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# MEASUREMENTS IN A FROZEN, PARTIALLY DISSOCIATED, HIGH-SPEED GAS STREAM

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The present investigation was undertaken to develop methods for evaluating the performance of arc-heated wind tunnels. In contrast to measurements made in conventional wind tunnels almost any measurement made in a stream of partially dissociated gas may contain a systematic error because the type and quantity of species are not precisely known. One of the most fundamental quantities for evaluation of wind-tunnel performance is stream energy content; it was therefore decided to measure the stream energy content by as many independent methods as possible and to attempt by comparison of the various methods to deduce the actual stream energy. In the course of the investigation a number of other stream properties were measured or deduced and these will be discussed.



The various methods used are as follows: (1) The average gross energy content was determined from a gross energy balance of the system; (2) the energy content was deduced from measurements of the cold-gas flow rate and the stagnation chamber pressure by calculating what the average energy content of the gas would have to be for the flow to pass through the nozzle throat at the measured rate; (3) the energy content of the stream was deduced from the stagnation region heating rates measured on a model placed in the stream; and (4) the average energy content in the core of an assumed mathematical flow model was deduced from measurements of stagnation, impact, and free-stream static pressures.

Before these methods are discussed in detail, the wind tunnel used in the investigation will be described. A diagram of the wind tunnel is shown in figure 1. The unit consisted of the arc heater which discharged a high-energy nitrogen stream into the plenum chamber of a contoured, water-cooled nozzle. From the nozzle, the gas stream discharged into a test chamber which was held at the required low pressure by a five-stage steam-jet ejector system. All tests were conducted at a uniform flow rate of 0.005 pound of dry nitrogen per second. The arc heater operated at a pressure of approximately 1/3 atmosphere. The nozzle had an outlet diameter of 4.1 inches and produced a Mach number of approximately 5.6 over an enthalpy range from 4000 to 9000 Btu per pound. The test-section pressure was held at approximately 250 microns of mercury absolute, and at this low pressure the nozzle boundary layer

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was relatively thick. A test core approximately 1-1/2 inches in diameter was produced except at the highest power levels.

The various measurements will now be described. Figure 2 is a diagram illustrating the methods used in determining the stream energy content. The energy-balance method is illustrated at the top of the figure. In this method the losses to the cooling water circulated through the walls of the arc heater, plenum chamber, and nozzle are subtracted from the energy input. The result is then divided by the gas flow rate to give the stream energy.

The center diagram illustrates the sonic throat methods which have often been used to estimate the energy content of arc-heated gas streams. These methods are based on solutions of the continuity, momentum, and energy equations combined with either an appropriate equation of state or tables and charts of the gas properties suitable for the flow conditions. In the equilibrium sonic throat method the gas is assumed to be in complete thermodynamic equilibrium from the plenum chamber to the sonic throat; whereas in the frozen sonic throat method the chemical and vibrational forms of energy are assumed to be frozen at the state of the plenum chamber. In both methods the gas is assumed to be in equilibrium in the plenum chamber. Evidence that this may not necessarily be true is supplied by spectroscopic examination of the gas in the plenum chamber which showed vibrational temperatures of $7000^\circ$ to $9000^\circ$, rotational temperatures of $2000^\circ$ to $3000^\circ$, and an electron density that would correspond to equivalent electron equilibrium temperatures of $4500^\circ$ to $5000^\circ$ Kelvin. Although there may be a nonequilibrium condition in the plenum chamber, it does not appear to affect certain of the results of measurements in the stream.

The exact relationships between the enthalpy, pressure, and nozzle throat area for equilibrium flow can be obtained from Mollier charts by iteration. For the case of frozen flow one relies on knowledge of the state properties of the gas in the settling chamber and a solution of the conservation equations. For convenience, approximate equations that provide an estimate of the equilibrium sonic throat energy content and the frozen sonic throat energy content are shown on the right of the figure. These equations give a stream energy that agrees with the exact calculations to approximately 7 percent for enthalpies from 1500 to 4000 Btu/lb at a pressure of 1/3 atmosphere.

The stagnation-point heat-transfer method shown in the bottom diagram is simply based on the measured heating rate in the stagnation region of a model placed on the stream center line. The enthalpy is calculated by applying the solutions to the boundary-layer equations for heating rate in terms of driving enthalpy potential as obtained by Fay and Riddell.

The stated objective of the investigation was to compare the results of a number of methods of measuring the energy content of the stream. Figure 3 shows the energy content of the stream plotted as a function of the input electrical energy per pound of gas. The energy-balance method, the sonic-throat methods, and the heat-transfer method are all compared in this figure. Notice that energy content determined by energy-balance and heat-transfer methods are in reasonable agreement. The heat-transfer method indicates slightly higher energy content but it should be remembered that this is a measurement of the stream-core energy whereas the energy-balance method gives the average stream energy over the nozzle exit area. Both methods show a higher value of stream energy than that determined by the sonic-throat methods. Both the heat-transfer method, in which a probe is used to recover the frozen energy of the stream, and the energy-balance method would be expected to measure the total energy content of the stream; whereas if the flow is chemically frozen as it expands from the stagnation chamber to the throat, the frozen sonic throat method will only measure the energy of the gas convertible to kinetic form. Estimates of the flow time compared to the recombination time indicate that the flow is frozen at very nearly stagnation chamber conditions.

Since the velocity was measured directly, a means is available for judging whether the stream is in fact frozen at the beginning of the expansion process. The direct measurement of velocity was accomplished by three methods, all of which depend on the partial ionization of the gas stream. Figure 4 illustrates the methods used. The first method consisted in an application of Faraday's generator rule wherein the potential developed by a conductor, in this case the partially ionized gas stream, moving through a magnetic field of known strength provided a measure of the stream velocity. The electromotive force generated by virtue of the stream velocity was detected by means of two 1/8-inch diameter cylindrical electrodes inserted coaxially into opposite edges of the stream at right angles to both the magnetic flux vector and the stream velocity vector. With the measured field strength, the measured distance separating the electrodes, and the measured voltage the stream velocity could be calculated from Faraday's Law, noted on the right of the figure.

The two other methods depended on measuring the time for random pulsations of the stream caused by inherent arc power fluctuations to travel a known distance in the flow direction. In the first of these, two Langmuir probes detected the stream potential pulsations caused by nonuniform stream ionization; in the second, two photomultiplier tubes detected variations in stream luminosity. In both cases, the signals were photographed from the display of a dual beam oscilloscope. The stream velocity could be calculated from the sweep speed, the phase relationship of the traces, and the distance separating the detectors. Each frame of the exposed film was examined to find those pairs of traces which had identical shapes. The remaining frames were discarded. Both methods indicated stream velocities varying from 5,000 to over 30,000 feet per second, so a statistical method was used to analyze the results. Figure 5 illustrates this method. A plot was made of the ratio of the number of data points showing a velocity below a given value to the total number of data points as a function of the velocity. A line was then faired through the calculated points. The derivative of the curve with respect to the velocity was plotted versus the velocity. The most probable stream velocity was then taken as the maximum point of this curve.

The velocity that may be expected in an arc-heated test stream can be calculated by the use of Mollier charts in the case of an equilibrium stream or by calculating an expansion exponent from stagnation conditions and assuming isentropic expansion for a frozen stream. A comparison of these calculated velocities and the measured velocities is shown in figure 6. Although there is considerable scatter in the data, the measured velocities show the correct order of magnitude. In fact, they are all below the velocity calculated from equilibrium flow assumptions using enthalpy from energy balance measurements. The presence of the rather large scatter in the data precludes a direct determination of whether or not the stream is frozen. Considerable effort is being expended to eliminate these rather large errors in velocity measurements. At the present time no one method appears superior to any of the others. However, some information on the amount of kinetic energy compared to total energy in the stream can be gleaned from these rather crude measurements of velocity.

A comparison of the total energy as determined from the energy-balance method with the kinetic energy determined from measured velocity and from frozen sonic flow is shown in figure 7. The shaded region represents the kinetic energy, $(u^2/2gJ) + c_pT$, calculated from the measured velocity and an estimate of the internal kinetic energy $c_pT$. The internal kinetic energy represents less than 13 percent of the total kinetic energy. It can be seen that the frozen sonic throat method gives a fairly good measure of the kinetic energy of a stream, provided the stream is frozen. Unfortunately the measured velocities do not show conclusively that the stream is frozen as would be expected by consideration of the estimates of flow time compared to recombination time.

In order to show that the stream was in fact frozen it was necessary to resort to other methods. The assumption that a stream is frozen at the conditions of the stagnation chamber makes a calculation of an effective expansion exponent possible, because a gas frozen throughout the expansion process behaves as a perfect gas. This frozen expansion exponent will be markedly different from the expansion exponent calculated for equilibrium flow when the flow is isentropic. A method for determining the effective expansion exponent is shown in figure 8. This method requires the measurement of the stagnation pressure, the impact pressure, and the stream static pressure. It is assumed that the flow through the nozzle is isentropic with a constant expansion exponent and that Rayleigh's equation relating the impact pressure to the static pressure applies.

These are the usual assumptions for the flow of a perfect gas. The bottom two equations contain two unknowns, Mach number and expansion exponent, and their simultaneous solution yields both of these quantities.

A comparison of the measured expansion exponent and the expansion exponents calculated from frozen and equilibrium assumptions will show the state of the gas. In figure 9 this comparison is made. It is shown that the stream was frozen for the lower enthalpy cases. The departure of the expansion exponent from the frozen case at the highest energy level can be attributed to the absorption of the stream core by the nozzle boundary layer; this was shown by impact pressure surveys across the stream. In this case the isentropic equations do not apply and the method fails.

The expansion exponent determined by the previously described methods can be related to the temperature at which the stream freezes through the use of equilibrium Mollier charts for nitrogen. This information allows all of the stream properties to be calculated. A comparison of the gas energy content as determined from the effective expansion exponent method with the other methods is shown in figure 10. It can be seen that the total energy and the kinetic energy as calculated by this method agree with the total energy and kinetic energy determined by other means at the lower energy input levels where the isentropic equations apply.

As a result of this investigation some general conclusions can be drawn:

1. The energy content determined from heat-transfer or energy-balance methods appears to yield the sum of the stream kinetic and chemical energy.

2. If the flow freezes at or near the beginning of the expansion process from the stagnation chamber to the nozzle throat, the sonic-throat methods yield only the kinetic energy of the stream.

3. If the flow processes are frozen at the beginning of the expansion, the effective expansion exponent method yields both stream total and kinetic energy.

4. More research is needed to refine the present velocity measuring techniques.

## APPENDIX A

## SYMBOLS

| | |
|---|---|
| A | amperes |
| A* | nozzle throat area |
| B | magnetic field strength |
| $c_p$ | specific heat at constant pressure |
| d | spacing between probes |
| E | electric field strength |
| g | gravitational constant |
| h | total energy content of the gas |
| J | mechanical equivalent of heat |
| $\dot{m}$ | gas flow rate |
| M | Mach number |
| p | pressure |
| $\dot{q}$ | heating rate |
| R | gas constant |
| S | sweep speed |
| T | temperature |
| u | stream velocity |
| V | volts |
| $\dot{w}$ | water flow rate |
| x | body coordinate along surface |
| Z | compressibility |
| $\Gamma$ | expansion exponent in equation $p\rho^{-\Gamma}$ = const. |

| | |
|---|---|
| $\delta$ | distance along abscissa between oscilloscope traces |
| $\rho$ | gas density |
| $\theta$ | time |

## Subscripts

| | |
|---|---|
| EqSF | equilibrium sonic flow |
| FSF | frozen sonic flow |
| t | total conditions |
| e | external to boundary layer |
| 1 | conditions ahead of shock wave |
| 2 | conditions behind shock wave |

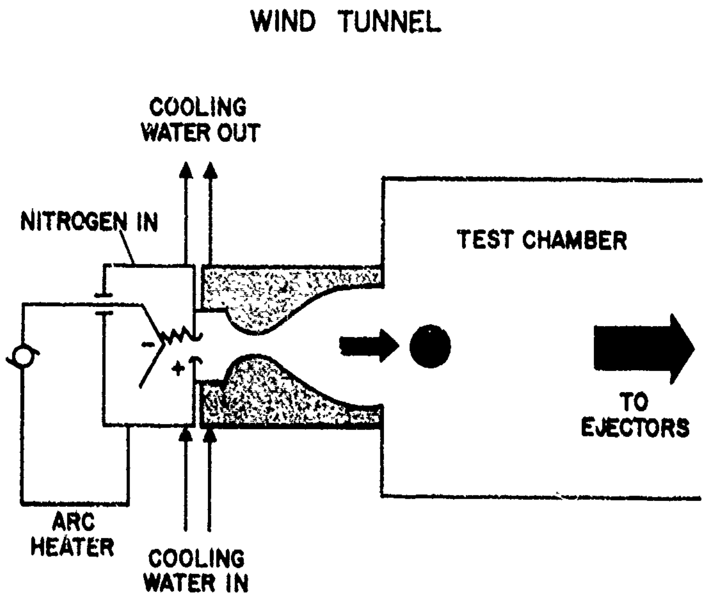



Figure 1.

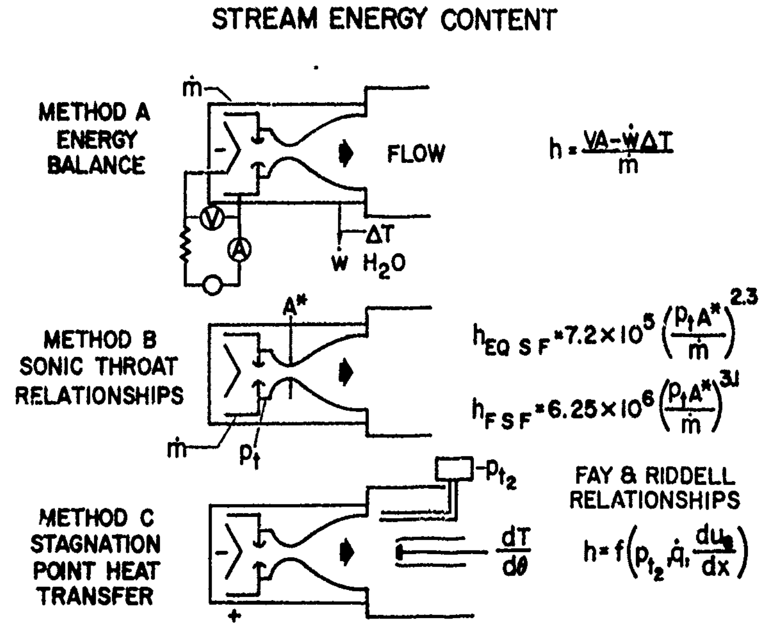



Figure 2.

COMPARISON OF MEASURED VALUES OF STREAM ENERGY

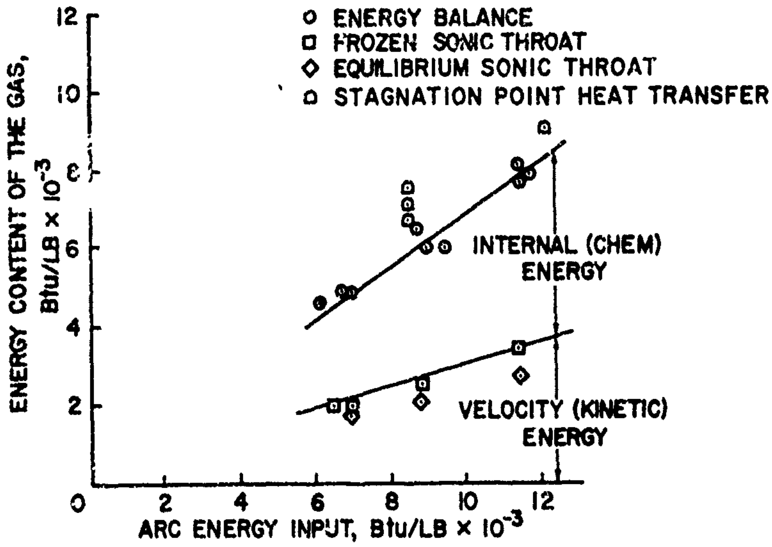



Figure 3.

STREAM VELOCITY

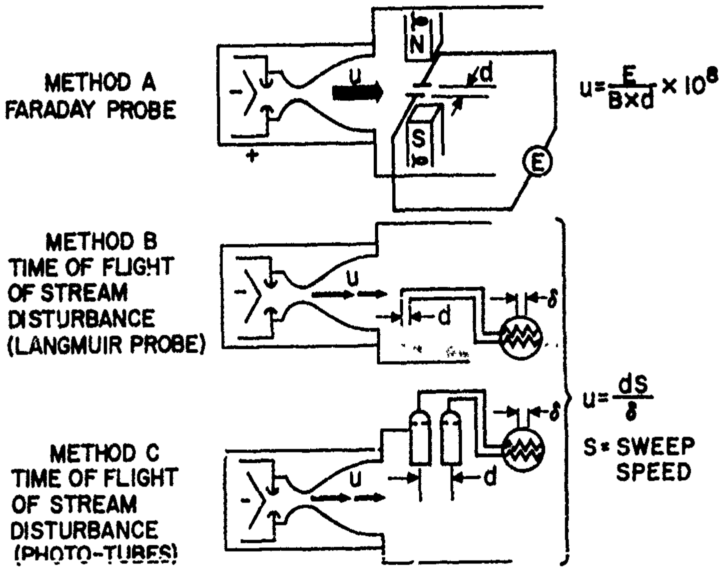



Figure 4.

METHOD OF ANALYZING VELOCITY DATA

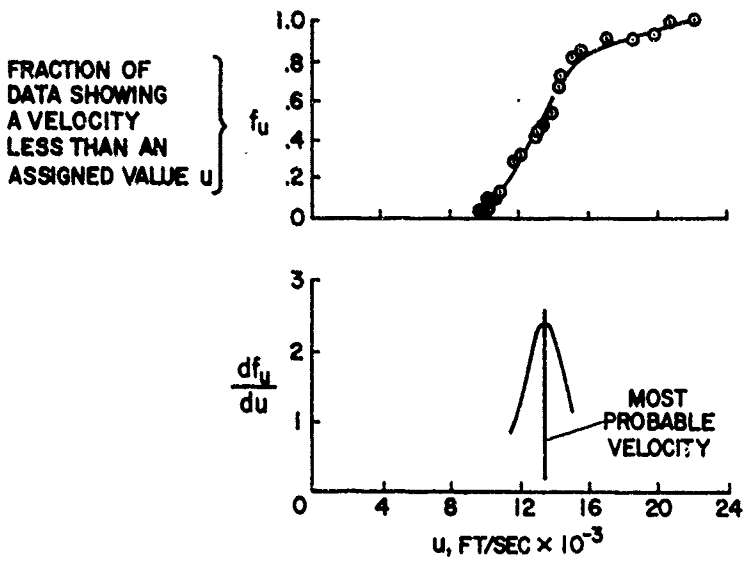



Figure 5.

COMPARISON OF METHODS OF DETERMINING VELOCITY

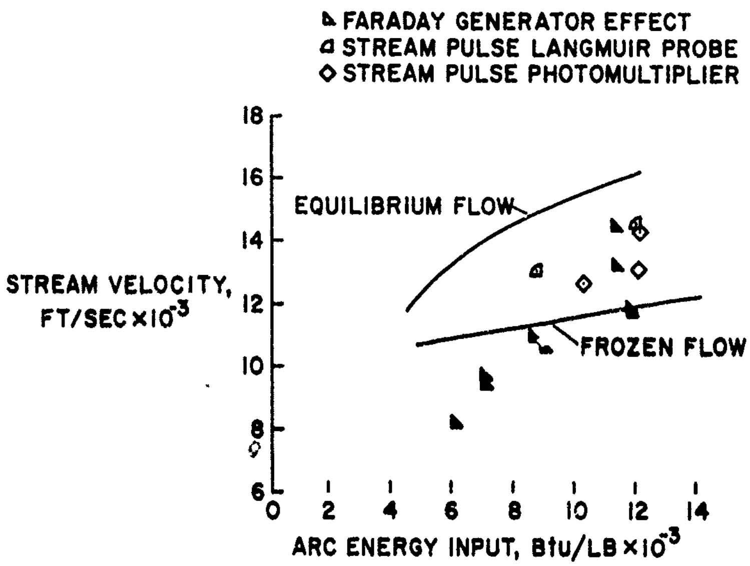



Figure 6.

COMPARISON OF MEASURED VALUES OF STREAM ENERGY

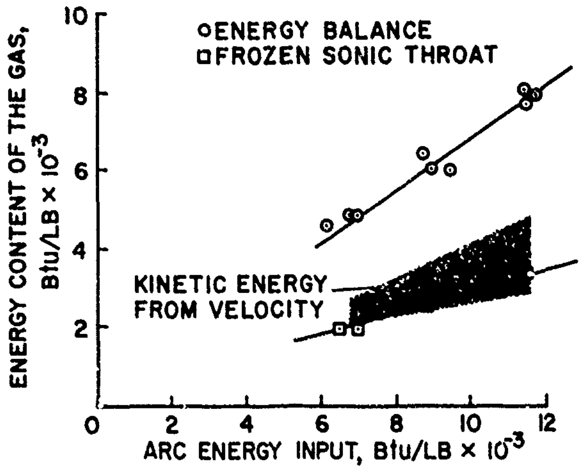
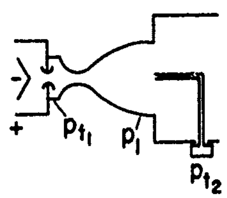



Figure 7.

STREAM ENERGY CONTENT FROM THREE PRESSURE MEASUREMENTS




$$p\rho^{-\Gamma} = \text{CONST}$$

$$\frac{p_{t_2}}{p_{t_1}} = \left[\frac{(\Gamma+1)M^2}{(\Gamma-1)M^2+2}\right]^{\frac{\Gamma}{\Gamma-1}} \left[\frac{\Gamma+1}{2\Gamma M^2-(\Gamma-1)}\right]^{\frac{1}{\Gamma-1}}$$

$$\frac{p_{t_2}}{p_1} = \left[\frac{(\Gamma+1)M^2}{2}\right]^{\frac{\Gamma}{\Gamma-1}} \left[\frac{\Gamma+1}{2\Gamma M^2-(\Gamma-1)}\right]^{\frac{1}{\Gamma-1}}$$

Figure 8.

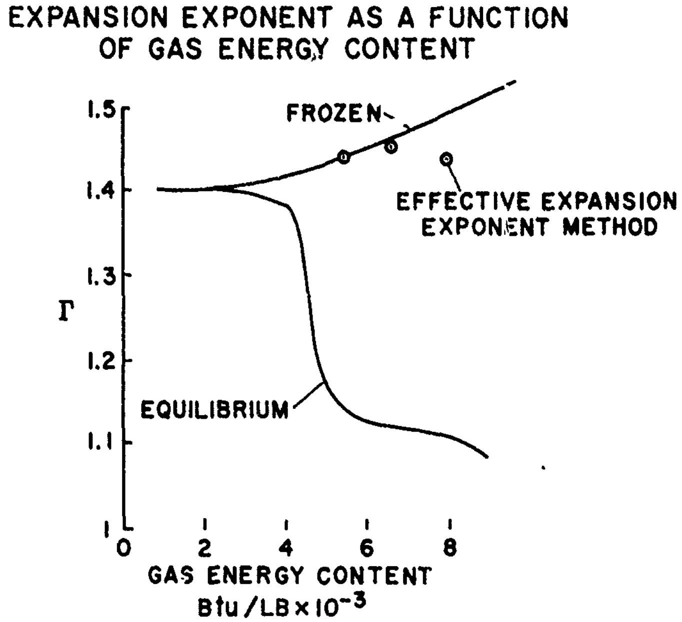



Figure 9.

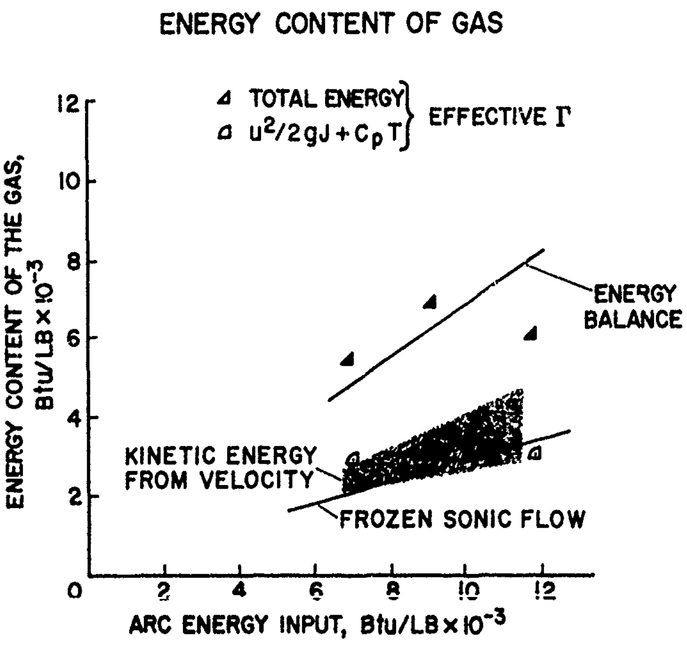



Figure 10.