[redacted]

~~CONFIDENTIAL~~

Copy 304
RM E56J15

NACA RM E56J15

2869

Reg# 1346

RESEARCH MEMORANDUM

EXPERIMENTAL INVESTIGATION OF WATER INJECTION IN SUBSONIC DIFFUSER OF A CONICAL INLET OPERATING AT FREE-STREAM MACH NUMBER OF 2.5

By Andrew Beke

Lewis Flight Propulsion Laboratory
Cleveland, Ohio

Classi... ch...ed to ....Unclassified..)

By ... NASA Tech Pub Announcement #12...
(OFFICER AUTHORIZED TO CHANGE)

By .... 14 April 62........

NK ....
GRADE OF OFFICER MAKING CHANGE)

15 Feb 61 ....

CLASSIFIED DOCUMENT

This material contains information affecting the National Defense of the United States within the meaning of the espionage laws, Title 18, U.S.C., Secs. 793 and 794, the transmission or revelation of which in any manner to an unauthorized person is prohibited by law.

NATIONAL ADVISORY COMMITTEE
FOR AERONAUTICS
WASHINGTON
January 15, 1957

[redacted]

~~CONFIDENTIAL~~

NACA RM E56J15 [redacted]

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

RESEARCH MEMORANDUM

EXPERIMENTAL INVESTIGATION OF WATER INJECTION IN SUBSONIC DIFFUSER OF A CONICAL INLET OPERATING AT FREE-STREAM MACH NUMBER OF 2.5

By Andrew Beke

SUMMARY

The on-design performance of a spike-type nose inlet with various amounts of water injection in the subsonic diffuser was investigated at zero angle of attack. The inlet consisted of a 30° half-angle cone and a sharp-lip cowl for on-design performance at a free-stream Mach number of 2.5 followed by a 16-inch-diameter, 11-foot-long subsonic diffuser section.

The inlet total temperature of 630° R could be reduced to 540° R at the diffuser exit with liquid-air ratios of about 0.04 with no apparent change in the critical pressure recovery. The observed temperature drops were 40 percent less than the theoretically predicted values, and the amount of water evaporated was 35 to 50 percent less than that theoretically possible.

INTRODUCTION

An analytical investigation of water injection in the subsonic diffuser based on 100-percent evaporation is reported in reference 1 as a possible technique for turbojet-engine - inlet matching at supersonic speeds. However, little experimental data are available on the actual amount of evaporation obtainable with inlets operating at supersonic speeds as well as on the effect of water injection on inlet performance. A brief experimental investigation was therefore undertaken to determine the effects of liquid evaporation upon supersonic-inlet performance.

A spike-type nacelle inlet was investigated with liquid-air ratios up to 4 percent at a free-stream Mach number of 2.5 in the 10- by 10-foot supersonic wind tunnel at the NACA Lewis laboratory. Inlet total-pressure recovery and total-temperature ratio were obtained over a range of corrected airflows. Temperature changes for various liquid-air ratios

[redacted]

[redacted]

were compared with theoretical values, and the associated relative humidities and evaporation efficiencies are reported herein.

SYMBOLS

The following symbols are used in this report:

A	area, sq ft
P	total pressure, lb/sq ft
T	total temperature, $^{\circ}R$
ΔT	total-temperature change, $T_0 - T_5$, $^{\circ}R$
w	air or liquid flow rate, lb/sec
$\frac{w\sqrt{\theta}}{\delta A}$	corrected weight flow per unit diffuser-discharge area, lb/(sec)(sq ft)
x	longitudinal distance from cowl lip, in.
δ	ratio of total pressure to NACA standard sea-level pressure of 2116 lb/sq ft
η	evaporation efficiency, $\frac{(w_l/w_a)_{th}}{(w_l/w_a)_{ac}}$ at $\Delta T_{th} = \Delta T_{ex}$
θ	ratio of total temperature to NACA standard sea-level temperature of 518.7° R
φ	relative humidity, $p_v/p_{s.v.}$

Subscripts:

a	air
ac	actual
e	evaporation
ex	experimental
l	liquid
s.v.	saturated vapor

th	theoretical
v	vapor
x	longitudinal
0	free stream
5	diffuser discharge, station 145

4211

APPARATUS AND PROCEDURE

The 16-inch nacelle inlet used in this investigation is shown schematically in figure 1. It consisted of a single-conical-shock nose inlet with a sharp-lip cowl and about a 11-foot subsonic-diffusion section. The inlet had a 30° half-angle cone located so that the conical shock would intersect the cowl lip at a free-stream Mach number of 2.5. The internal slope of the cowl lip was approximately 10°, while the external angle was about 15°. Variation of the subsonic-diffuser area and the isentropic-flow velocity at critical inlet conditions is shown in figures 2 and 3, respectively.

CA-1 back

Water was injected into the subsonic-diffuser section 10 inches downstream of the cowl lip (fig. 1) by means of 10 manifolded, commercial nozzles rated at 40 gallons per hour at 100 pounds per square inch. The nozzles were flush-mounted on the cowl wall, and the water was injected approximately normal to the airstream direction. Water flow rates were recorded on standard flow-metering devices and were checked by an independent calibration of the liquid-injection system.

Total-temperature and static-pressure measurements were made at the diffuser-discharge station slightly upstream of the mass flow control plug, station 145 (fig. 1). Although station 145 is not the diffuser exit of the inlet, it serves as a representative duct length between the inlet and compressor face for many turbojet-engine installations. Because of the presence of water in the airstream, both shielded and unshielded thermocouples were used (fig. 1). Thus the temperatures obtained with the shielded rake could be compared with those from the unshielded rake to determine if the shielded thermocouples were reliably reading dry-bulb or airstream temperature.

Eight static-pressure orifices were located circumferentially about the diffuser discharge, station 145. Mass flow total-pressure recoveries were computed by the choked-plug method using the measured average total temperatures from the shielded-thermocouple rake and the circumferentially located static-pressure orifices. Due to expected inaccuracies in obtaining air temperatures in the presence of water vapor, checks of the experimentally measured temperature were made by calculating the temperature from the known inlet airflow and static-pressure recoveries at supercritical inlet flow conditions. Good agreement between the experimentally measured and calculated values of temperature was obtained in the region of critical inlet flow for the entire range of liquid-air ratios investigated. The theoretical relative humidities and temperature drops were obtained by the method outlined in reference 1.

RESULTS AND DISCUSSION

The total-pressure and -temperature ratios and corrected airflow for the range of liquid-air ratios investigated are presented in figure 4, and a comparison of experimental and theoretical temperature relations is shown in figure 5.

In figure 4 (for convenience in use with the corrected airflow parameter) the ratio of the square root of the total temperatures and the associated total-pressure recoveries at various corrected airflows are presented with and without water injection. The diffuser-exit total temperatures decreased with increased liquid injection. The largest decrease in diffuser-exit temperature represents a temperature change from 630° R to about 540° R ($w_l/w_a = 0.037$). There also appears, for a given liquid-air ratio, a slight reduction of the diffuser temperature ratio with increased corrected airflow. This is probably due to improved liquid dispersal resulting from increased agitation by movement of the terminal shock farther into the diffuser as the corrected airflow is increased.

Increased liquid-air ratios appeared to have negligible effect on critical inlet total-pressure ratio. However, as would be expected because of the effect of temperature on θ, the critical inlet corrected airflow decreased from 15.7 without water injection to about 15 at a liquid-air ratio of about 4 percent. This reduction of critical inlet corrected airflow, which is about 5 percent, is also reflected in the lower corrected airflow at which pulsing occurs with increased liquid injection (fig. 4, top). For example, without injection the stability limit is at a corrected airflow of 14.0, whereas it is at 13.5 for a liquid-air ratio of about 0.04. However, the percentage of subcritical airflow spillage is about the same with and without injection, so that there is no increase in the stability margin resulting from liquid injection.

The feasibility of using water injection as a means for engine-inlet matching as well as thrust augmentation depends a great deal upon the evaporation efficiency as well as the quantities of water which can be injected without saturating the diffuser airflow. Therefore, a comparison is made in figure 5 between the experimental temperature drops obtained and the theoretical values. The theoretical values are based on the complete evaporation in a one-dimensional channel having an initial subsonic Mach number equal to that behind the terminal shock at critical inlet flow (see fig. 3).

As apparent in the lower portion of figure 5, the experimental temperature changes are 40 percent less than the theoretically expected temperature changes below the saturation point. In the saturated region, the data slightly exceed the theoretical $\Delta T/T_0$, possibly because of the data scatter which is a maximum of about 10° F. It may also have resulted from the difference in the assumed and actual effective velocity at which the water evaporates (fig. 3). The evaporation efficiency (center curve), based on the ratio of the ideal to the actual liquid-air ratio used to obtain the same temperature change, fell 35 percent below theoretical at $w_l/w_a = 0.01$ and decreased to about 50 percent below theoretical with increased liquid injection. The deviation of the theoretical from the experimental values of relative humidity (fig. 5, top) obviously resulted from the lesser amounts of vapor actually produced in contrast with the amount it was theoretically possible to evaporate. In considering engine performance, if the quantities of actual vapor in the air do not reach a value of more than 2 percent, the water vapor would not have a significant effect upon corrected engine parameters (ref. 2). However, if the total injected amount of water (about 4 percent) is evaporated partially in the diffuser and the remainder in the mechanical compression process, reference 3 indicates that engine performance may begin to fall off because of reduced primary burner and afterburner efficiency.

Since water injection may be used for turbojet-engine - inlet matching (ref. 1), it is desirable to consider the experimental results in view of the matching problem. The temperature changes found in figure 4 provide up to an 8-percent increase in turbojet-engine corrected rotative speed for an engine operating at a constant mechanical speed. If, for example, turbojet-engine - inlet combination were operating with airflow spillage equal to the proportional increase of engine corrected airflow associated with the 8-percent corrected rotative speed margin, the inlet and engine could be matched with no spillage and with concomitant thrust gains by using water injection.

Under actual flight conditions in the tropopause, the total temperature would be 890° R, so that temperature changes as well as evaporation presumably should be higher than indicated by the data which were obtained at 630° R. Therefore, the available "matching-margin" also would be greater. Other factors which would tend to affect evaporation (consequently, temperature changes) are the altitude and the diffuser-inlet Mach number (see appendix A, ref. 1).

SUMMARY OF RESULTS

An investigation of water injection in the subsonic diffuser of a typical supersonic inlet operating at a free-stream Mach number of 2.5 indicated the following results:

1. The inlet total temperature of 630° R was reduced to 540° R at a liquid-air ratio of about 4 percent.

2. Critical inlet total-pressure recovery was negligibly affected by water injection, and the evaporation cooling effectively reduced the critical diffuser-discharge corrected airflow up to about 5 percent.

3. Temperature drops were 40 percent less than the maximum theoretically obtainable, and evaporation efficiency was 35 to 50 percent less than theoretical.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, October 19, 1956

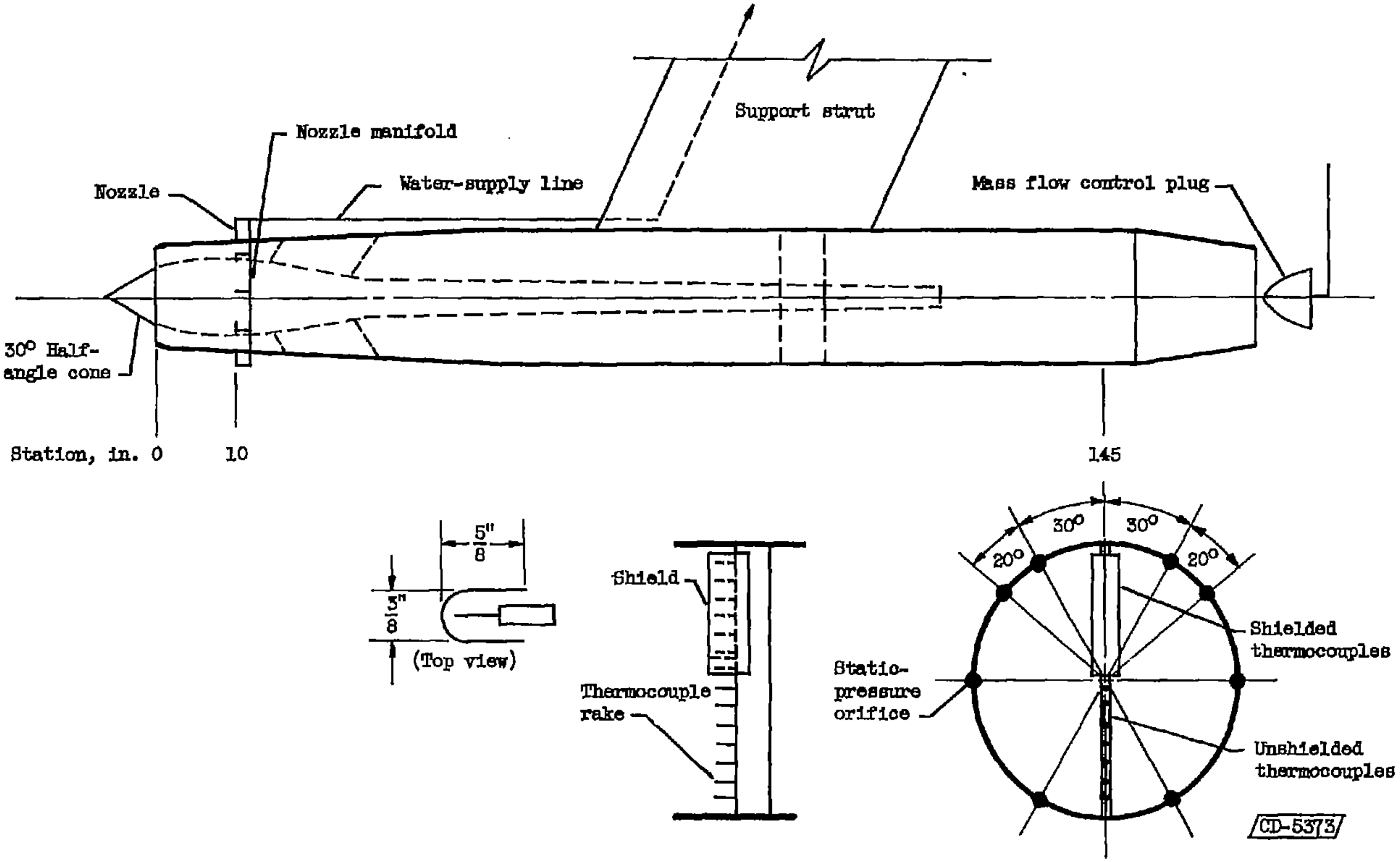
REFERENCES

1. Beke, Andrew: Analytical Investigation of the Effect of Water Injection on Supersonic Turbojet-Engine - Inlet Matching and Thrust Augmentation. NACA TN 3922, 1956.

2. Samuels, John C., and Gale, B. M.: Effect of Humidity on Performance of Turbojet Engines. NACA TN 2119, 1950.

3. Dietz, Robert O., Jr, Wishneck, George, and Kuenzig, John K.: Altitude-Wind-Tunnel Investigation of Thrust Augmentation of a Turbojet Engine. IV - Performance with Tail-Pipe Burning and Water Injection. NACA RM E7L16, 1948.

4277



Thermocouple details

Station 145 instrumentation

Figure 1. - Schematic diagram of 16-inch nacelle inlet and instrumentation.

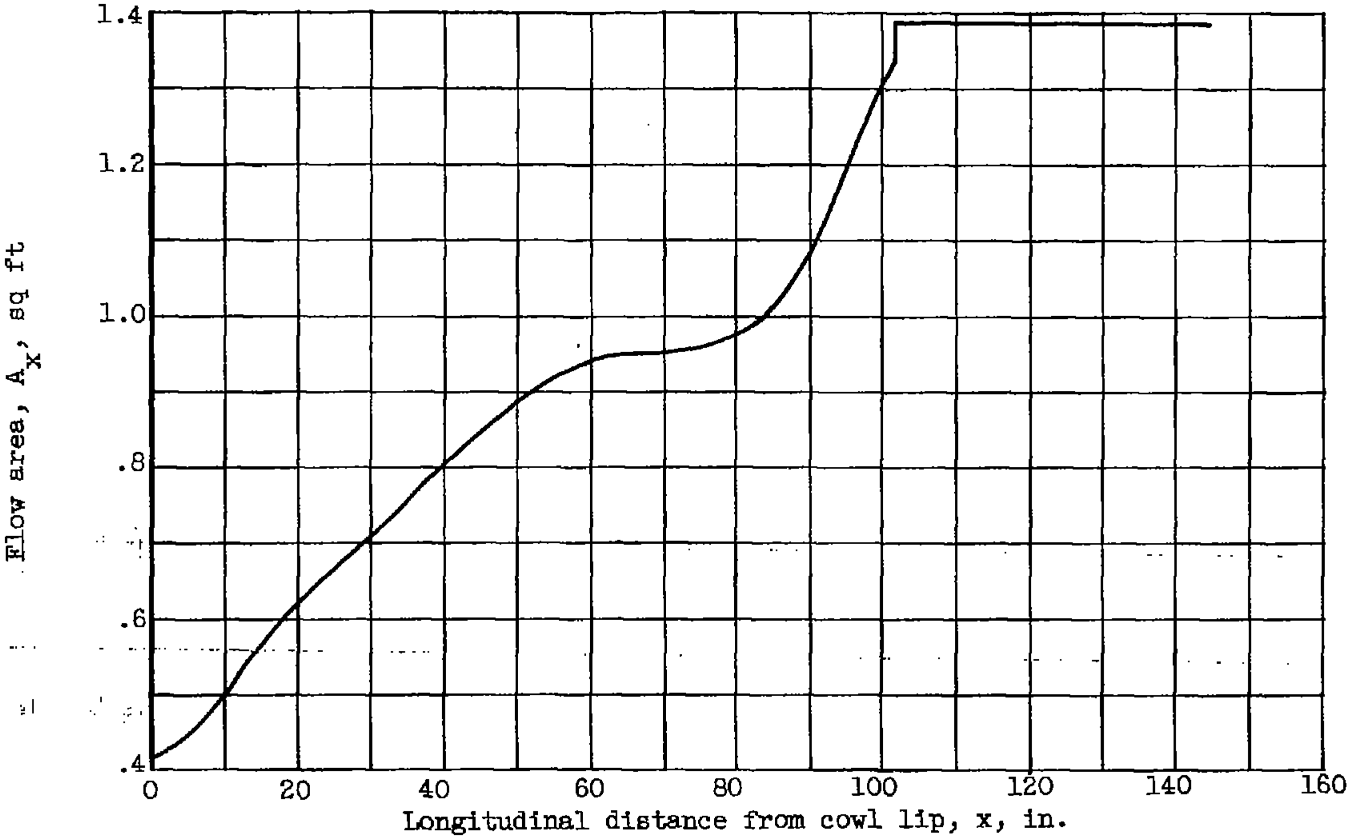


Figure 2. - Subsonic-diffuser-area variation.

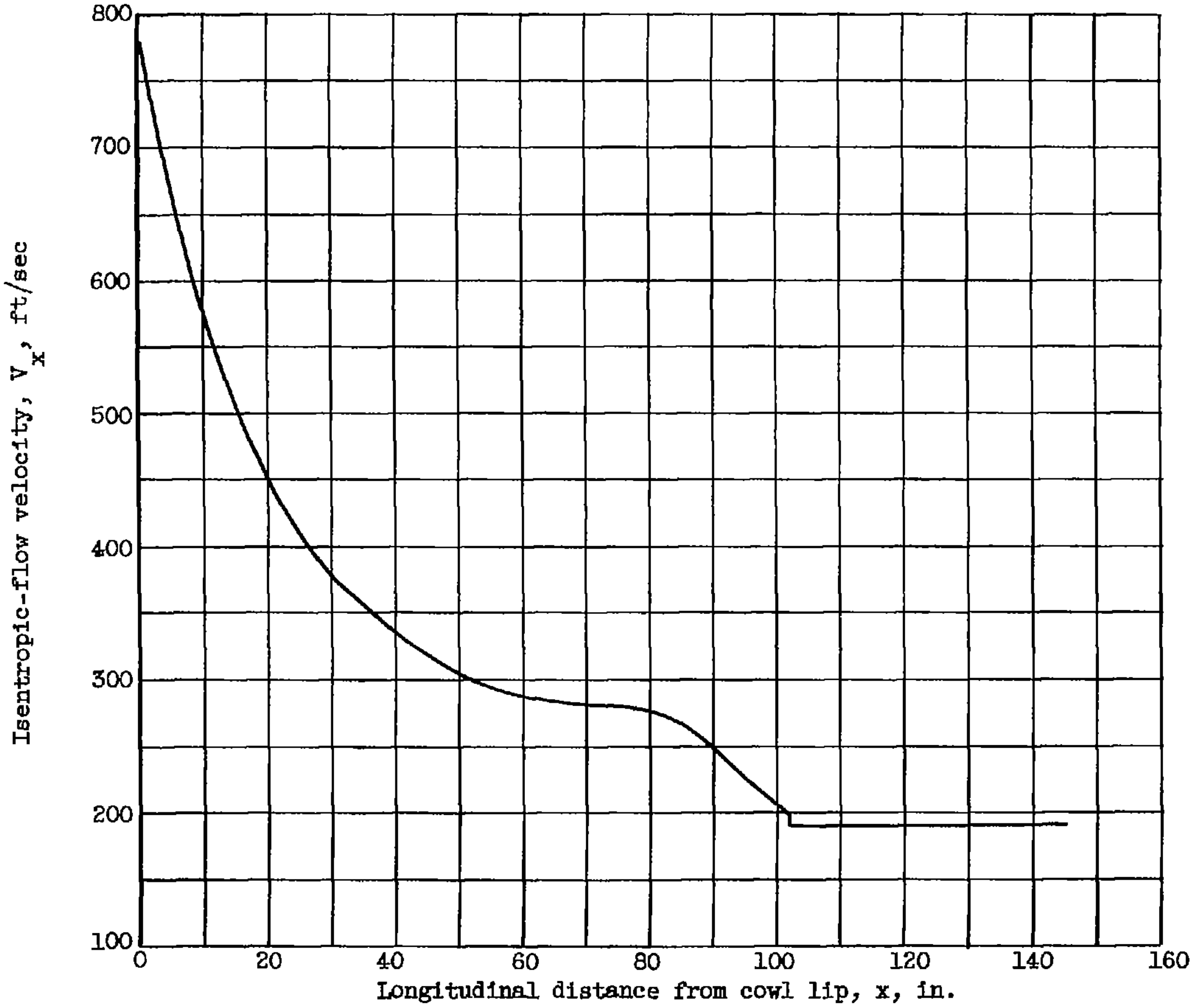


Figure 3. - Subsonic-diffuser velocity distribution. Inlet total temperature, 630° R.

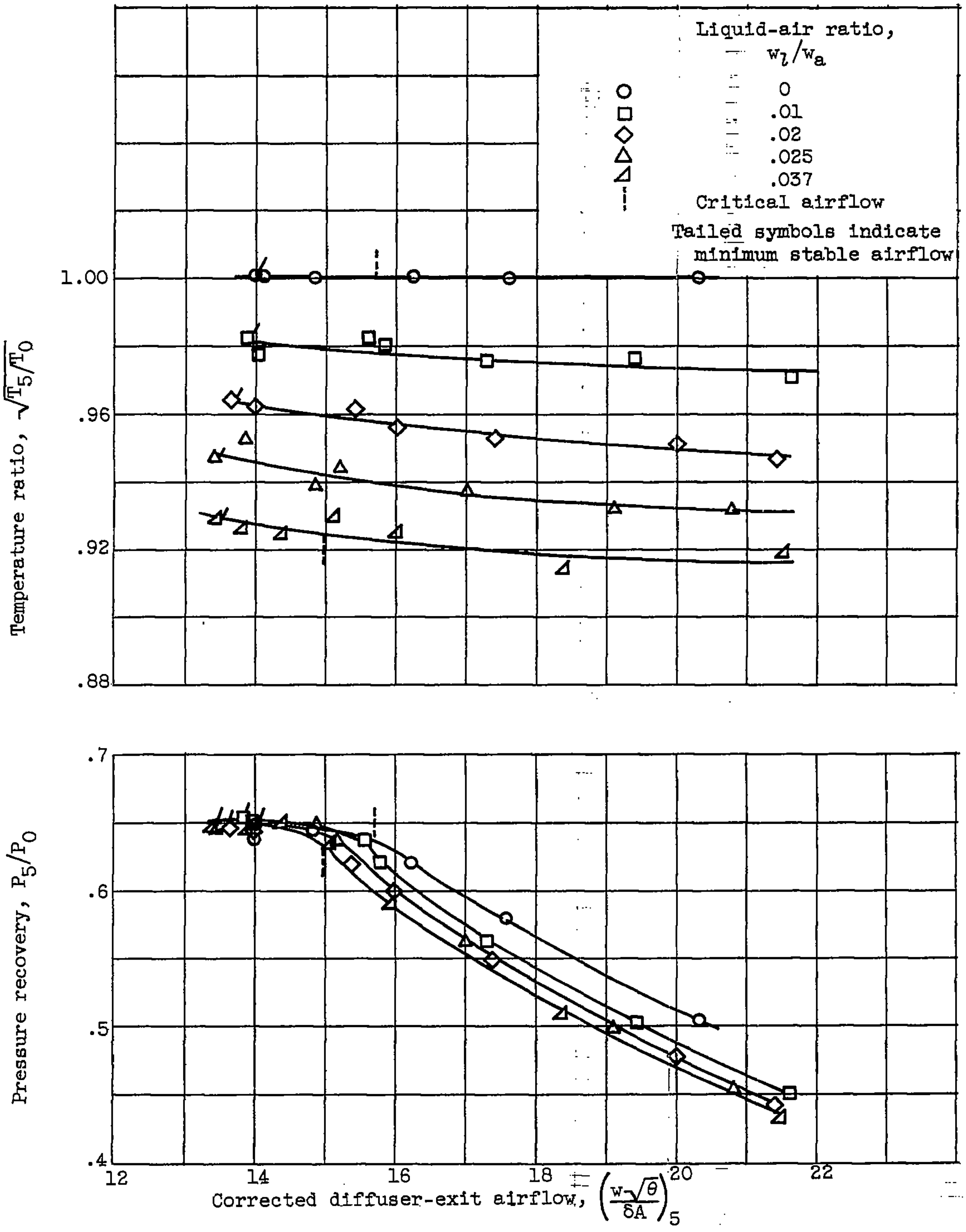


Figure 4. - Inlet performance at various liquid-air ratios. Free-stream Mach number, 2.5; inlet total temperature, 630° R; inlet total pressure, 119 pounds per square foot.

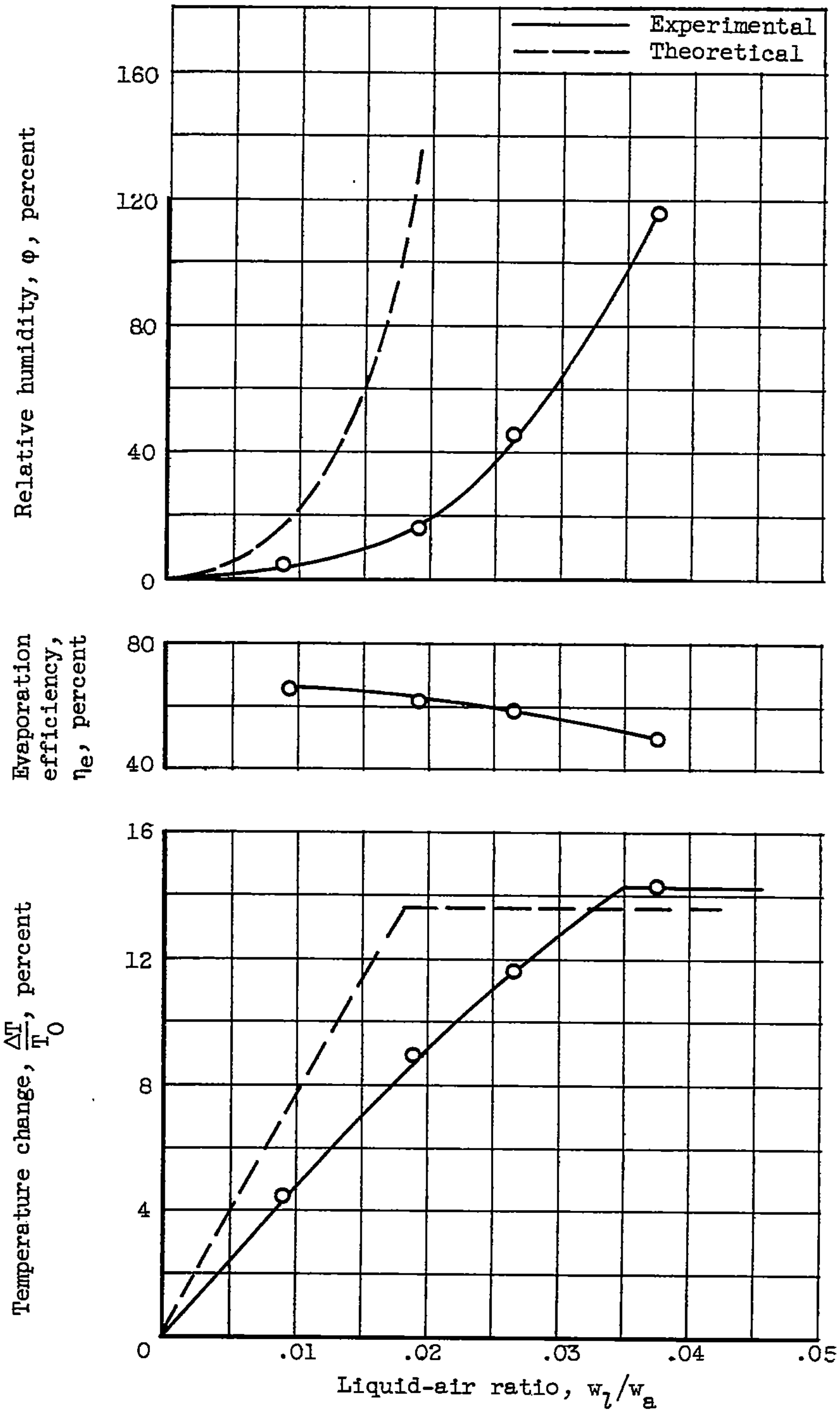


Figure 5. - Comparison of experimental and theoretical temperature and humidity relations at critical inlet flow.