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Contingency Power for a Small Turboshaft Engine by Using Water Injection Into Turbine Cooling Air

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INTO TURBINE COOLING AIR

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ABSTRACT

Because of one-engine-inoperative (OEI) requirements, together with hot-gas reingestion and hot-day, high-altitude takeoff situations, power augmentation for multiengine rotorcraft has always been of critical interest. However, power augmentation by using overtemperature at the turbine inlet will shorten turbine life unless a method of limiting thermal and mechanical stresses is found. A possible solution involves allowing the turbine inlet temperature to rise to augment power while injecting water into the turbine cooling air to limit hot-section metal temperatures. An experimental water injection device was installed in an engine and successfully tested. Although concern for unprotected subcomponents in the engine hot section prevented demonstration of the technique's maximum potential, it was still possible to demonstrate increases in power while maintaining nearly constant turbine rotor blade temperature.

INTRODUCTION

Power augmentation for multiengine rotorcraft is of critical interest for such situations as operation with one engine inoperative (OEI), hot-gas reingestion, and hot-day, high-altitude takeoff. According to an earlier study (Ref. 1), one method of power augmentation is overspeed and overtemperature at the turbine inlet. However, power augmentation by using overtemperature at the turbine inlet will shorten turbine life unless a method of limiting thermal and mechanical stress is found.

A possible solution to this dilemma (Ref. 2) involves allowing the temperature at the turbine inlet to rise to augment power while injecting water into the turbine cooling air to maintain the hot-section metal temperatures. The latent heat of vaporization of the injected water is used as a heat sink to cool the compressor bleed air that is used for cooling the hot section. NASA Lewis has conducted a research study into the feasibility of supplementing turbine cooling by water injection during contingency power events on turboshaft engines. This study included aspects of basic heat transfer (Refs. 3 and 4) and

analytical feasibility and design (Refs. 5 and 6) as well as the experimental demonstration that is the subject of this report. The demonstration was on a T700-GE-701 turboshaft engine as an adjunct to an Army and NASA Small Turboshaft Engine Program (STEP).

Power augmentation by injecting water into the turbine cooling air is not a new concept. Water injection into the turbine cooling air and the combustor is currently being used in the Rolls-Royce Pegasus engine, the propulsion system for the Harrier aircraft (Ref. 7). What is new is the application of this technique to a small engine. The study by Van Fossen (Ref. 2) showed a large enough payoff in short-term power augmentation to warrant an experimental investigation along with a study of other contingency power techniques.

The study by Hirschkron (Ref. 6) showed significant potential advantage with four contingency power systems, one of which was the water-injection-into-turbine cooling scheme. The four systems were close enough to one another to be competitive in a practical engineering evaluation. It is significant to note that water injection into the compressor, which is currently used for power augmentation on some turbine engines, had lower payoff benefits than these four systems.

Before water injection into turbine cooling air can be given serious consideration for incorporation into a small turbine engine, a turbine cooling analysis is needed. The program undertaken and reported herein was an attempt to develop an experimental data base with which to evaluate the analyses in Ref. 5 and the studies in Ref. 6.

Consistent with the available resources, the demonstration was confined to a study of water injection into the compressor bleed air used for cooling the first-stage, high-pressure turbine blades. These rotor blades were chosen for study because the effect on life and the possible consequences during contingency power use, with significant increases in temperature, would be more severe than for any other component. The studies completed on engine cycle, heat transfer, and life analysis indicated that the concept is feasible. However, the

logistics of carrying water for this technique and the modifications to the engine control for contingency power situations must be addressed before a system can become operational. Hirschcron (Ref. 6) describes some of these installation and operational factors, such as design changes to a baseline engine to incorporate the water injection system and the system control and limits.

The objective of the tests was to demonstrate higher power output of a turboshaft engine while maintaining the turbine blade temperature by injecting water into the turbine cooling air. The results of these tests are presented in terms of the response of augmented power and turbine blade metal temperature to humid-air cooling during engine operation over a range of power settings. The experimental results of these tests are compared with the analytical results of Hirschcron (Ref. 5).

APPARATUS AND PROCEDURE

Engine

The engine used for the investigation, a T700-GE-701, was a front-drive turboshaft engine. It had an integral particle separator; a five-stage-axial-flow, single-stage-centrifugal-flow compressor; a throughflow annular combustor; a two-stage-axial-flow gas generator; and a free two-stage-axial-flow power turbine. Figure 1 shows a schematic of the engine.

Water Injection System

Figure 2 shows the water injection hardware. This consisted of water supply tubing and a water distribution ring installed within the engine combustor midframe assembly. The supply tubing entered the engine midframe outer housing through one of two igniter ports. It was then routed around the combustor and under the inner combustor shroud, where it mated with the distribution ring. The 0.250-in.-diameter tubing was enclosed in another 0.375-in.-diameter tube to the point where it passed under the shroud. The distribution ring was positioned around a bearing housing directly upstream of the turbine cooling air accelerator assembly. Briefly, the accelerator is a device to accelerate and direct axial flow in a tangential direction so as to aid flow distribution into the turbine rotor. The distribution ring, also of 0.250-in.-diameter tubing, contained five equally spaced 0.037-in.-diameter holes positioned in such a way as to direct the water into the accelerator passages and allow it to evaporate in the turbine cooling air.

Figure 3 shows a schematic representation of the water injection supply system. This consisted of a pressurized reservoir of distilled water, a high-pressure gaseous nitrogen supply, valves, tubing, and system-monitoring instrumentation.

Engine Instrumentation

The instrumentation used for the engine test program consisted both of hot-section instrumentation specifically installed for the contingency power tests and of the normal complement of instrumentation for monitoring engine operation. The hot-section instrumentation consisted of thermocouples and static pressure taps. The thermocouples on the injector tube were positioned to indicate the condition of the water as it pro-

gressed from the supply tank to the distribution ring. The thermocouples and static pressure probes upstream and downstream of the accelerator measured the quality of the steam/air mixture and determined the mass flow through the accelerator. The remaining instrumentation on the seals, the turbine nozzles, the turbine shrouds, the turbine nozzle platforms, and the combustor liner was used to observe the condition of the hot section.

Pyrometer

The most important instrument required for the test was an optical pyrometer. The pyrometer assembly consisted of a photodiode, a lens, and the associated electronics within a water-cooled case. Figure 4 shows the location of the pyrometer in the engine hot section. It was mounted on a first-stage turbine nozzle segment within the engine midframe and directed at the leading edge of the first-stage turbine blades. The signal lead and the cooling water supply and return tubing were routed through specially prepared holes in the outer midframe housing.

The pyrometer system output was connected to an oscilloscope for real-time display and photographing and to a wide-band frequency-modulated (FM) tape recorder for subsequent data recording and analysis. Also part of the system was a once-per-revolution speed signal that was recorded and used as an index marking to identify specific turbine blades.

Model Tests

Before the engine test a model test of the water injection system was performed to obtain accelerator calibration data, to verify assumptions made during conceptual design studies, and to gain operational experience with the system.

Engine Tests

The conditions under which the engine was tested with the turbine cooling water injection system are summarized in Table I. The water injection concept was initially demonstrated at settings below intermediate rated power (IRP). IRP is defined as the maximum power setting that can be maintained

TABLE I.—ENGINE SETTINGS FOR CONTINGENCY
POWER INVESTIGATION USING WATER-AIR
TURBINE COOLING

Test	Identification	Water/cooling air ratio, percent
1.0	Shakedown	-----
2.0	Baseline data	-----
3.0	Shakedown of water injection system	-----
4.0	Turbine inlet temperature < IRP:	
4.1	Base	0 to 10
4.2	Base + 100 deg F	0 to 10
4.3	Base + 135 deg F	0 to 10
5.0	Turbine inlet temperature ≥ IRP:	
5.1	IRP	0 to 6
5.2	IRP+	0 to 6

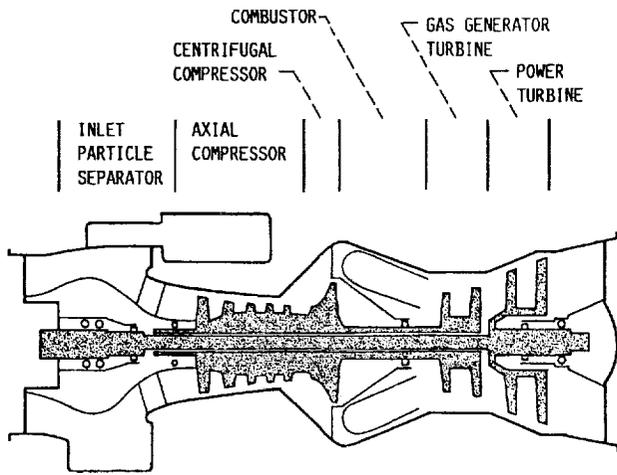


FIG. 1 SCHEMATIC OF ENGINE.

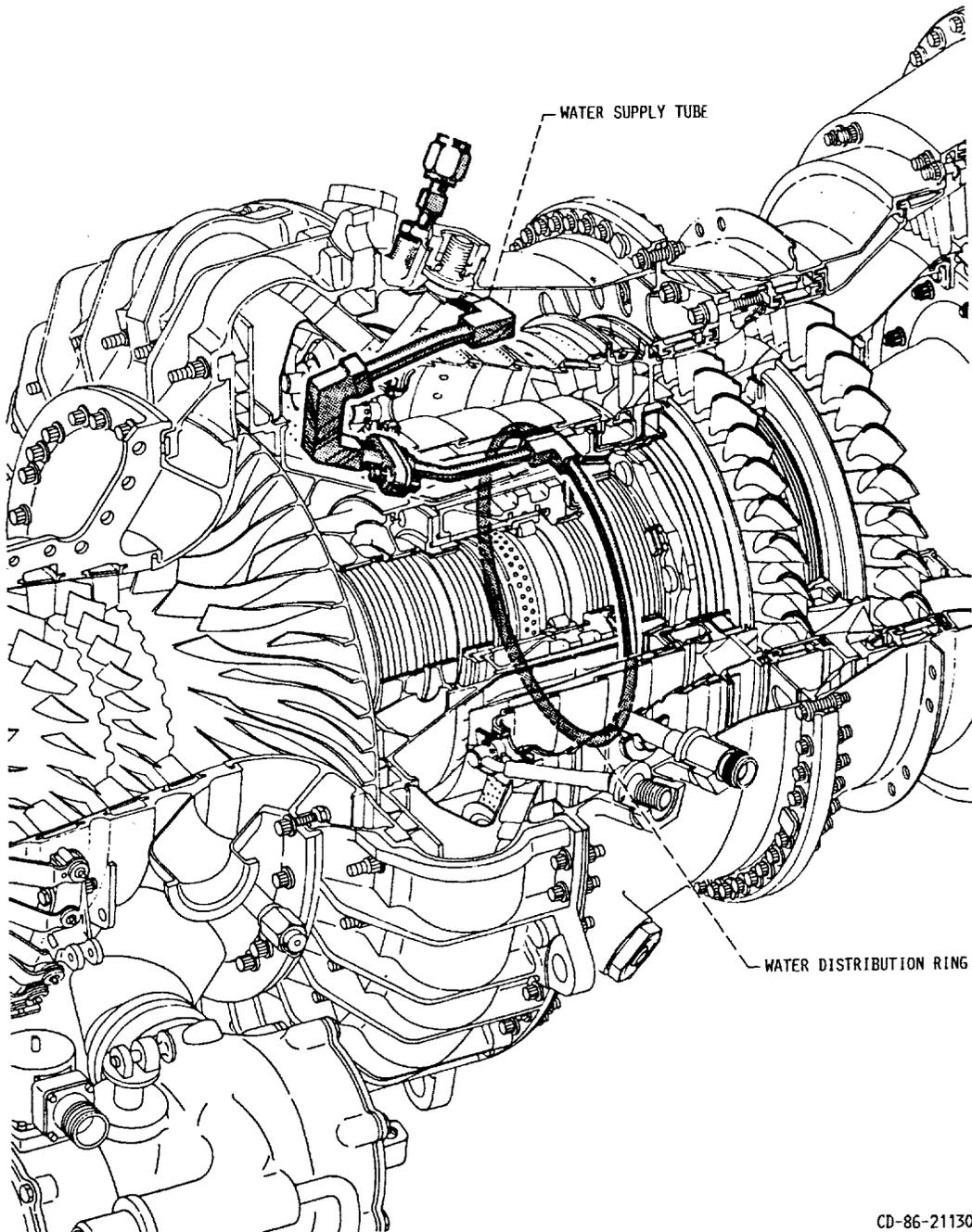


FIG. 2 WATER INJECTION SYSTEM INSTALLED IN ENGINE.

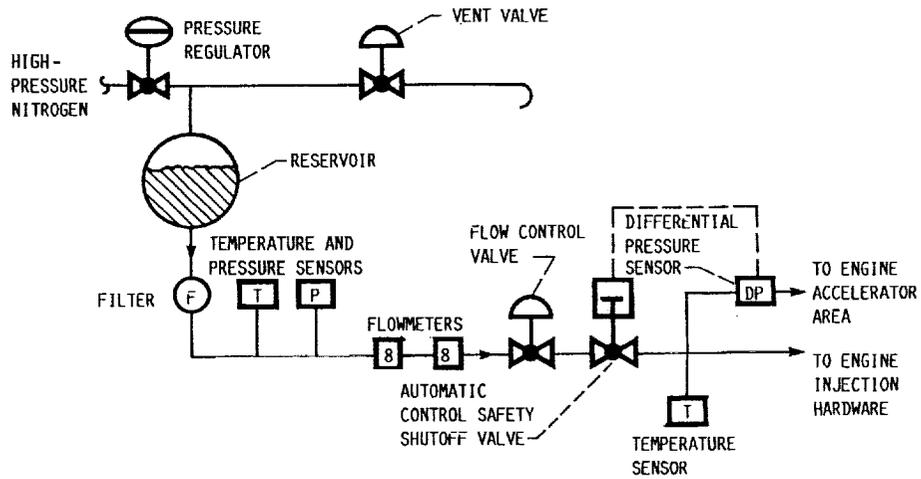


FIG. 3 SCHEMATIC OF WATER INJECTION SUPPLY SYSTEM.

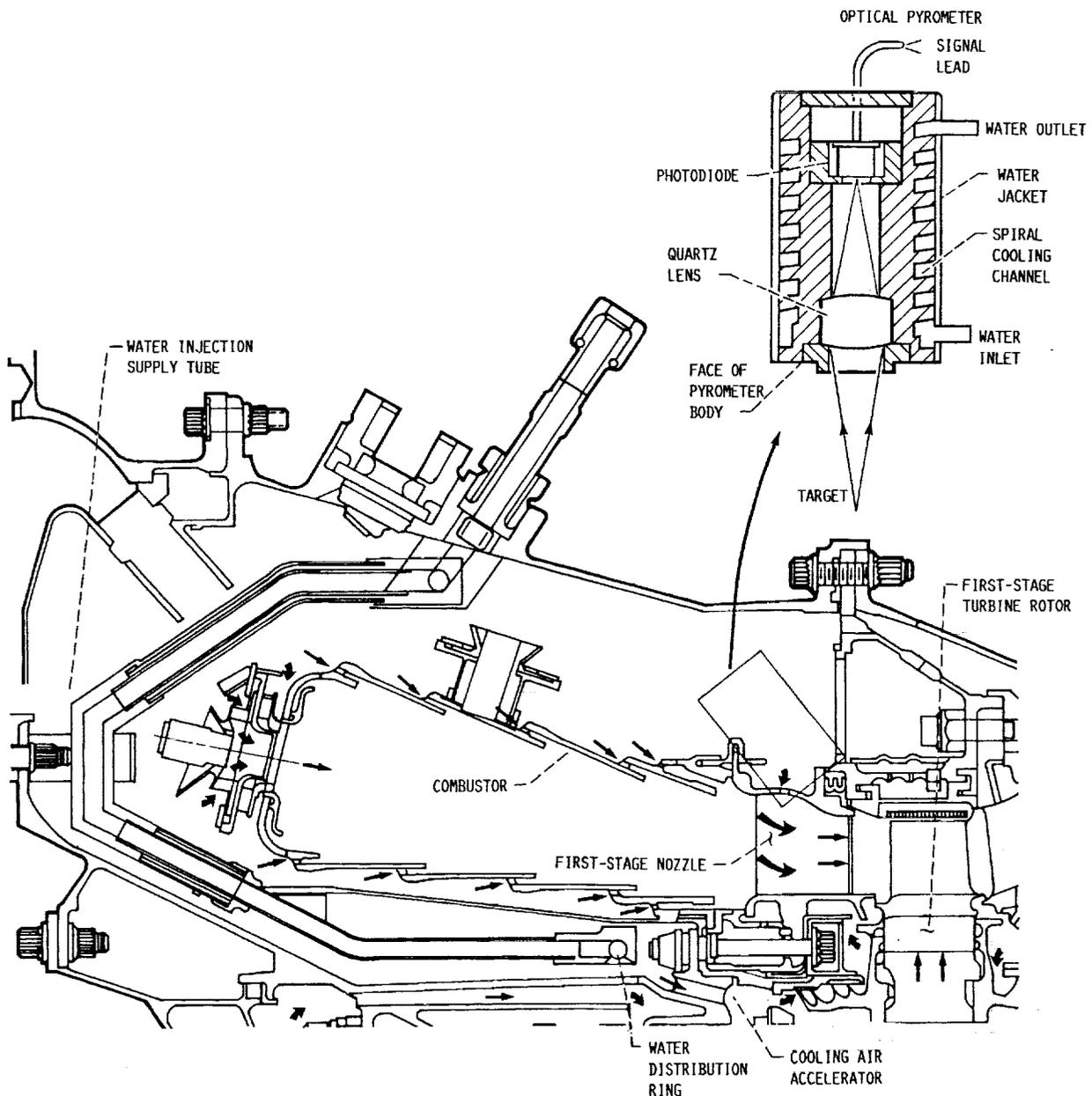


FIG. 4 LOCATION OF PYROMETER IN ENGINE HOT SECTION.

for 30 min without loss of hot-section life. Data were obtained at several water-flow rates to validate the measuring system and the predictions of metal temperature versus water-flow rate before testing above IRP was begun.

The objective of the engine test was to increase the maximum power output by raising the turbine inlet temperature while keeping the bulk temperature of the first-stage turbine rotor blades within limits.

The test procedure followed a conservative approach. A "derated" part-power base setting was selected where no water was injected. Measurements were then systematically made at increasing power levels while injecting water. By taking fairly small increments in temperature, the engineers could observe any unpredicted trends should they occur. Each water-flow rate was held for 1 to 2 min. Hot-section temperature limits were established and adhered to as the test progressed.

The baseline data from which exploration at temperatures above IRP was conducted, the guidelines used from Hirschkron (Ref. 5), and our experimental observations are discussed in the following statements:

(1) Temperature data from the thermocouples described in the section "Engine Instrumentation" were recorded. These data were extrapolated and used as a guide during the subsequent exploration to higher turbine inlet temperatures.

(2) Significant deviations of test data from predicted values would warrant further investigation and corrective action, including inspection of hot-section hardware. No significant deviations were seen during the engine testing.

(3) A number of routine inspections of hot-section hardware would be performed to establish a correlation between the hot-section condition and the temperature levels above the established baseline. A new baseline would be established each time a hot-section inspection was conducted. No abnormalities were seen during the inspections.

(4) The blade leading-edge temperatures would be measured with the optical pyrometer.

RESULTS AND DISCUSSION

The results of model tests with the water injection system are presented, as well as the results of the engine tests. The model results affected the choice of injection configuration for the engine and were used to calibrate the cooling system.

Model Tests

The model tests were conducted to determine the water flow that could be effectively added to the turbine cooling airflow of the full-scale turboshaft engine. This information was obtained as well as information on the mass flow function for the turbine cooling air system accelerator. This was also an opportunity to gain operational experience with the water supply system before its use with the engine.

The upper limit of water addition was to be determined by plotting the temperature of the mixture against the water/cooling air ratio (Fig. 5). The point at which the water had little additional effect was anticipated to be shown by a corresponding change in slope on the aforementioned curve. The cooling effectiveness of the water addition was of significance at least to a water/cooling air ratio of 13 percent, the limit of the test rig.

The model tests were conducted with either 5 holes or 15 holes in the distribution ring. No significant transient or steady-state differences were noted between these two configurations. The 5-hole configuration was chosen for the engine tests because it resulted in a higher pressure differential in the supply system and thus allowed greater control of the water.

Engine Tests

The engine test results include a visual inspection report that was compiled after testing had been completed and a detailed discussion of the engine data. The test results show the benefits of water injection into the turbine cooling air and include a comparison of engine data with both the model test data and the predicted results from the conceptual design study (Ref. 5).

Overall Engine Condition

A borescope inspection showed no visual signs of hot-section distress. No engine hot-section disassembly was performed, nor was it required. Operational limits regarding gas generator and power output shaft speeds and temperature were never exceeded so as to retain as much turbine blade life as possible. This restriction was also imposed because the engine is a test bed intended for future research work.

This is not to insinuate that no risk was involved in the program. Quite the opposite was true. For the maximum power situations the engine electronic control unit (ECU) was locked out. The engine operator was thus required to monitor and limit rotor speed and turbine temperature. Because of the configuration of the facility power absorber controls, and since the engine ECU was locked out, the power absorber command signal required manual biasing (by a second operator) to control engine power output speed and to reach the higher power levels. The addition of water injection required a third operator who affected the operating level of the engine. Considering these test variables, a key factor in the successful completion of the testing was the support personnel's expertise.

No atypical vibrations were observed during the testing, nor was a compressor stall indicated. The system used for stall detection was proven to be reliable in previous engine tests. The pyrometer performed flawlessly for the duration of the tests, approximately 26 hr, and fulfilled its intended purpose as the primary data source.

Transient System Response

A consideration during the design and planning stage of the program was the state of the water/steam passing through the

injection system. Too much water downstream of the turbine cooling air accelerator (Fig. 4) could conceivably result in "flooding" and sudden cooling of such components as seals. With too little water the first-stage turbine blades would not be cooled enough to allow for higher turbine inlet temperatures as fuel was added. A maldistribution of the coolant might lead to temperature nonuniformities in the seals downstream of the accelerator and eventual turbine distress. The time to charge the system, or the time to reach a steady-state condition, before the turbine temperature could be increased was also a consideration.

The concerns about control of the engine and the water injection system if flooding, insufficient cooling, and maldistribution of flow occurred were minimized mainly by the test techniques employed and the hardware developed for the program. Regarding the transient response of the system, for a typical water/cooling air ratio of approximately 6 percent, approximately 5 sec elapsed from the time water flow was initiated until a change in temperature was observed. This occurred at a thermocouple measuring a temperature near the water distribution ring. Furthermore, a significant drop in temperature did not occur until about 3 sec later. It should be noted that the time differential between water addition and temperature drop must be taken into account in an operational system. The thermocouples downstream of the accelerator, where the air/steam mixture should be most completely mixed, showed a greater delay.

Steady-State Results

Water was added to the turbine cooling air as described in the section "Water Injection System." With water addition the rotor speed (Fig. 6) decreased as did the power output (Fig. 7). These figures show that adding water in itself did not necessarily result in a net gain in engine performance. In fact, just the opposite effect is revealed in these parameters.

The loss in speed and, in turn, the loss in power were anticipated during the conceptual design study. Turbine cooling air flow is greater with water injection because the cooling air becomes denser as water is added. Thus, more compressor air is diverted for turbine cooling, and less air is available to drive the turbine than with dry turbine cooling air. The result is a decrease in rotor speed. Another consideration was that the cooler turbine blades become shorter, thus increasing the tip clearance and causing a drop in turbine efficiency (Ref. 5). Hirschcron (Refs. 5 and 6) addresses other effects on the engine and components with water injection, but insufficient instrumentation was available in the test-bed engine to verify his analytical work. A significant result of these studies was that turbine life was estimated to be over 30 times shorter without water injection than with it at a turbine inlet gas temperature 300 deg F above IRP.

The speed decrease would be only one consequence of water injection if this were an operational system. The additional heat sink available in the turbine cooling air because of the water's latent heat of vaporization did lower the first-stage, turbine blade, leading-edge temperature (Fig. 8) even as rotor speed and power decreased. The water addition permitted operation at a higher turbine rotor inlet temperature, as would be accomplished in a real-world contingency power situation by a throttle push or a fuel increase.

The throttle push was done and Fig. 9 shows the results for engine operation at or near IRP where contingency power is normally applicable. These data were obtained by increasing the rotor speed after water addition until it was approximately equal to the speed before water addition. The result was a turbine blade leading-edge temperature that was approximately the same with and without water injection but a higher power output with water injection.

The power increase was approximately 3 to 5 percent for a 6- to 7-percent water addition. This allowed a corresponding turbine rotor inlet temperature increase of about 60 deg F. This result agreed with the rate of power increase estimated in the conceptual design study. If the restraints previously mentioned for this test-bed engine did not exist and it were possible to raise the turbine rotor inlet temperature by 300 deg F as was done in the conceptual design study, a 17-percent increase in power could be realized.

The model data (Fig. 5) show the potential for cooling effectiveness to at least a 13-percent water/cooling air ratio. However, data were not gathered at IRP, or above, beyond a 6- to 7-percent water/cooling air ratio (Fig. 8) because there was concern about possible thermal shock and seal distortion near the humid-air mixing station. Thermocouple readings of the humid air downstream of the accelerator did show a temperature maldistribution that increased with increasing water/cooling air ratio. One explanation for the maldistribution is that it could be a configuration-dependent mixing problem (i.e., type of distribution ring, number of holes in the ring, engine configuration, etc.).

Comparison of Engine and Model Results

Engine and model test results disagreed in predicting the water/cooling air ratio beyond which this configuration would show no increase in cooling capacity. This can be seen by comparing Figs. 5 and 8, which show marked differences in slope (or decreases in temperature) at the various water/cooling air ratios. This lends credence to the argument that the engine data are limited in water/cooling air ratio effectiveness by configuration constraints rather than saturation conditions.

Comparison of Engine and Conceptual Design Results

Comparing first-stage, turbine blade, leading-edge temperatures from the engine test results and the conceptual design study was difficult because the engine test was run at varying turbine inlet temperatures while the study was performed at a constant turbine inlet temperature. An attempt was made (Fig. 10) to compare the test and study results by using a dimensionless temperature parameter. This parameter contained key temperatures, such as turbine inlet temperature, coolant temperature, and turbine blade leading-edge temperature. The equation is $T^* = (T_M - T_C)/(T_G - T_C)$ where T_C is the coolant temperature downstream of the accelerator, T_G is the calculated turbine-rotor-inlet gas temperature, and T_M is the first-stage, turbine blade, leading-edge temperature.

Considering the limited amount of data available and the limited range of conditions covered during engine tests, the results are reasonable. The disagreement can be explained by

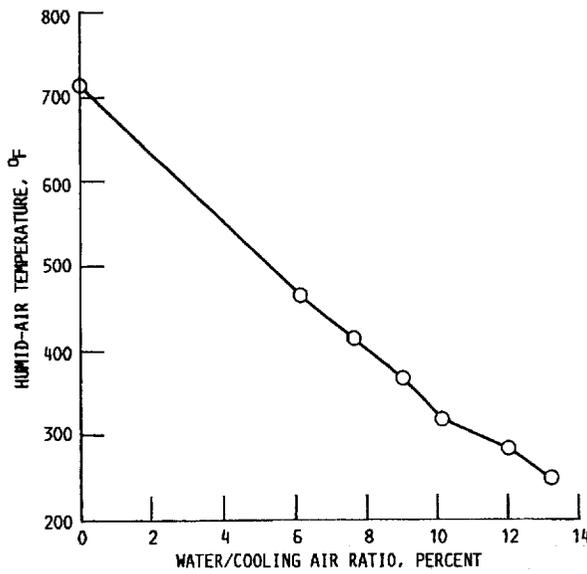


FIG. 5. - EFFECT OF WATER/COOLING AIR RATIO ON HUMID-AIR TEMPERATURE DOWNSTREAM OF ACCELERATOR. FIVE-HOLE DISTRIBUTION RING; AIRFLOW RATE, 0.46 LB/SEC.

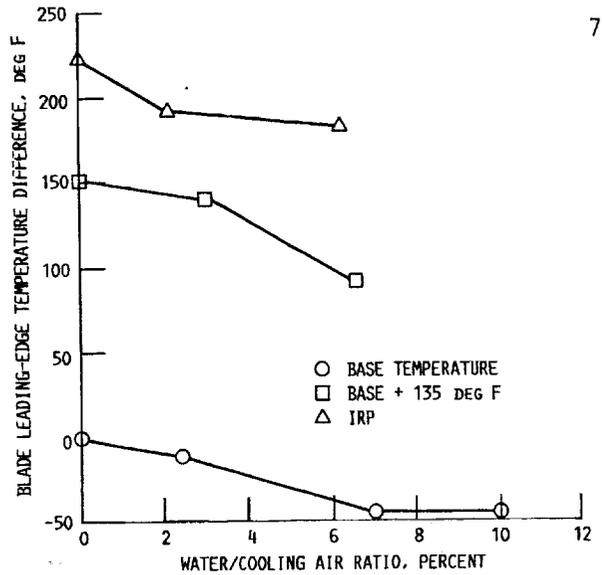


FIG. 8 EFFECT OF WATER/COOLING AIR RATIO ON FIRST-STAGE, TURBINE BLADE, LEADING-EDGE TEMPERATURE.

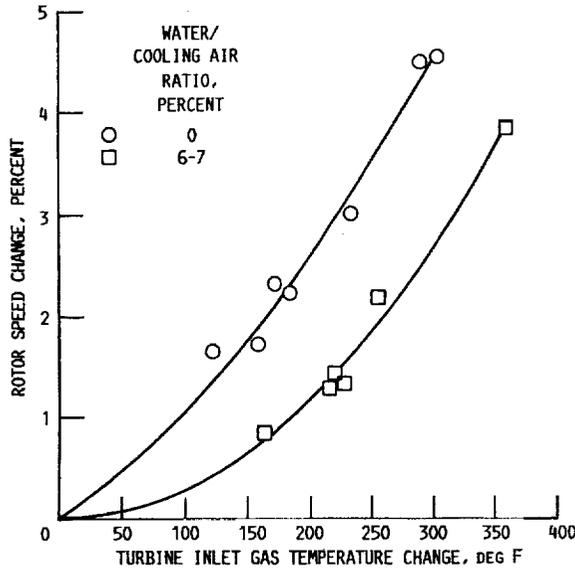


FIG. 6 EFFECT OF WATER ADDITION ON ROTOR SPEED AND TURBINE INLET TEMPERATURE (CHANGE FROM BASE CONDITION).

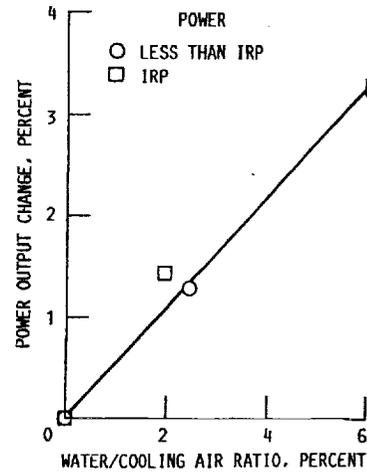


FIG. 9 EFFECT OF WATER/COOLING AIR RATIO ON POWER OUTPUT WITH FIRST-STAGE, TURBINE BLADE, LEADING-EDGE TEMPERATURE CONSTANT.

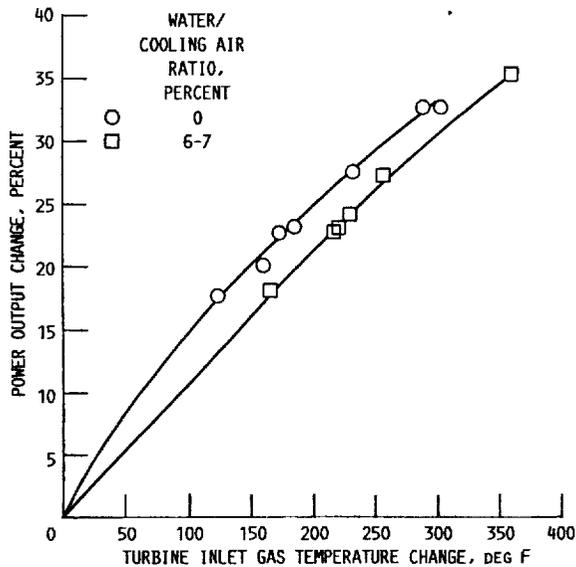


FIG. 7 EFFECT OF WATER ADDITION ON POWER OUTPUT AND TURBINE INLET TEMPERATURE (CHANGE FROM BASE CONDITION).

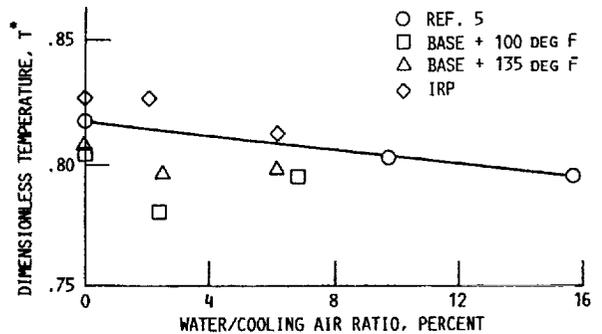


FIG. 10 EFFECT OF WATER/COOLING AIR RATIO ON DIMENSIONLESS TEMPERATURE. $T^* = (T_M - T_C)/(T_G - T_C)$.

the lack of instrumentation for accurately determining the mixed air/steam temperature downstream of the accelerator due to space restrictions.

CONCLUDING REMARKS

An experimental investigation was conducted into the feasibility of supplementing turbine cooling air through water injection. The results of this investigation led to the following observations:

(1) A unique system for injecting and evaporating water into the turbine cooling air was successfully designed, fabricated, installed, and tested in a small turbine engine.

(2) The results of the tests demonstrated the potential for increases in power of 17 percent corresponding to increases in turbine inlet temperature of 300 deg F, while maintaining constant turbine rotor blade temperature.

(3) Concern for unprotected subcomponents in the hot section prevented demonstration of the technique's higher potential.

(4) Further development of this unique system is required to optimize its potential for contingency power.

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