thrust augmentation against total injected liquid flow. A curve of the thrust augmentation available by water injection for the 12.0-inch-diameter exhaust nozzle is included for comparison. The thrust augmentation possible by water-alcohol injection is shown by dashed curves for both conditions, that is: (1) tail-pipe gas temperature maintained constant by exhaust nozzle adjustment and (2) exhaust-nozzle diameter maintained constant at 12.0 inches. This thrust augmentation for constant tail-pipe gas temperatures was obtained by multiplying the augmentation provided by 1.6 pounds per second of water alone (from fig. 5(a)) by both the ratio of the
thrust increase with alcohol injection shown in figure 7(a) and the ratio of the estimated thrust increase obtained when the exhaust-nozzle size was sufficiently reduced to raise the gas temperatures of figure 7(b) to a constant value. This adjustment of the data to a common exhaust-gas temperature was based on cross plots of thrust and temperature against exhaust-nozzle size obtained from the data without injection. A maximum possible thrust augmentation of 40 percent for injection of 1.6 pounds per second of water and 0.4 pound per second of alcohol for a rotor speed of 16,500 rpm and a cowl-inlet-air temperature from 534° to 543° R is indicated by the curve obtained from this analysis of the data.

Kerosene and Carbon-Dioxide Injection

The investigation of engine performance with injection of refrigerants that were considered of secondary importance were the injection of kerosene and carbon dioxide.

Kerosene injection. - The uncorrected performance data for runs with kerosene injection are presented in figure 9 for a rotor speed of 16,500 rpm, an ambient cell temperature of about 535° R, and a 12.5-inch-diameter exhaust nozzle. Figure 9(a) shows that the injection of kerosene increases the thrust only 17 pounds for an injection rate of 603 pounds per hour. The tail-pipe gas temperature (fig. 9(b)) was found to be higher for the injection of kerosene than for no injection. The total kerosene flow (fig. 9(c)) was increased 235 pounds per hour at an injection rate of 603 pounds per hour into the compressor inlets at a rotor speed of 16,500 rpm. Figure 9(d) indicates that the air flow for the injection of kerosene was slightly lower than for no injection.

Carbon-dioxide injection. - The uncorrected performance data from runs with carbon-dioxide injection have been plotted in figure 10 against the time elapsed from the opening of the valves on the carbon-dioxide bottles. Curves of engine performance without injection have been included in the figure for comparison. The thrust increase for the injection of carbon dioxide alone was 320 pounds, representing a thrust augmentation of 23.5 percent, for an injected carbon-dioxide flow of 4.6 pounds per second (indicated rotor speed, 16,150 rpm; ambient cell temperature, 526° to 530° R). Injection of carbon dioxide resulted in a slight decrease in tail-pipe gas temperature and considerable increase in fuel flow.

Carbon-dioxide injection with water-alcohol mixture. - The uncorrected performance data for runs of the engine with injection of carbon dioxide with 1.7 pounds per second of a 9:8 mixture of
water and alcohol by weight are presented in figure 11. Curves of engine performance with injection of 1.7 pounds per second of the water-alcohol mixture alone (at speeds corresponding to those during injection of carbon dioxide) as well as curves of performance without injection are included for comparison. Because of difficulty with the instrumentation, no tail-pipe gas temperature measurements were made during this run. A thrust increase for injection of 3.5 pounds per second of carbon dioxide with 1.7 pounds per second of the 9:8 mixture of water and alcohol was 575 pounds representing a thrust augmentation of 36 percent. Of this thrust increase, which was obtained at an indicated rotor speed of 16,450 rpm, an ambient cell temperature from 507° to 514° R, and with an engine fitted with a constant-size exhaust nozzle, the water and alcohol contributed about 315 pounds, or about 20-percent augmentation. Thus, the injection of 3.5 pounds per second of carbon dioxide with 1.7 pounds per second of a mixture of water and alcohol provided a thrust augmentation 16 percent higher than obtained with injection of the water and alcohol alone.

SUMMARY OF RESULTS

The following results were obtained from the investigation of the performance of a 1600-pound-thrust centrifugal-flow-type turbojet engine at zero flight speed, sea-level conditions, and with injection of various refrigerants at the compressor inlets:

Water and Water-Alcohol Injection

1. A thrust augmentation of 23.2 percent was obtained by the injection of 2.0 pounds of water per second at a corrected rotor speed of 16,500 rpm and for an inlet-air temperature of 534° to 540° R using a constant exhaust-nozzle diameter of 12.5 inches. This thrust augmentation was increased to 35.8 percent by adjustment of the exhaust-nozzle size to maintain a constant rated tailpipe gas temperature of 1640° R.

2. In the low flow range of water-alcohol injection (approximately 0.52 lb/sec of mixture), the thrust augmentation decreased slightly as the injected mixture was enriched with alcohol.

3. At high injected water flows (approximately 1.6 lb/sec), the addition of alcohol to the injected liquid was more effective than the addition of more water. A maximum thrust augmentation of 40 percent is available by the injection of 1.6 pounds of water...
per second and 0.4 pound of alcohol per second when the tail-pipe gas temperature is maintained constant at the rated value of 1640\degree R by exhaust-nozzle adjustment.

4. Operation of the engine without adjustment of the fuel throttle from the normal operating position (at the same speed) is possible by selecting an injection mixture of alcohol and water that is roughly 20-percent alcohol by weight.

Kerosene and Carbon-Dioxide Injection

1. The increase in thrust with injection of kerosene was very slight reaching a maximum of 17 pounds for an injection rate of 603 pounds per hour at an indicated rotor speed of 16,500 rpm, an inlet-air temperature of 535\degree R, and a constant-area exhaust nozzle of 12.0-inch diameter. The accompanying increase in total fuel flow was 235 pounds per hour.

2. Thrust increase for the injection of 4.6 pounds per second of carbon dioxide alone was 320 pounds, representing a thrust augmentation of 23.5 percent at an indicated rotor speed of 16,150 rpm, an inlet-air temperature of 526\degree to 530\degree R, and with a 12.0-inch-diameter exhaust nozzle.

3. Thrust increase for the injection of 3.5 pounds per second of carbon dioxide with 1.7 pounds per second of a 9:8 mixture of water and alcohol, at an indicated rotor speed of 16,450 rpm, an inlet-air temperature of 507\degree to 514\degree R, and with a 12.0-inch-diameter
exhaust nozzle was 575 pounds. This increase represents a total thrust augmentation of 36 percent of which 16 percent was contributed by the carbon dioxide.

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National Advisory Committee for Aeronautics,
Cleveland, Ohio.
### TABLE I - PERFORMANCE OF CENTRIFUGAL-FLOW-TYPE TURBOJET ENGINE WITH WATER AS FUEL

Data as observed and corrected to standard sea-level conditions at

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<tr>
<th>Run</th>
<th>Barometric pressure (lb/sq in. absolute)</th>
<th>Exhaust nozzle diameter (in.)</th>
<th>Water flow, (W_w) (lb/sec)</th>
<th>Rotor speed, (N) (rpm)</th>
<th>Thrust, (F) (lb)</th>
<th>Air flow, (W_a) (lb/sec)</th>
<th>Fuel flow, (W_f) (lb/hr)</th>
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### NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

Committee for Aeronautics
### INJECTION OF WATER AND WATER-ALCOHOL MIXTURES AT COMPRESSOR INLETS

cowl inlet: temperature $T_0$, 519°F; pressure $P_0$, 14.70 lb/sq in.

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<th>Compressor-outlet total temperature, $T_{0c}$ (°R)</th>
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**NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS**
### TABLE I - PERFORMANCE OF CENTRIFUGAL-FLOW-TYPE TURBOJET ENGINE WITH BARO-EXHAUST WATER FLOW W;

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<th>Exhaust-diameter (in.)</th>
<th>Water flow, ( W ) (lb/sec)</th>
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<th>Thrust, ( F ) (lb)</th>
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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS
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### OF WATER AND WATER-ALCOHOL MIXTURES AT COMPRESSOR INLETS - Concluded

#### (a) Injection of water - Concluded

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#### (b) Injection of water-alcohol mixtures

| 1700 | 1700       | 0.472| 0.472      | 539  | 14.42      | 862  | 830        |
| 1560 | 1565       | 1.433| 1.434      | 537  | 14.42      | 843  | 814        |
| 1815 | 1817       | 1.054| 1.025      | 539  | 14.41      | 787  | 757        |
| 1690 | 1686       | 0.969| 0.988      | 539  | 14.41      | 793  | 756        |
| 1570 | 1569       | 0.856| 0.853      | 540  | 14.41      | 790  | 765        |
| 1425 | 1420       | 0.886| 0.911      | 542  | 14.41      | 806  | 771        |
| 1290 | 1282       | 0.677| 0.800      | 542  | 14.42      | 810  | 776        |
| 1137 | 1137       | 0.656| 0.556      | 543  | 14.42      | 816  | 780        |

### NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS
Figure 1. - Diagram of setup for refrigerant-injection investigations on centrifugal-flow-type turbojet engine.
Figure 2. Pressure and temperature instrumentation and refrigerant-injection equipment for a centrifugal-flow-type turbojet engine.
Figure 3. Injection setup showing carbon dioxide injection apparatus in foreground.
Initial temperature of carbon dioxide in bottle (°F) | Weight of carbon dioxide in bottle (lb)
---|---
28.0 | 72
72.0 | 69
74.5 | 69
100.5 | 70
103.0 | 70

Figure 4. - Instantaneous carbon-dioxide flow for several 75-pound-capacity carbon-dioxide bottles at different initial temperatures.
Figure 5. - Engine performance for various injected water flows for runs A and B. Corrected rotor speed, 16,500 rpm; cowl-inlet air temperature, 534° to 540° R.
Figure 5. - Continued. Engine performance for various injected water flows for runs A and B. Corrected rotor speed, 16,500 rpm; cowl-inlet air temperature, 5340° to 5400° R.
Figure 5. - Continued. Engine performance for various injected water flows for runs A and B. Corrected rotor speed, 16,500 rpm; cowl-inlet air temperature, 534° to 540° R.
Figure 5. - Concluded. Engine performance for various injected water flows for runs A and B. Corrected rotor speed, 16,500 rpm; cowl-inlet air temperature, 534° to 540° R.
Figure 6. - Engine performance for various water-alcohol mixtures injected during run D. Corrected total mixture flow, approximately 0.52 pound per second; corrected rotor speed, 16,000 rpm; exhaust-nozzle diameter, 12.0 inches; cowl-inlet air temperature, 537° to 543° R.
Figure 6. - Continued. Engine performance for various water-alcohol mixtures injected during run D. Corrected total mixture flow, approximately 0.52 pound per second; corrected rotor speed, 16,000 rpm; exhaust-nozzle diameter, 12.0 inches; cowl-inlet air temperature, 537° to 543° R.
Figure 6. - Concluded. Engine performance for various water-alcohol mixtures injected during run D. Corrected total mixture flow, approximately 0.52 pound per second; corrected rotor speed, 16,000 rpm; exhaust-nozzle diameter, 12.0 inches; cowl-inlet air temperature, 537° to 543° R.
Figure 7. - Engine performance for various water-alcohol mixtures injected during run E. Corrected water flow nearly constant at 1.6 pounds per second; exhaust-nozzle diameter, 12.0 inches; cowl-inlet air temperature, 541° to 546° R.
Figure 7. - Continued. Engine performance for various water-alcohol mixtures injected during run E. Corrected water flow nearly constant at 1.6 pounds per second; exhaust-nozzle diameter, 12.0 inches; cowl-inlet air temperature, 5410° to 5460° R.
Figure 7. - Concluded. Engine performance for various water-alcohol mixtures injected during run E. Corrected water flow nearly constant at 1.6 pounds per second; exhaust-nozzle diameter, 12.0 inches; cowl-inlet air temperature, 541° to 546° R.
Figure 8. - Thrust augmentation of centrifugal-flow-type turbojet engine by water and water-alcohol injection at a corrected rotor speed of 16,500 rpm; cowl-inlet air temperature, 534° to 543° R.
Figure 9. - Engine performance for various injected kerosene flows. Average ambient cell temperature, 535°F; 12.5-inch-diameter exhaust nozzle.
Figure 9. - Continued. Engine performance for various injected kerosene flows. Average ambient cell temperature, 535° R; 12.5-inch-diameter exhaust nozzle.
Figure 9. - Continued. Engine performance for various injected kerosene flows. Average ambient cell temperature, 535\(^{\circ}\) R; 12.5-inch-diameter exhaust nozzle.
Figure 9. - Concluded. Engine performance for various injected kerosene flows. Average ambient cell temperature, 535° R; 12.5-inch-diameter exhaust nozzle.
Figure 10. - Effect on engine performance of injection of carbon dioxide. Ambient cell temperature, 526° to 530° R; ambient cell pressure, 14.27 to 14.28 pounds per square inch; 12.5-inch-diameter exhaust nozzle.
Figure 11. - Effect on engine performance of injection of carbon dioxide with 1.7 lb/sec of 9:8 mixture of water and alcohol (alcohol consisting of 50-percent ethyl alcohol and 50-percent pure synthetic methyl alcohol). Ambient cell temperature, 5070 to 5140 R; ambient cell pressure, 14.50 to 14.51 pounds per square inch; 12.5-inch-diameter exhaust nozzle.