THE CONSTRICTED-ARC SUPERSONIC JET

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Presented at the Nineteenth Semiannual Meeting
of the Supersonic Tunnel Association

Ottawa, Canada
May 16-17, 1963

N65-20107
(ACCESSION NUMBER)
17
(PAGES)
TMX 56181
(NASA CR OR TMX OR AD NUMBER)
(THRU)
1
(CODE)
11
(CATEGORY)
FACILITY FORM 602

GPO PRICE $
CSFTI ~~OTS~~ PRICE(S) $

Hard copy (HC) 1.00
Microfiche (MF) .50

INTRODUCTION

The requirement for extremely high enthalpy gas streams to simulate atmosphere entry conditions has resulted in the development of a new type plasma jet. The design (fig. 1) is based on considerations which have emerged from an analysis by Stine and Watson of Ames (ref. 1), and employs a direct-current arc which passes through the supersonic nozzle. Enthalpies in excess of 30,000 Btu/lb are produced by forcing the gas to flow coincident with the arc column within an elongated, well-cooled throat which acts to thermally constrict the discharge. Most of the heating occurs in the constant area throat, or constrictor tube. However, additional power can also be released in the supersonic nozzle section. Thus, any losses in the expanding portion of the nozzle area, in effect, are made up, and the high enthalpy which exists in the constrictor tube is available at the test section.

The purpose of this report is to give a brief description of the constricted-arc supersonic jet, to present some experimental data showing the performance of this device, and to compare the experimental results with the theory of Stine and Watson.

SYMBOLS

A	parameter in the expression $\sigma = A\varphi$, mho sec/Btu
c_p	specific heat at constant pressure, Btu/lb$^{\circ}$F
h	enthalpy, Btu/lb (reference H = -3500 at 0° R)
H	enthalpy, Btu/lb (reference H = 0 at 530° R)
I	current, amperes
k	thermal conductivity, Btu/ft$^{\circ}$F sec
p_i	impact pressure, mm of Hg
q	heat flux, Btu/ft^{2}sec
r	radial distance, ft
$\dot{w}$	gas flow rate, lb/sec
z	axial distance along constrictor tube, ft
z_o	characteristic length, $\dot{w}c_p/\pi k$, ft
σ	electric conductivity, mho/ft
φ	thermal conductivity potential, $\int k\,dt$

Subscripts

$( )_E$ radially average

$( )_s$ stagnation point

$( )_w$ constrictor tube wall

APPARATUS

The new plasma generator developed at Ames is shown schematically in figure 1. The three basic components are the upstream electrode (cathode), the constrictor nozzle, and the downstream electrode (anode) which is at the supersonic end of the nozzle. It is the constrictor nozzle and its placement between the two electrodes that differentiate this unit from the more conventional plasma generators.

In a conventional plasma generator where the gas is heated in an arc chamber prior to entering the supersonic nozzle, much of the gas bypasses the arc and remains cold. If a plenum chamber is provided upstream of the nozzle to allow the temperature of the gas to become uniform, heat is lost to the plenum chamber walls. Additional heat is lost to the nozzle and the energy of the gas in the test section is always far less than the energy of the gas within or near the arc column. In the constricted-arc supersonic jet, however, the arc is forced completely through the nozzle thus providing continuous heating of the gas up to the test section. The constrictor forces all of the gas through or very near the arc column. Therefore, the energy of the gas which emerges from the unit is much nearer the high energy of the gas within the arc column.

Two constricted-arc supersonic-jet units have been constructed and subjected to preliminary tests. The first has a 1/4-inch-diameter constrictor (fig. 2(a)) and the second has a 1/2-inch-diameter constrictor (fig. 2(b)). Although the units differ somewhat in detail, their operation and the function of the components are very similar. At the left (fig. 2) is a small commercially available plasma generator containing a pointed thoriated tungsten rod which serves as the cathode for the pilot discharge and as the upstream electrode for the main discharge. An arc is first struck in the pilot generator. The hot ionized jet soon provides a path of conducting gases between it and the main anode at the downstream end of the nozzle. This then permits the striking of the main discharge.

The thoriated tungsten cathode rod produces negligible contamination when operated below its melting point and when protected by a shield of inert gas. To shield this electrode, argon or nitrogen is fed to the pilot jet. The flow of shield gas required is small compared to main flow of gas introduced in the main plenum; hence, dilution of the test gas is minor. The downstream electrode, operated as the anode, is constructed of several water-cooled copper elements. A ballast resistor in series with each element provides approximately equal current division between them.

The constrictor nozzles are shown in greater detail in figure 3. The smaller unit has a throat diameter of 1/4 inch and a jet exit diameter of 1-1/3 inches. The larger unit has a 1/2-inch throat and a 5-1/4-inch exit. These units were designed using the following major guidelines:

(1) The cross-stream area of the constrictor is chosen to choke the desired mass flow at the desired pressure. (Pressure ranged from 0.3 atmosphere to 0.8 atmosphere for data presented herein.)

(2) The length of the constrictor is chosen sufficiently great to allow the total enthalpy to approach a desired asymptotic value.

(3) The constrictor nozzle must be adequately cooled to contain the high enthalpy gas.

(4) The constrictor nozzle must provide adequate insulation in the axial direction to prevent short circuiting.

The latter two requirements were met by building the unit of water-cooled copper disks insulated from each other by thin wafers of boron nitride. The boron nitride wafers are cooled by conduction to the copper disks.

TESTS AND RESULTS

Tests of the constricted-arc supersonic jets are still in progress and are far from complete. However, detailed measurements of the enthalpy build-up within the constrictor tube have been made in the 1/4-inch unit and radial surveys of impact pressure and stagnation-point heat transfer have been made at the nozzle exit of the 1/2-inch unit.

Conventional steady-state instrumentation was used to measure voltage, current, heat losses to the various water-cooled parts, gas flow rate, and plenum chamber pressure. The measurements were made both on a local and an over-all basis. Except for one special case noted in a later section, enthalpy was deduced from the measurements by means of a power balance. It was convenient to use nitrogen gas for the majority of tests because the entire flow could be put through the pilot arc. However, those few tests with a mixture of nitrogen and air indicate that the results presented are essentially equivalent to those for air.

During tests of the units, difficulty was experienced in reproducing conditions at the test sections. It appears that two stable modes of arc operation during which ambiguous measurements can be taken are possible in the regions of expanding flow downstream of the constrictors. The enthalpy determined at the test section, however, is little different from that at the constrictor exit, regardless of which mode of operation occurs. Nevertheless, the enthalpy values reported for the 1/4-inch unit are those corresponding to a location at the constrictor exit, where measurements were always single valued.

Constrictor Enthalpy

The average total enthalpy at the downstream end of the constrictor tube is shown in figure 4 as a function of flow rate for various currents. At low flow and high current, average enthalpies of about 30,000 Btu/lb were achieved. As flow rate is increased at constant current, the average enthalpy decreases moderately. At constant flow rate, however, the average enthalpy is about directly proportional to current.

Since the measurements of arc power input to the gas and power loss to the constrictor tube walls were made on a local basis, it was possible to obtain the distribution of the enthalpy with longitudinal distance, figure 5. For the test at low flow rate, the enthalpy achieved an asymptotic value fairly quickly. For the test at high flow rate, however, the enthalpy was still increasing at the downstream end of the constrictor tube.

The addition of heat to the expanding, supersonic flow undoubtedly reduces the Mach number. Nevertheless, no doubt exists that the exit flow is supersonic, since luminous shock diamonds are clearly visible in the discharge, and bow waves can be formed ahead of blunt obstacles placed in the jet.

Comparison of Experiment With Theory

The experimental results can be compared with the theory of Stine and Watson, reference 1. One of the assumptions in the theory is that heat from the arc column is lost to the constrictor wall only by radial conduction. That is, losses due to axial conduction and to radiation can be neglected. If so, then heat loss should depend on enthalpy and not on flow rate. In figure 6 the constrictor-wall heat flux is plotted for a typical station along the constrictor tube as a function of local enthalpy with mass flow as a parameter. The relation between heat flux and local enthalpy is approximately linear. Since these data cover a wide range of nitrogen flow rates, they show both that heat flux is a function only of local total enthalpy, as predicted by the theory of reference 1, and that radiation is not an important heat-loss mechanism.

Next, the enthalpy predicted by the theory can be compared with the experimental enthalpy determined by means of the power balance. The average total enthalpy according to reference 1 is:

$$h_E = 4.08\times10^{-3} \frac{c_p}{k} \frac{A}{A^{1/2}} \frac{I}{r} \left[1 - \exp\left(\frac{11.5z}{z_o}\right)\right]^{1/2}, \quad \frac{\text{Btu}}{\text{lb}}$$

where

$$z_o = \frac{(c_p/k)\dot{w}}{\pi}, \quad \text{ft}$$

If published values for the parameters c_p/k and A for nitrogen are employed, one finds that the predicted enthalpy is much too high. However, sufficient test data exist to enable experimental values of c_p/k and A to be determined. Using experimentally determined values of c_p/k and A, the curve of $H_E r/I$ versus z/z_o shown in figure 7 is obtained. The parameter $H_E r/I$ is used since it is a function of z/z_o only. The experimental values of $H_E r/I$ are also shown on this plot. Excellent agreement between experiment and theory for the 1/4-inch and 1/2-inch constrictors indicates that reference 1 can be used to predict the performance of constricted arcs.

Radial Flow Profiles

The 1/2-inch supersonic-arc plasma jet was used to obtain radial profiles of impact pressure and stagnation-point heat transfer. These are shown in figure 8. Although a region exists near the stream axis where the impact pressure is reasonably constant, there is no region where the stagnation-point heat transfer is constant. If one assumes that the stagnation-point heat transfer is proportional to the first power of enthalpy and to the square root of impact pressure, an enthalpy profile can be obtained from these two curves, as is also shown in figure 8. Although this latter curve is somewhat less peaked than the curve for stagnation-point heat transfer, there is still essentially no region where a steep enthalpy gradient does not exist. Thus, test bodies which are small in comparison to the jet exit diameter are required to make use of the high enthalpy existing at the jet center line.

It was found that the center-line enthalpy was about 2.7 times the average heat-balance enthalpy. Thus, for an average total enthalpy of 14,600 Btu/lb, a peak enthalpy of 38,000 Btu/lb was obtained. Similar data indicate that maximum center-line enthalpies of approximately 80,000 Btu/lb have been achieved from the smaller unit.

CONCLUSIONS

The experimental investigation of a constricted arc has led to the following conclusions:

1. An arc can be passed entirely through a supersonic nozzle without disrupting the flow. The current and voltage are steady, and no large scale fluctuations of the stream luminosity can be observed. Luminous shock diamonds in the discharge indicate that the flow is supersonic.

2. Average enthalpies of 30,000 Btu/lb in nitrogen have been obtained. The enthalpy is approximately proportional to the current for a given flow rate. Tests with air yield comparable enthalpy levels.

3. Local measurements show that the stagnation enthalpy and heat loss to the wall increase exponentially with distance along the constrictor tube. The analysis of Stine and Watson yields a description of the enthalpy build-up with length which agrees with the observed build-up provided the experimentally determined gas properties are used.

4. Radial profiles of impact pressure and stagnation heat transfer indicate that the enthalpy profile is sharply peaked at the center line of the jet. It was found that the center-line enthalpy was about 2.7 times the average heat-balance enthalpy.

REFERENCE

1. Stine, Howard A., and Watson, Velvin R.: The Theoretical Enthalpy Distribution of Air in Steady Flow Along the Axis of a Direct-Current Arc. NASA TN D-1331, 1962.

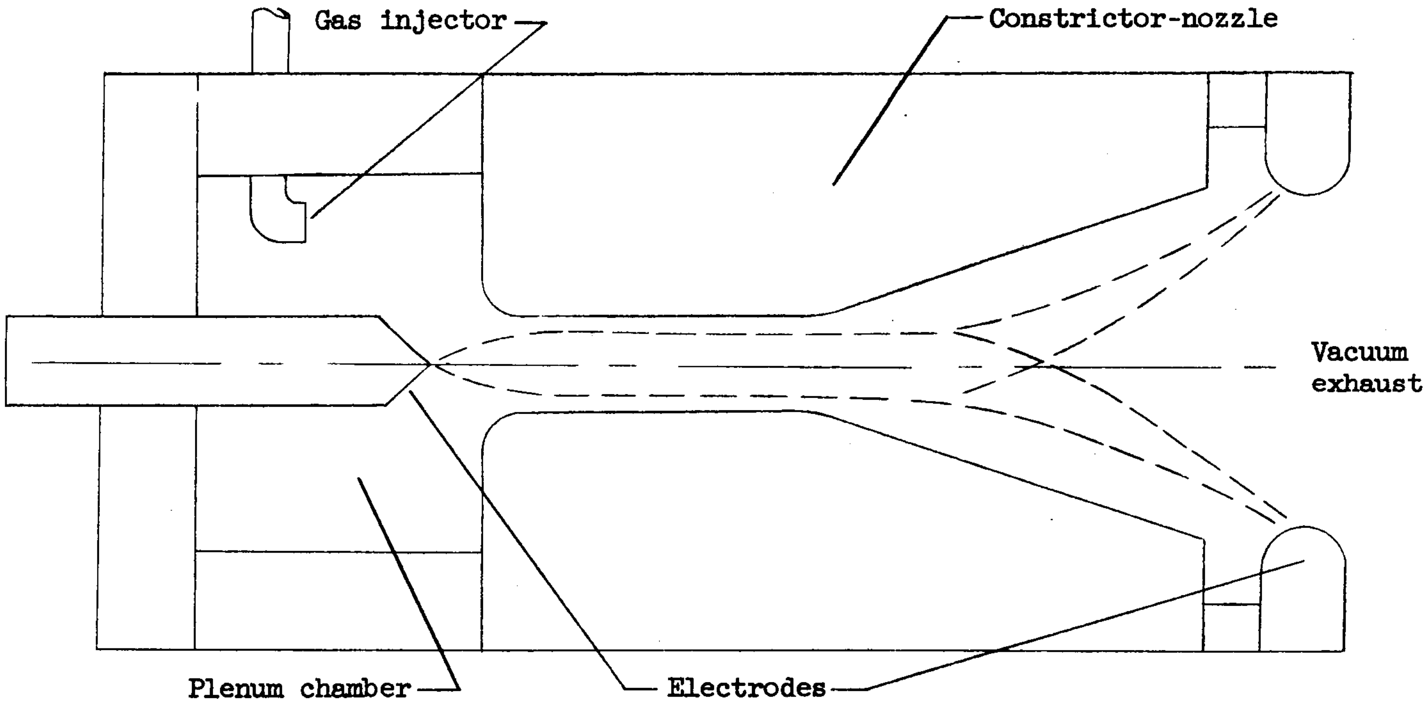

Figure 1.- Schematic drawing of the constricted-arc supersonic jet.

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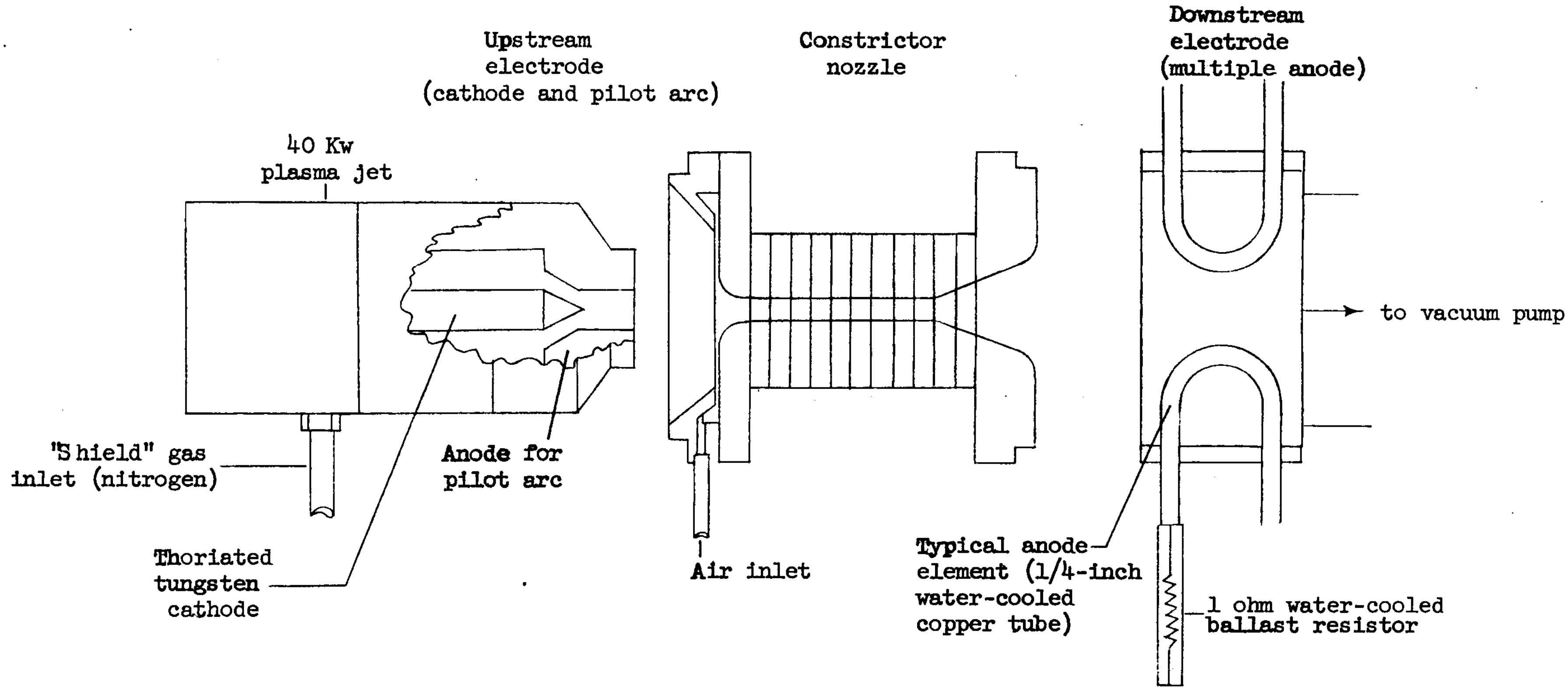

(a) 1/4-inch-diameter throat.

Figure 2.- Arrangement of components of the constricted-arc supersonic jet.

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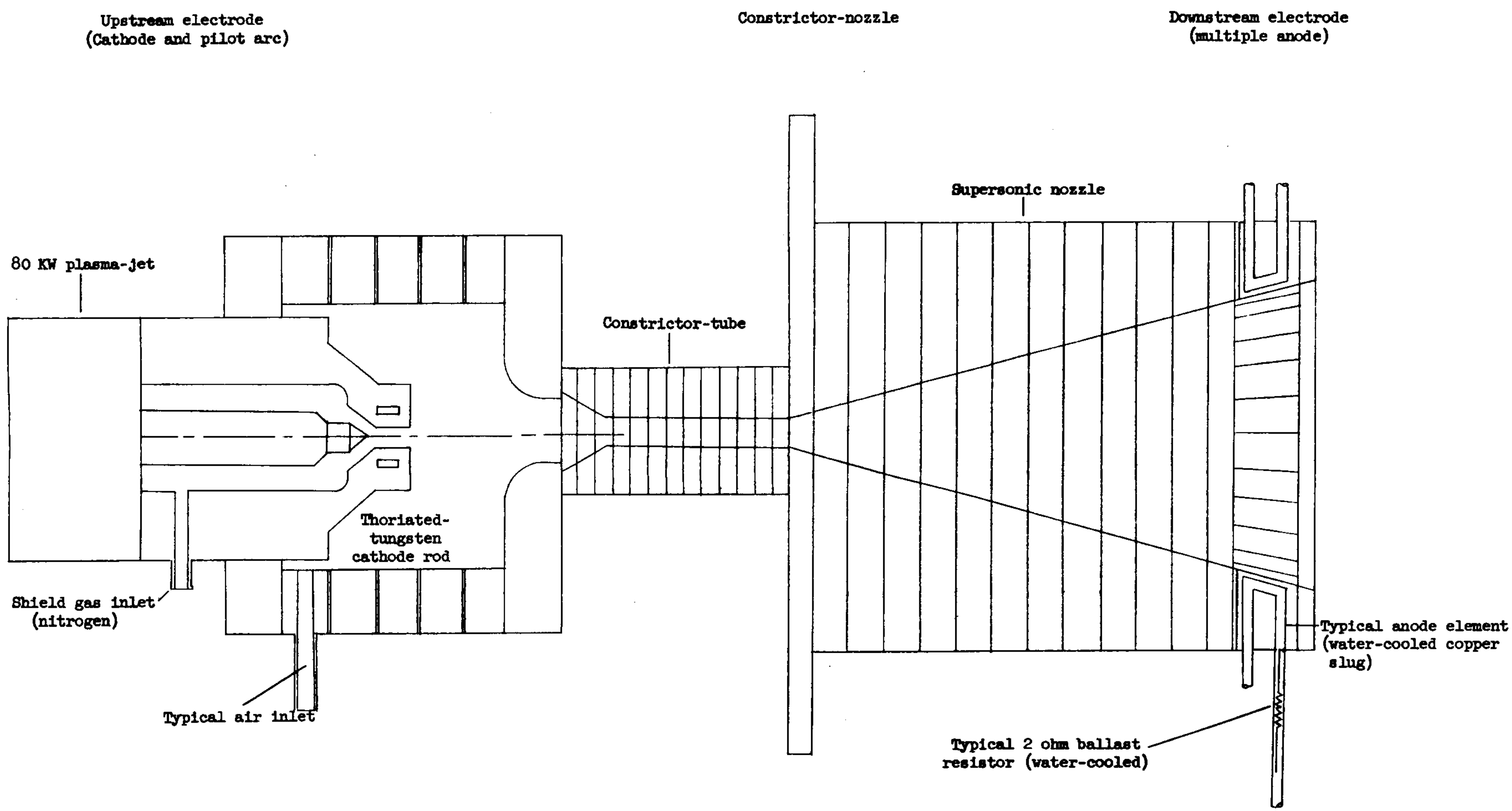
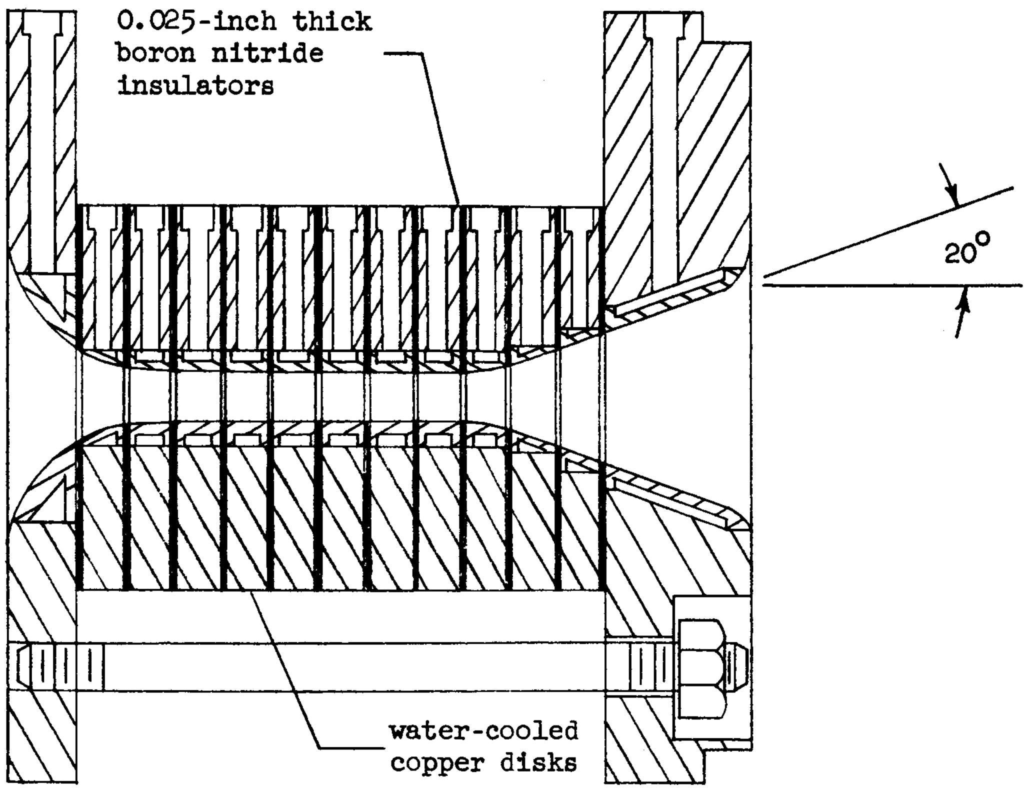


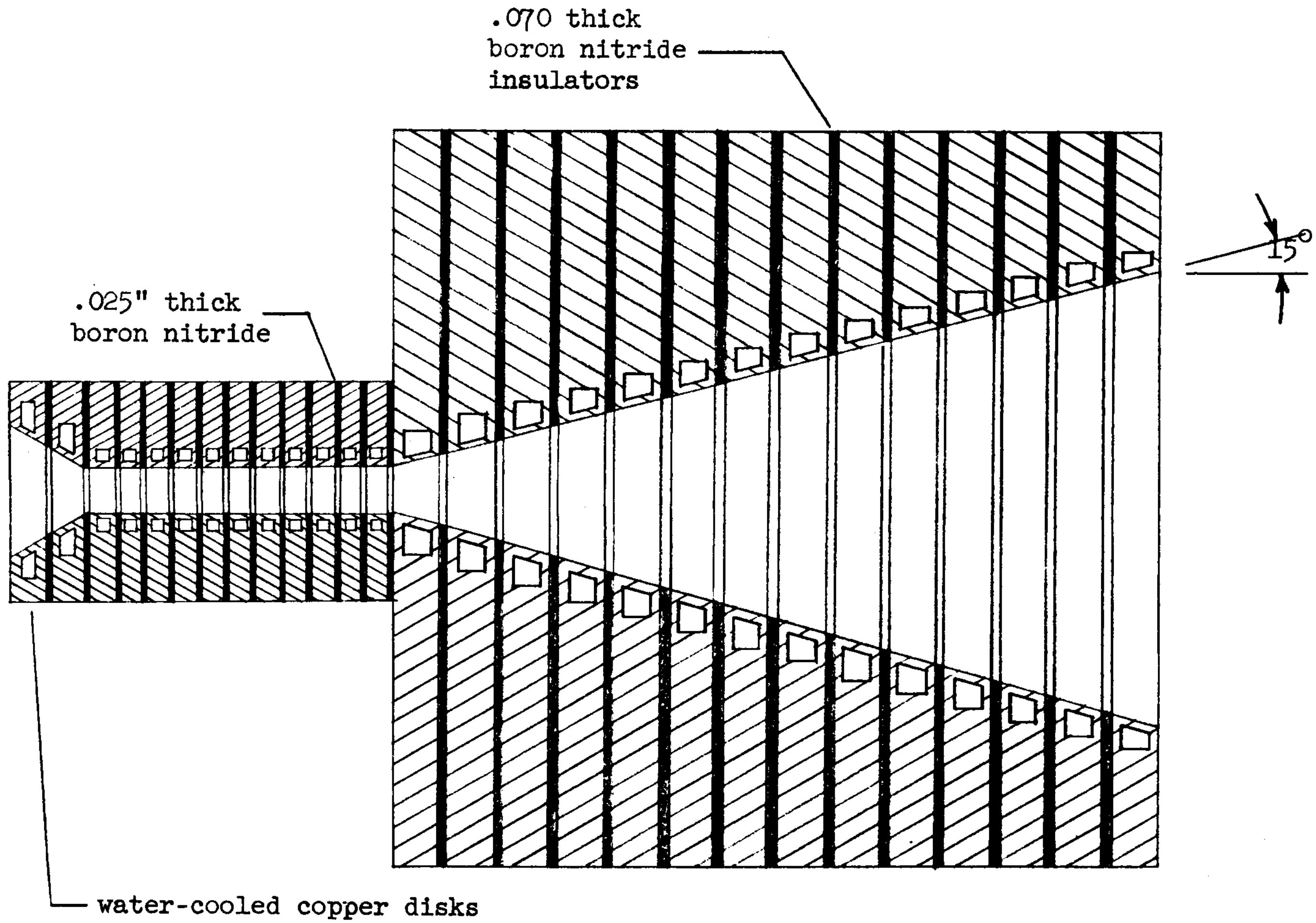
(b) 1/2-inch-diameter throat.

Figure 2.- Concluded.



(a) 1/4-inch-diameter throat.

Figure 3.- Nozzle-constrictor construction.



(b) 1/2-inch-diameter throat.

Figure 3.- Concluded.

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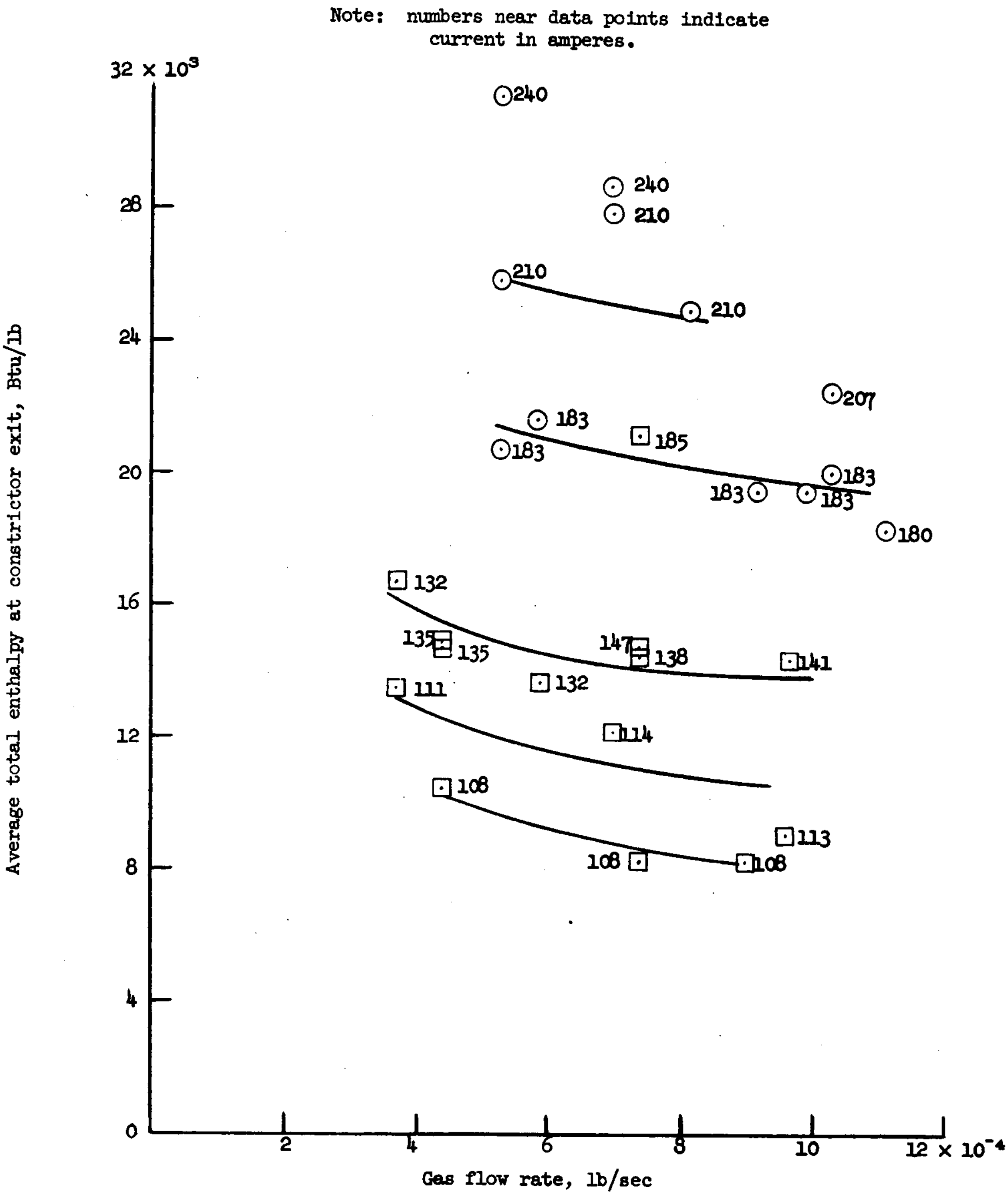

Figure 4.- Constrictor average total enthalpy versus nitrogen flow rate for various arc currents.

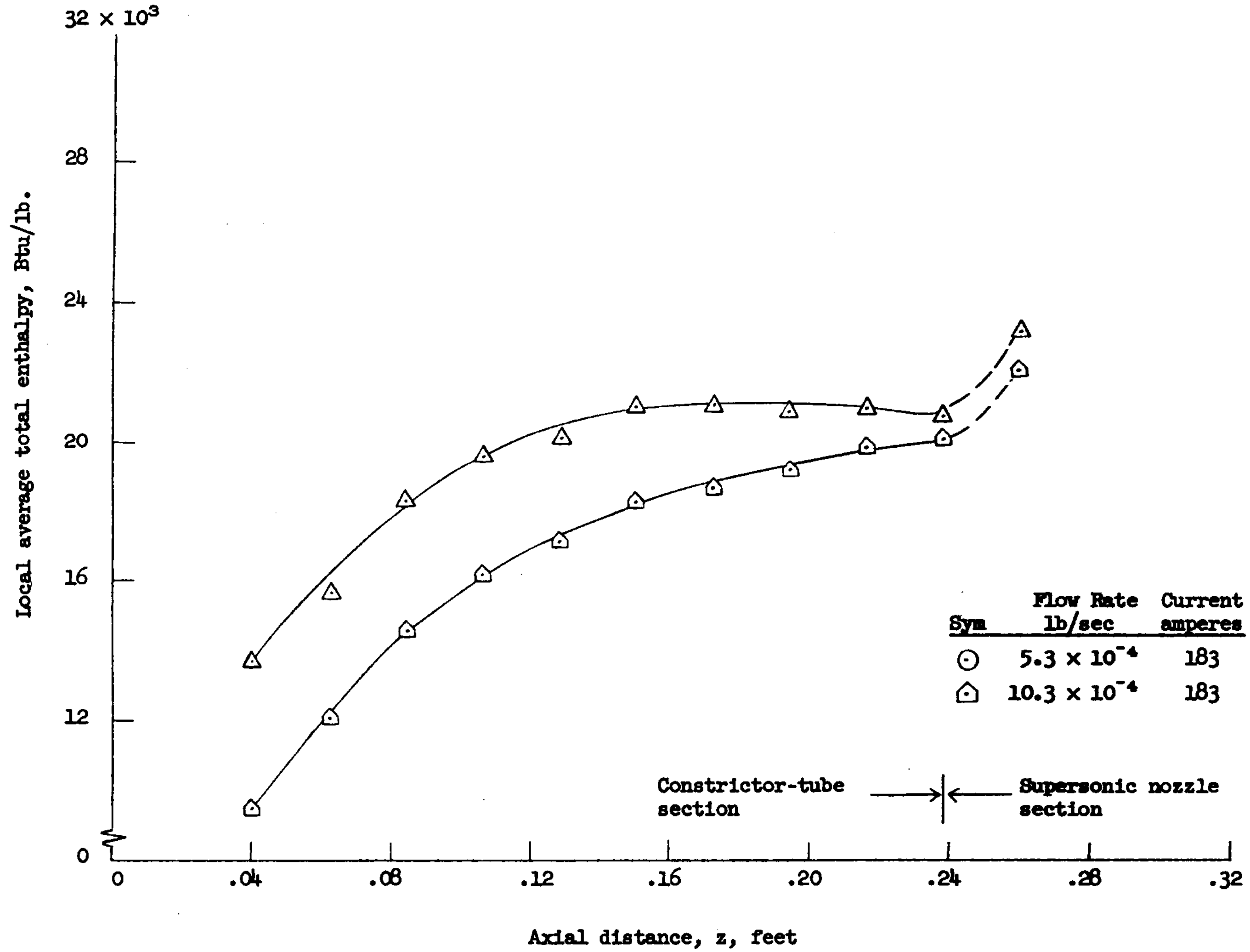

Figure 5.- Average total enthalpy at constrictor exit as a function of axial distance for various arc currents and nitrogen flow rates (1/4-inch-diameter throat).

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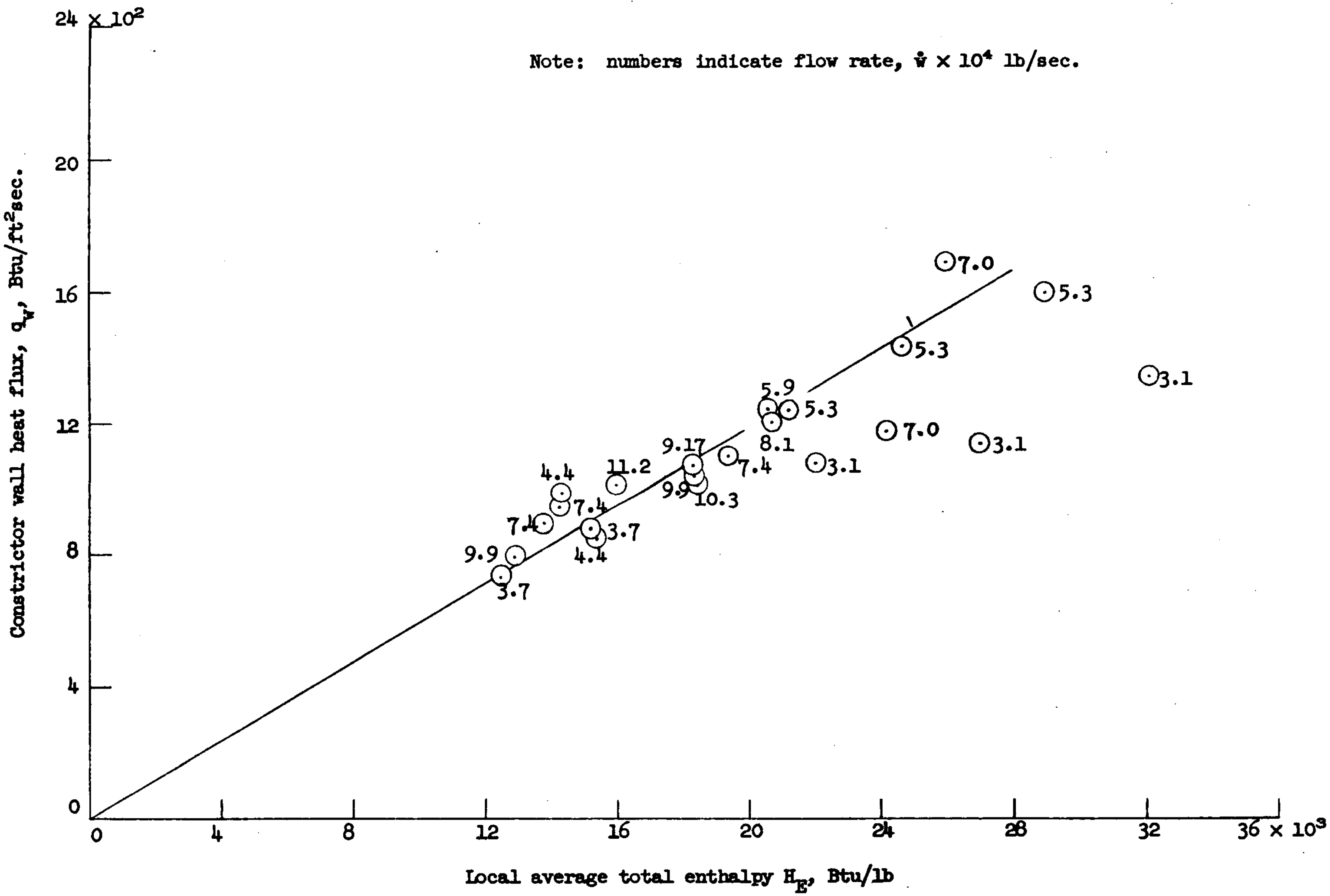

Figure 6.- Constrictor wall heat flux versus local average total enthalpy for various nitrogen flow rates; z = 0.15 feet (1/4-inch-diameter throat).

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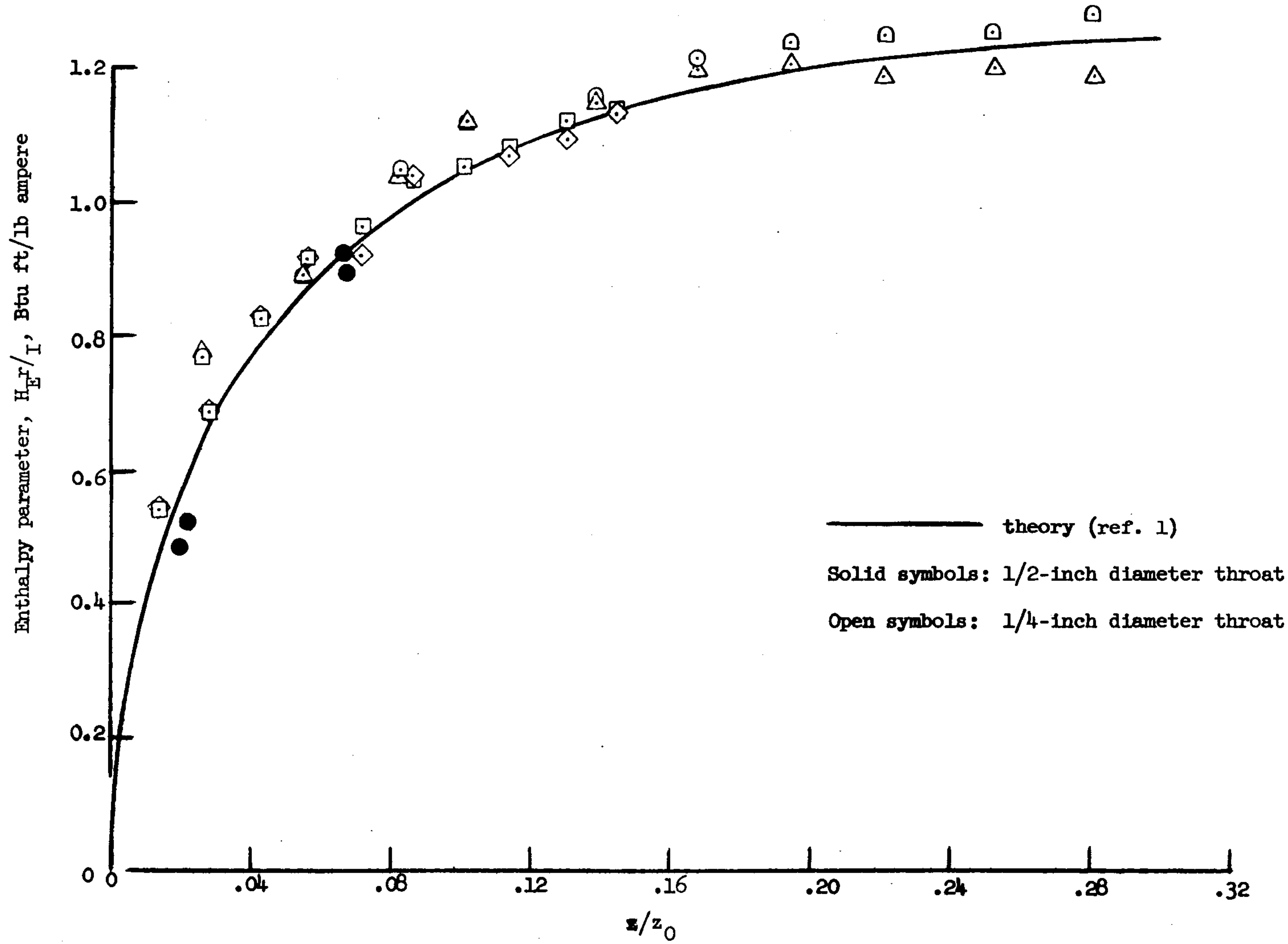

Figure 7.- Enthalpy parameter, $H_E r/I$, as a function of the dimensionless axial distance, z/z_0.

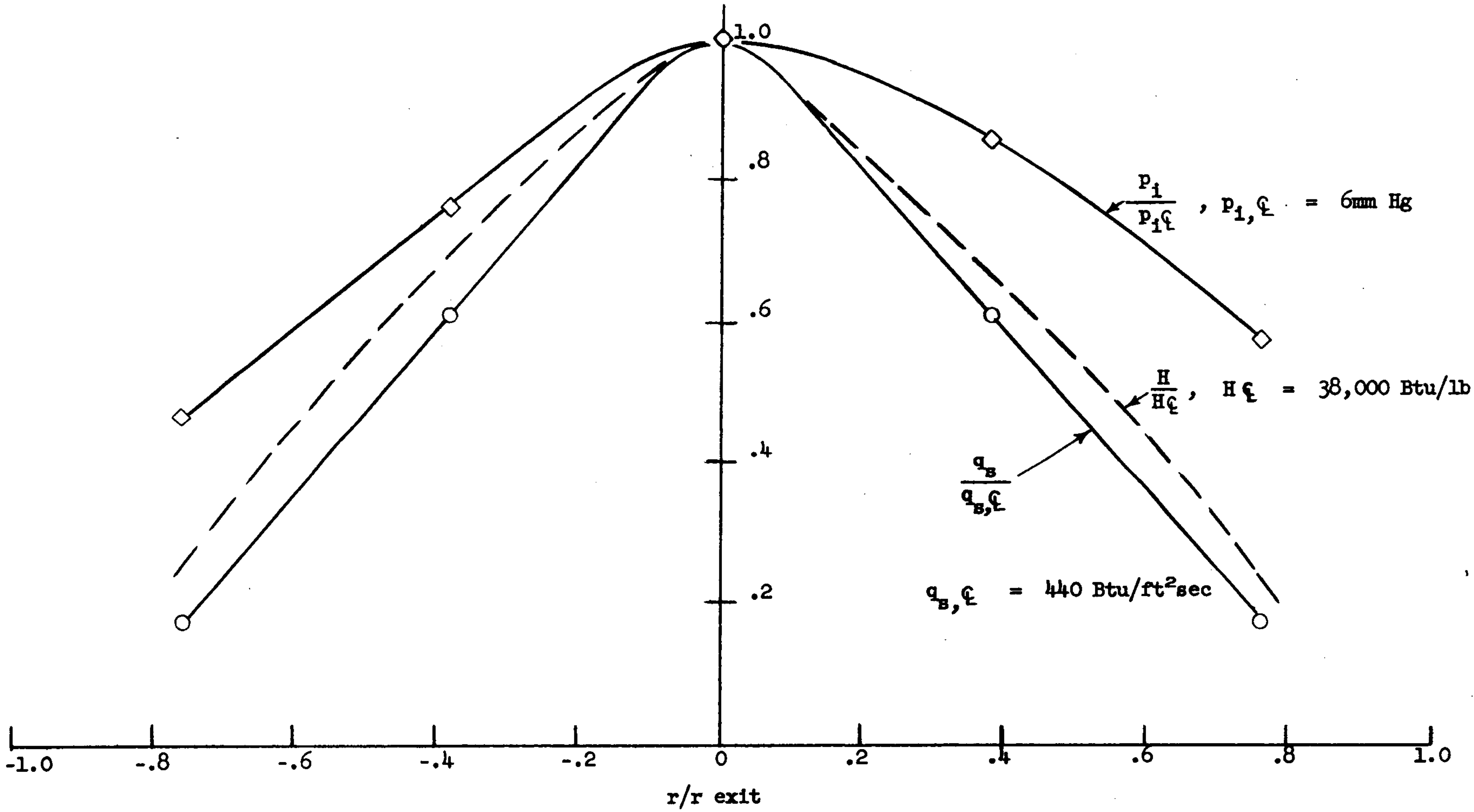

Figure 8.- Typical radial profiles of impact pressure, stagnation-point heat-transfer rate, and derived total enthalpy.