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Standard Test Method for Calculation of Stagnation Enthalpy from Heat Transfer Theory and Experimental Measurements of Stagnation-Point Heat Transfer and Pressure[1]

This standard is issued under the fixed designation E637; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

INTRODUCTION

The enthalpy (energy per unit mass) determination in a hot gas aerodynamic simulation device is a difficult measurement. Even at temperatures that can be measured with ~~thermocouples,~~ thermocouples **(1),** there are many corrections to be made at 600 K and above. Methods that are used for temperatures above the range of thermocouples that give bulk or average enthalpy values are energy balance (see Practice E341), sonic flow **(~~1~~2, ~~2~~3)**,[2] and the pressure rise method **(~~3~~4)**. Local enthalpy values (thus distribution) may be obtained by using either an energy balance probe (see Method E470), or the spectrometric technique described in Ref **(~~4~~5)**.

1. Scope

1.1 This test method covers the calculation from heat transfer theory of the stagnation enthalpy from experimental measurements of the stagnation-point heat transfer and stagnation pressure.

1.2 *Advantages:*

1.2.1 A value of stagnation enthalpy can be obtained at the location in the stream where the model is tested. This value gives a consistent set of data, along with heat transfer and stagnation pressure, for ablation computations.

1.2.2 This computation of stagnation enthalpy does not require the measurement of any arc heater parameters.

1.3 *Limitations and Considerations*—There are many factors that may contribute to an error using this type of approach to calculate stagnation enthalpy, including:

1.3.1 *Turbulence*—The turbulence generated by adding energy to the stream may cause deviation from the laminar equilibrium heat transfer theory.

1.3.2 *Equilibrium, Nonequilibrium, or Frozen State of Gas*—The reaction rates and expansions may be such that the gas is far from thermodynamic equilibrium.

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[1] This test method is under the jurisdiction of ASTM Committee E21 on Space Simulation and Applications of Space Technology and is the direct responsibility of Subcommittee E21.08 on Thermal Protection.

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[2] The boldface numbers in parentheses refer to the list of references appended to this method.

1.3.3 *Noncatalytic Effects*—The surface recombination rates and the characteristics of the metallic calorimeter may give a heat transfer deviation from the equilibrium theory.

1.3.4 *Free Electric Currents*—The arc-heated gas stream may have free electric currents that will contribute to measured experimental heat transfer rates.

1.3.5 *Nonuniform Pressure Profile*—A nonuniform pressure profile in the region of the stream at the point of the heat transfer measurement could distort the stagnation point velocity gradient.

1.3.6 *Mach Number Effects*—The nondimensional stagnation-point velocity gradient is a function of the Mach number. In addition, the Mach number is a function of enthalpy and pressure such that an iterative process is necessary.

1.3.7 *Model Shape*—The nondimensional stagnation-point velocity gradient is a function of model shape.

1.3.8 *Radiation Effects*—The hot gas stream may contribute a radiative component to the heat transfer rate.

1.3.9 *Heat Transfer Rate Measurement*—An error may be made in the heat transfer measurement (see Method E469 and Test Methods E422, E457, E459, and E511).

1.3.10 *Contamination*—The electrode material may be of a large enough percentage of the mass flow rate to contribute to the heat transfer rate measurement.

1.4 *Units*—The values stated in SI units are to be regarded as standard. No other units of measurement are included in this standard.

1.4.1 *Exception*—The values given in parentheses are for information only.

1.5 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate ~~safety~~ safety, health, and ~~health~~environmental practices and determine the applicability of regulatory limitations prior to use.*

1.6 *This international standard was developed in accordance with internationally recognized principles on standardization established in the Decision on Principles for the Development of International Standards, Guides and Recommendations issued by the World Trade Organization Technical Barriers to Trade (TBT) Committee.*

2. Referenced Documents

2.1 *ASTM Standards:*[3]

E341 Practice for Measuring Plasma Arc Gas Enthalpy by Energy Balance
E422 Test Method for Measuring Net Heat Flux Using a Water-Cooled Calorimeter
E457 Test Method for Measuring Heat-Transfer Rate Using a Thermal Capacitance (Slug) Calorimeter
E459 Test Method for Measuring Heat Transfer Rate Using a Thin-Skin Calorimeter
E469 Measuring Heat Flux Using a Multiple-Wafer Calorimeter (Withdrawn 1982)[4]
E470 Measuring Gas Enthalpy Using Calorimeter Probes (Withdrawn 1982)[4]
E511 Test Method for Measuring Heat Flux Using a Copper-Constantan Circular Foil, Heat-Flux Transducer

3. Significance and Use

3.1 The purpose of this test method is to provide a standard calculation of the stagnation enthalpy of an aerodynamic simulation device using the heat transfer theory and measured values of stagnation point heat transfer and pressure. A stagnation enthalpy obtained by this test method gives a consistent set of data, along with heat transfer and stagnation pressure for ablation computations.

4. Enthalpy Computations

4.1 This method of calculating the stagnation enthalpy is based on experimentally measured values of the stagnation-point heat

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[3] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

[4] The last approved version of this historical standard is referenced on www.astm.org.

transfer rate and pressure distribution and theoretical calculation of laminar equilibrium catalytic stagnation-point heat transfer on a hemispherical body. The equilibrium catalytic theoretical laminar stagnation-point heat transfer rate for a hemispherical body is as follows (~~5~~6):

$$q\sqrt{\frac{R}{P_{t_2}}} = K_i\left(H_e - H_w\right) \tag{1}$$

where:

q = stagnation-point heat transfer rate, W/m^2 (or Btu/ft^2·s),
P_{t_2} = model stagnation pressure, Pa (or atm),
R = hemispherical nose radius, m (or ft),
H_e = stagnation enthalpy, J/kg (or Btu/lb),
H_w = wall enthalpy, J/kg (or Btu/lb), and
K_i = heat transfer computation constant.

4.2 *Low Mach Number Correction*—Eq 1 is simple and convenient to use since K_i can be considered approximately constant (see Table 1). However, Eq 1 is based on a stagnation-point velocity gradient derived using "modified" Newtonian flow theory which becomes inaccurate for $M_{\cancel{oo}\underline{\infty}}$ <2. An improved Mach number dependence at lower Mach numbers can be obtained by removing the "modified" Newtonian expression and replacing it with a more appropriate expression as follows:

~~$$H_e - H_w = \frac{K_M\dot{q}}{\left(P_{t_2}/R\right)^{0.5}}\left[\frac{\left(\beta D/U_{oo}\right)_{Eq\ 3}}{\left(\beta D/U_{oo}\right)_{x=0}}\right]^{0.5} \tag{2}$$~~

$$H_e - H_w = \frac{K_M\dot{q}}{\left(P_{t_2}/R\right)^{0.5}}\left[\frac{\left(\beta D/U_{\infty}\right)_{Eq\ 3}}{\left(\beta D/U_{\infty}\right)_{x=0}}\right]^{0.5} \tag{2}$$

Where the "modified" Newtonian stagnation-point velocity gradient is given by:

~~$$\left(\beta D/U_{oo}\right)_{x=0} = \left[\frac{4\left[(\gamma-1)M_{oo}{}^2+2\right]}{\gamma M_{oo}{}^2}\right]^{0.5} \tag{3}$$~~

$$\left(\beta D/U_{\infty}\right)_{x=0} = \left\{\frac{4\left[(\gamma-1)M_{\infty}{}^2+2\right]}{\gamma M_{\infty}{}^2}\right\}^{0.5} \tag{3}$$

A potential problem exists when using Eq 3 to remove the "modified" Newtonian velocity gradient because of the singularity at $M_{\cancel{oo}\underline{\infty}} = 0$. The procedure recommended here should be limited to $M_{\cancel{oo}\underline{\infty}}$ > ~~0.1~~0.1.

where:

β = stagnation-point velocity gradient, s^{-1},
D = hemispherical diameter, m (or ft),
U_∞ = freestream velocity, m/s (or ft/s),
$(\beta D/U_\infty)_{x\,=\,0}$ = dimensionless stagnation velocity gradient,
~~K_M = enthalpy computation constant, (N$^{1/2}$·m$^{1/2}$· s)/kg or (ft$^{3/2}$·atm$^{1/2}$·s)/lb, and~~
K_M = enthalpy computation constant, (N$^{1/2}$·m$^{1/2}$· s)/kg or (ft$^{3/2}$·atm$^{1/2}$·s)/lb,
M_∞ = the freestream Mach number, and
~~$M\infty$ = the freestream Mach number.~~
γ = dimensionless ratio of gas specific heat at constant pressure to its specific heat at constant volume.

For subsonic Mach numbers, an expression for $(\beta D/U_\infty)_{x\,=\,0}$ for a hemisphere is given in Ref (~~6~~7) as follows:

TABLE 1 Heat Transfer and Enthalpy Computation Constants for Various Gases

Gas	K_i, kg/(N$^{1/2}$·m$^{1/2}$·s) (lb/(ft$^{3/2}$·s·atm$^{1/2}$))	K_M, (N$^{1/2}$·m$^{1/2}$·s)/kg ((ft$^{3/2}$·s·atm$^{1/2}$)/lb)
Air	3.905 × 10^{-4} (0.0461)	2561 (21.69)
Argon	5.513 × 10^{-4} (0.0651)	1814 (15.36)
Carbon dioxide	4.337 × 10^{-4} (0.0512)	2306 (19.53)
Hydrogen	1.287 × 10^{-4} (0.0152)	7768 (65.78)
Nitrogen	3.650 × 10^{-4} (0.0431)	2740 (23.20)

$$\left(\frac{\beta D}{U_\infty}\right)_{x=0} = 3 - 0.755\, M_\infty^{\ 2} \qquad (M_\infty < 1) \tag{4}$$

For a Mach number of 1 or greater, $(\beta D/U_\infty)_{x=0}$ for a hemisphere based on "classical" Newtonian flow theory is presented in Ref (~~7~~8) as follows:

$$\left(\frac{\beta D}{U_\infty}\right)_{x=0} = \left\{ \frac{8\left[(\gamma-1)M_{\infty^2}+2\right]}{(\gamma+1)M_{\infty^2}} \left[\frac{1+\dfrac{\gamma-1}{2}}{\dfrac{\left[(\gamma-1)M_{\infty^2}+2\right]}{2\gamma M_{\infty^2}-(\gamma-1)}} \right]^{-\frac{1}{\gamma-1}} \right\}^{0.5} \tag{5}$$

A variation of $(\beta D/U_\infty)_{x=0}$ with M_∞ and γ is shown in Fig. 1. The value of the Newtonian dimensionless velocity gradient approaches a constant value as the Mach number approaches infinity:

$$\left(\frac{\beta D}{U_\infty}\right)_{x=0, M\to\infty} = \sqrt{4\left(\frac{\gamma-1}{\gamma}\right)} \tag{6}$$

and thus, since γ, the ratio of specific heats, is a function of enthalpy, $(\beta D/U_\infty)_{x=0}$ is also a function of enthalpy. Again, an iteration is necessary. From Fig. 1, it can be seen that $(\beta D/U_\infty)_{x=0}$ for a hemisphere is approximately 1 for large Mach numbers and $\gamma = 1.2$. K_M is tabulated in Table 1 using $(\beta D/U_\infty)_{x=0} = 1$ and K_i from Ref (~~5~~6).

4.3 *Mach Number Determination:*

4.3.1 The Mach number of a stream is a function of the total enthalpy, the ratio of freestream pressure to the total pressure, p/p_{t_1}, the total pressure, p_{t_1}, and the ratio of the exit nozzle area to the area of the nozzle throat, A/A'.Fig. 2(a) and Fig. 2(b) are reproduced from Ref (~~8~~9) for the reader's convenience in determining Mach numbers for supersonic flows.

4.3.2 The subsonic Mach number may be determined from Fig. 3 (see also Test Method E511). An iteration is necessary to determine the Mach number since the ratio of specific heats, γ, is also a function of enthalpy and pressure.

4.3.3 The ratio of specific heats, γ, is shown as a function of entropy and enthalpy for air in Fig. 4 from Ref (~~9~~10).S/R is the dimensionless entropy, and H/RT is the dimensionless enthalpy.

4.4 *Velocity Gradient Calculation from Pressure Distribution*—The dimensionless stagnation-point velocity gradient may be obtained from an experimentally measured pressure distribution by using Bernoulli's compressible flow equation as follows:

$$\frac{U}{U_\infty} = \frac{\left[1-(p/p_{t_2})^{\frac{\gamma-1}{\gamma}}\right]^{0.5}}{\left[1-(p_\infty/p_{t_2})^{\frac{\gamma-1}{\gamma}}\right]^{0.5}} \tag{7}$$

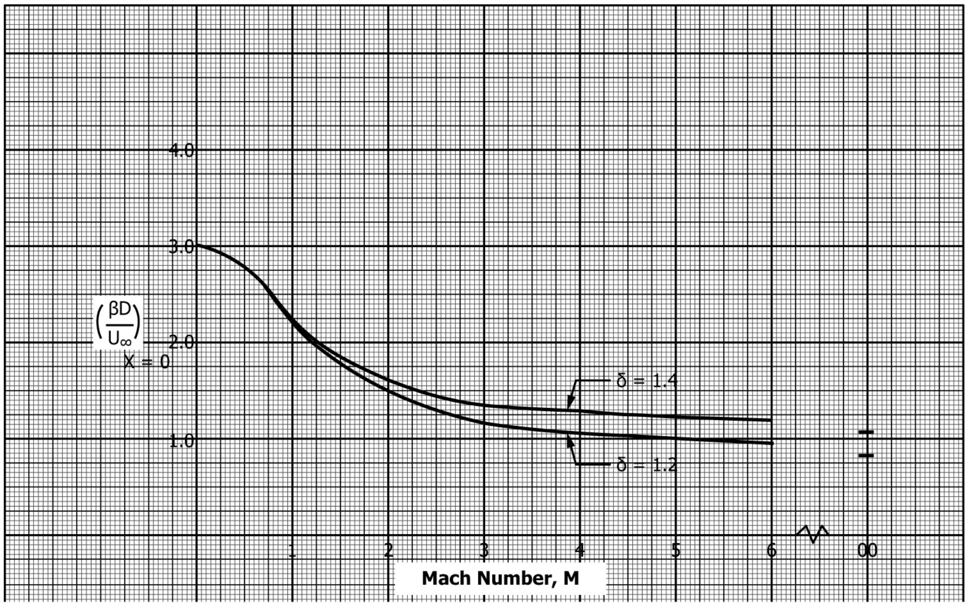
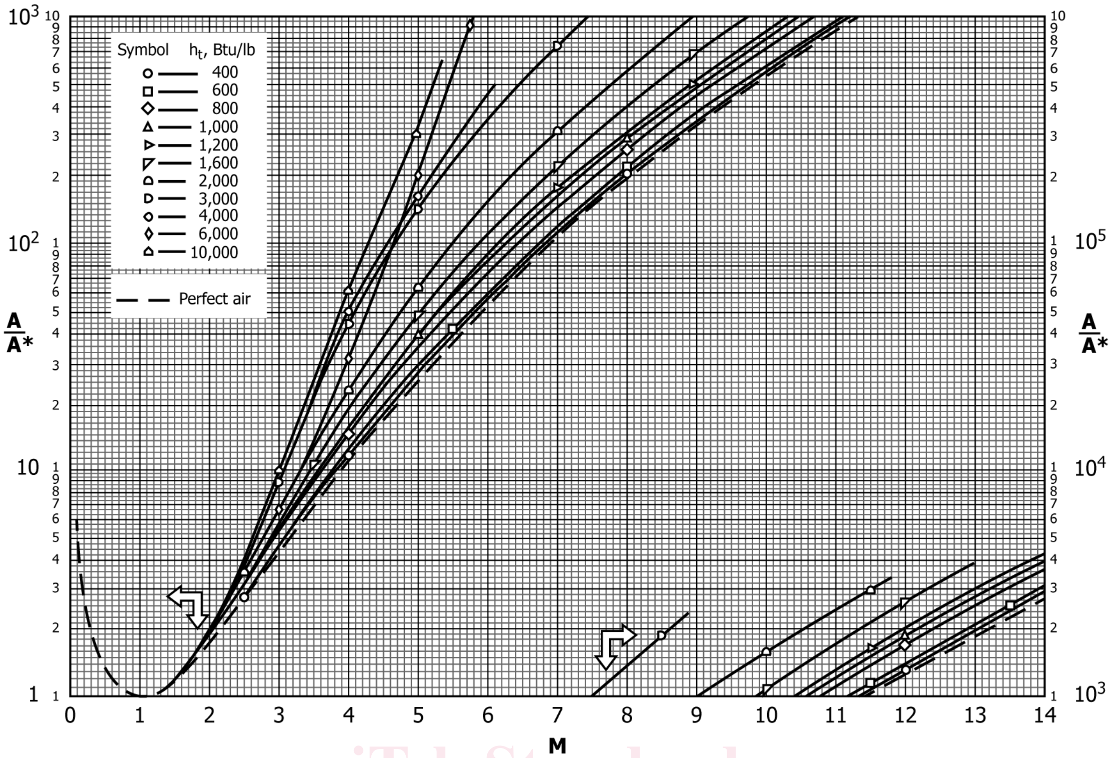
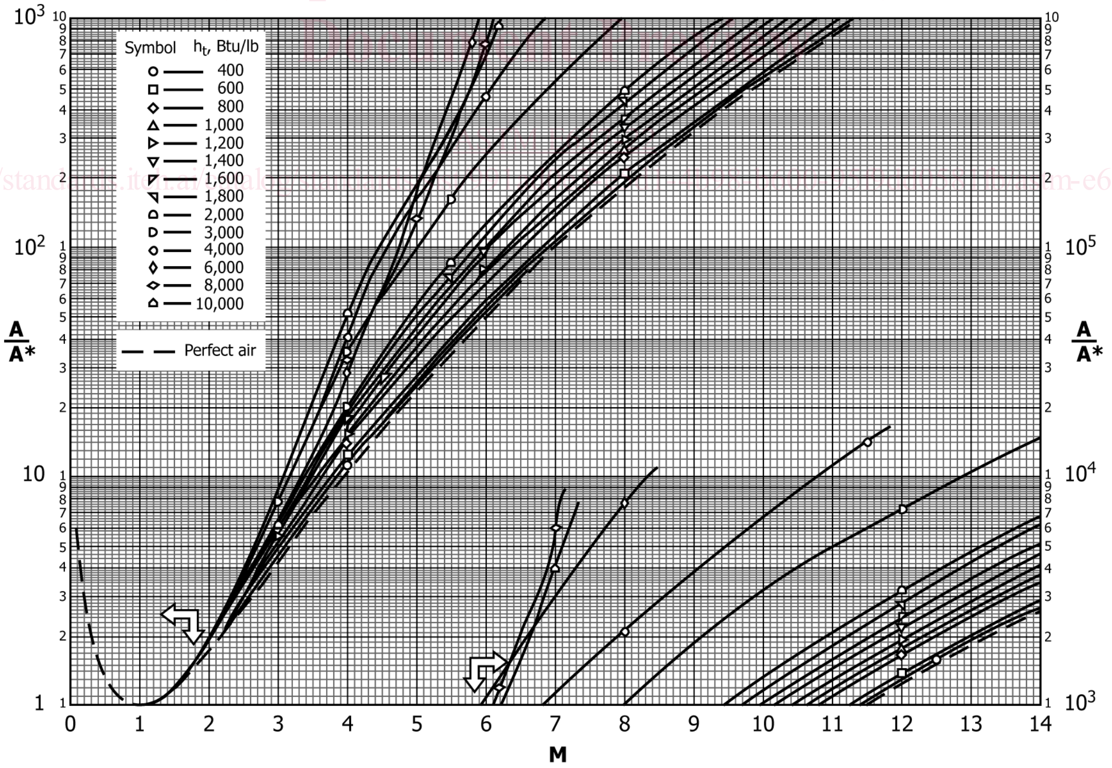


FIG. 1 Dimensionless Velocity Gradient as a Function of Mach Number and Ratio of Specific Heats



(a) p_t = 1 atm

FIG. 2 (a) Variation of Area Ratio with Mach Numbers



(b) p_t = 10 atm

FIG. 2 (b) Variation of Area Ratio with Mach Numbers *(continued)*

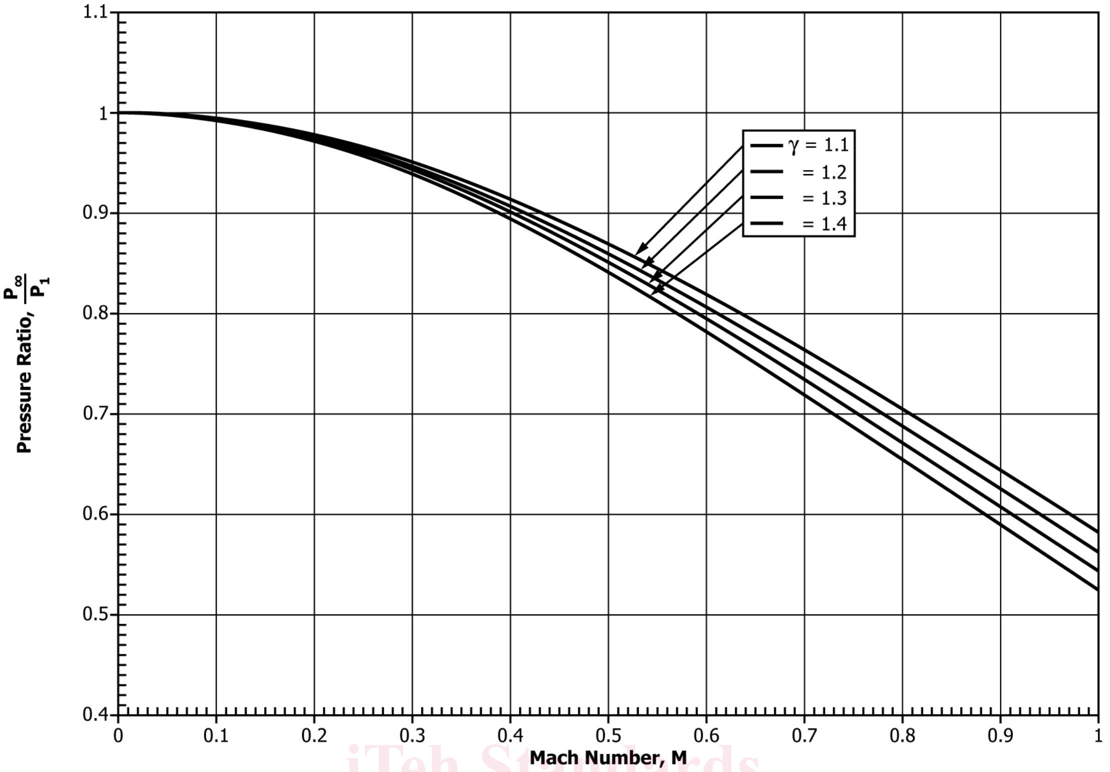


FIG. 3 Subsonic Pressure Ratio as a Function of Mach Number and γ

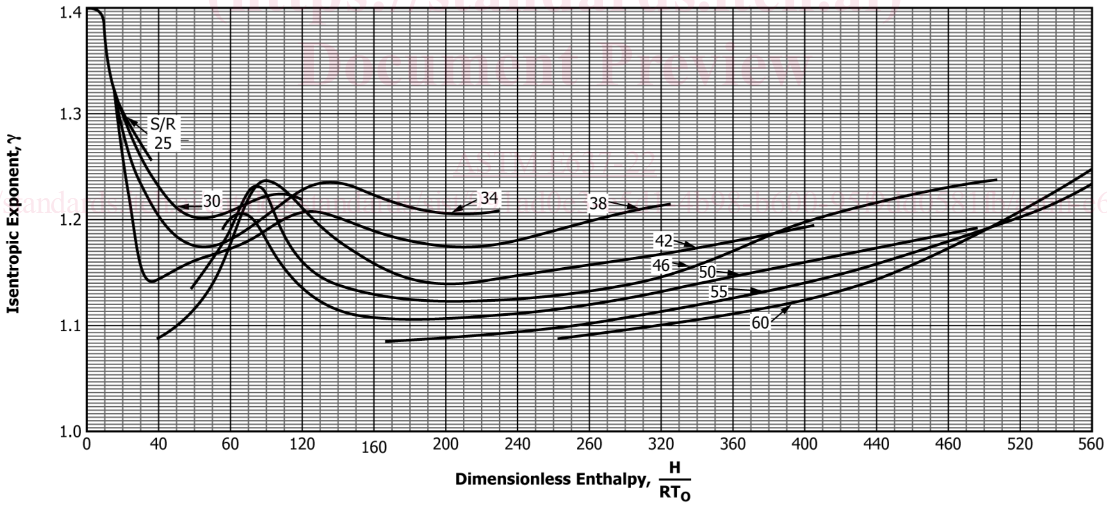


FIG. 4 Isentropic Exponent for Air in Equilibrium

$$\frac{U}{U_\infty} = \frac{\left[1-\left(p/p_{t_2}\right)^{\frac{\gamma-1}{\gamma}}\right]^{0.5}}{\left[1-\left(p_\infty/p_{t_2}\right)^{\frac{\gamma-1}{\gamma}}\right]^{0.5}} \tag{7}$$

where the velocity ratio may be calculated along the body from the stagnation point. Thus, the dimensionless stagnation-point velocity gradient, $(\beta D/U_\infty)_{x=0}$, is the slope of the U/U_∞ and the x/D curve at the stagnation point.

4.5 *Model Shape*—The nondimensional stagnation-point velocity gradient is a function of the model shape and the Mach number. For supersonic Mach numbers, the heat transfer relationship between a hemisphere and other axisymmetric blunt bodies is shown in Fig. 5 (~~10~~11). In Fig. 5, r_c is the corner radius, r_b is the body radius, r_n is the nose radius, and $\dot{q}_{s,h}$ is the stagnation-point heat transfer rate on a hemisphere. For subsonic Mach numbers, the same type of variation is shown in Fig. 6 (~~6~~7).

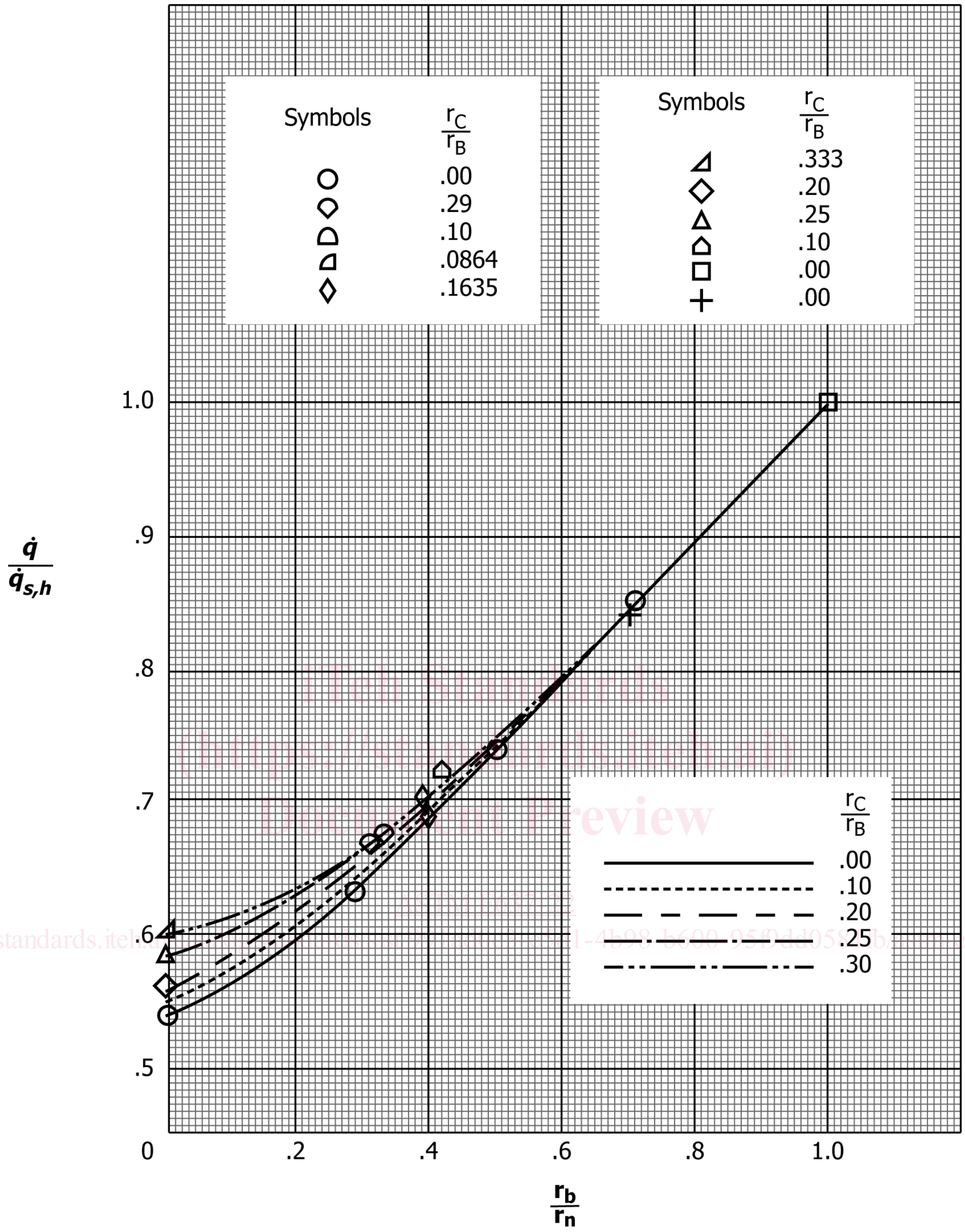


FIG. 5 Stagnation-Point Heating-Rate Parameters on Hemispherical Segments of Different Curvatures for Varying Corner-Radius Ratios

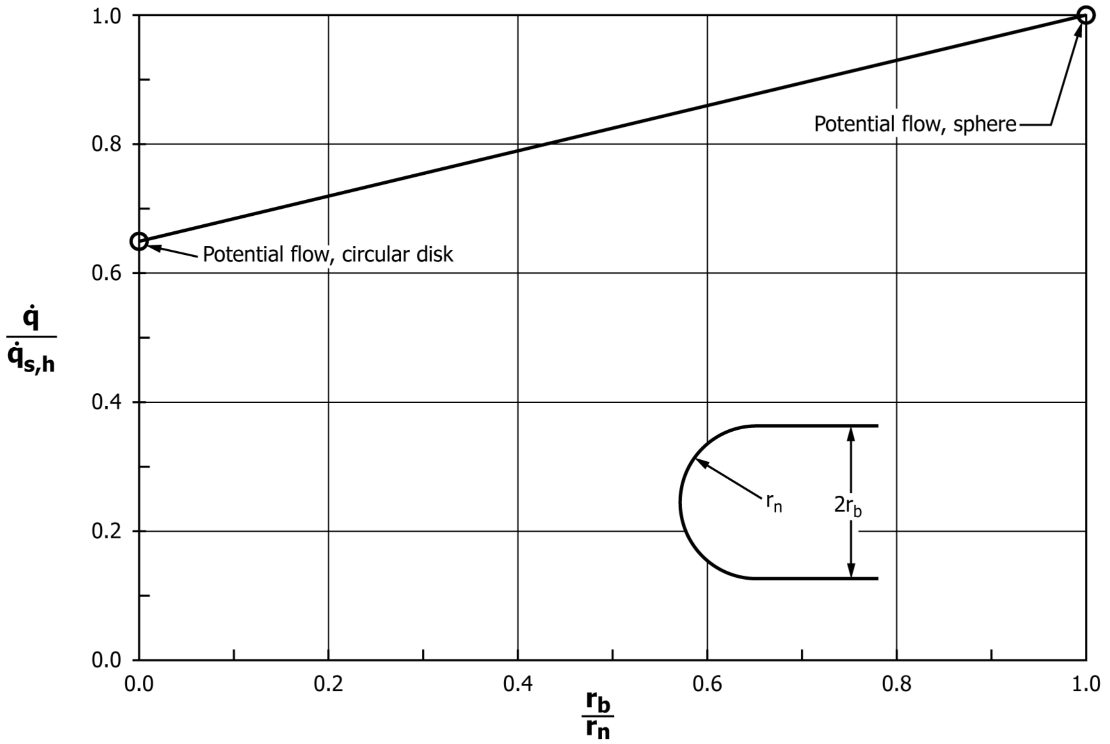


FIG. 6 Stagnation-Point Heat Transfer Ratio to a Blunt Body and a Hemisphere as a Function of the Body-to-Nose Radius in a Subsonic Stream

4.6 *Radiation Effects:*

4.6.1 As this test method depends on the accurate determination of the *convective* stagnation-point heat transfer, any radiant energy absorbed by the calorimeter surface and incorrectly attributed to the convective mode will directly affect the overall accuracy of the test method. Generally, the sources of radiant energy are the hot gas stream itself or the gas heating device, or both. For instance, arc heaters operated at high pressure (10 atm or higher) can produce significant radiant fluxes at the nozzle exit plane.

4.6.2 The proper application requires some knowledge of the radiant environment in the stream at the desired operating conditions. Usually, it is necessary to measure the radiant heat transfer rate either directly or indirectly. The following is a list of suggested methods by which the necessary measurements can be made.

4.6.2.1 *Direct Measurement with Radiometer*—Radiometers are available for the measurement of the incident radiant flux while excluding the convective heat transfer. In its simplest form, the radiometer is a slug, thin-skin, or circular foil calorimeter with a sensing area with a coating of known absorptance and covered with some form of window. The purpose of the window is to prevent convective heat transfer from affecting the calorimeter while transmitting the radiant energy. The window is usually made of quartz or sapphire. The sensing surface is at the stagnation point of a test probe and is located in such a manner that the view angle is not restricted. The basic radiometer view angle should be 120° or greater. This technique allows for immersion of the radiometer in the test stream and direct measurement of the radiant heat transfer rate. There is a major limitation to this technique, however, in that even with high-pressure water cooling of the radiometer enclosure, the window is poorly cooled and thus the use of windows is limited to relatively low convective heat transfer conditions or very short exposure times, or both. Also, stream contaminants coat the window and reduce its transmittance.

4.6.2.2 *Direct Measurement with Radiometer Mounted in Cavity*—The two limitations noted in 4.6.2.1 may be overcome by mounting the radiometer at the bottom of a cavity open to the stagnation point of the test probe (see Fig. 7). Good results can be obtained by using a simple calorimeter in place of the radiometer with a material of known absorptance. When using this configuration, the measured radiant heat transfer rate is used in the following equation to determine the stagnation-point radiant heat transfer, assuming diffuse radiation:

$$\dot{q}_{r_1} = \frac{1}{\alpha_2 F_{12}} \dot{q}_{r_2} \tag{8}$$

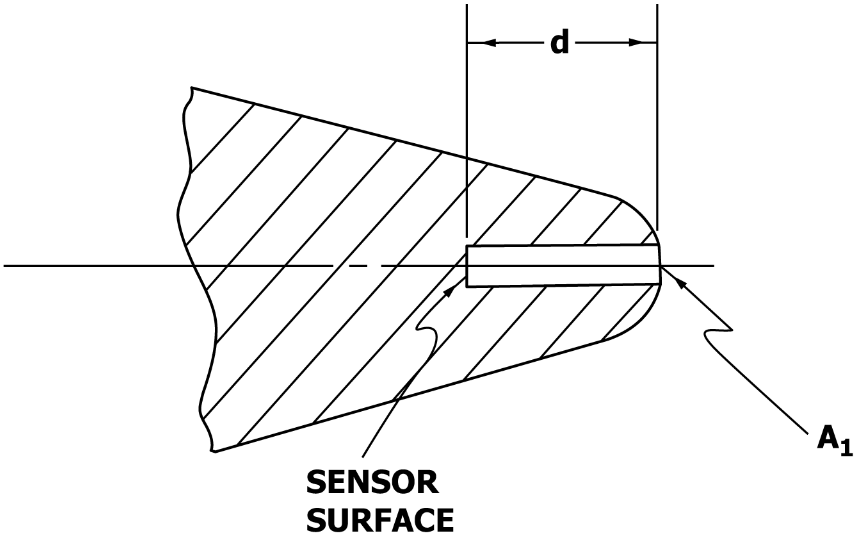


FIG. 7 Test Probe

where:

$\dot{q}_{r_1}$ = radiant transfer at stagnation point,
$\dot{q}_{r_2}$ = radiant transfer at bottom of cavity (measured),
α_2 = absorptance of sensor surface, and
F_{12} = configuration factor.

For a circular cavity geometry (recommended), F_{12} is Configuration A-3 of Ref (~~11~~12) and can be determined from the following equation:

$$F_{12} = 1/2\left[X - \left(X^2 - 4E^2D^2\right)^{1/2}\right] \tag{9}$$

where:

E = r_2/d,
D = d/r_1,
X = $1 + (1 + E^2)D^2$, and

r_1, d, and r_2 are defined in Fig. 8.

The major limitation of this particular technique is due to heating of the cavity opening (at the stagnation point). If the test probe is inadequately cooled or uncooled, heating at this point can contribute to the radiant heat transfer measured at the sensor and produce large errors. This method of measuring the radiant heat transfer is then limited to test conditions and probe configurations that allow for cooling of the probe in the stagnation area such that the cavity opening is maintained at a temperature less than about 700 K.

4.6.2.3 *Indirect Measurement*—At the highest convective heating rates, the accurate determination of the radiant flux levels is difficult. There are many schemes that could be used to measure incident radiant flux indirectly. One such would be the

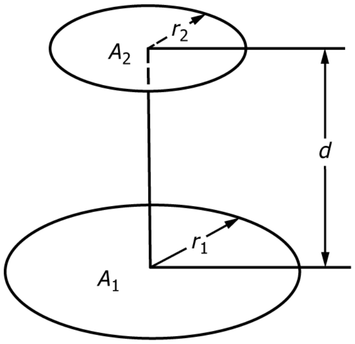


FIG. 8 Circular Cavity Configuration (see Eq 8)

measurement of the radiant flux reflected from a surface in the test stream. This technique depends primarily on the accurate determination of surface reflectance under actual test conditions. The surface absorptance and a measurement of the surface temperature at the point viewed by the radiant flux measuring device are required so that the radiant component contributed by the hot surface may be subtracted from the measured flux, yielding the reflected radiant flux. (The basic limitation to this method of measuring the radiant environment is the almost complete absence of reliable reflectance data for high-temperature materials.) This can be overcome somewhat by actual calibrations with the measuring system to be used and a controllable radiant source. To be most accurate, such calibrations should be done at the surface temperature expected during actual measurements in the test stream.

4.7 *Test Stream Current Determination:*

4.7.1 Most of the methods of measuring heat transfer rates use some type of thermocouple device attached to an electrically conducting (metallic) surface. In most arc-heated test streams, it is necessary to either ground the metal surface or to use a "floating" readout system. Experience has shown that test streams that produce a small amount of current to a special test probe do not make a significant contribution to the heat transfer rate measurement. Large values of current produce increasingly larger errors in enthalpy computation.

4.7.2 The test probe with circuit set up is shown in Fig. 9. A copper rod 50 mm in diameter by 50 mm in length is used for a flat face model. A No. 12 insulated copper wire is attached to the back face and a tetrafluoroethylene tube (50 mm in diameter by 100 mm in length) serves as the electrical insulator from the tunnel. The copper lead is electrically connected to ground through a noninductive shunt with a reasonably large impedance. The shunt can be made with a length of 30 m of No. 12 insulated copper wire that is doubled back upon itself (15 m length) and then wound into a compact coil. A commercially available voltmeter (DVM) or an oscillograph with proper galvanometer element may be used to obtain a current-to-test model measurement as a function of time. The system can be calibrated by use of a low-voltage dc current power supply applied between the test model and ground or just across the noninductive shunt.

4.7.3 Experience has shown that leak currents to the test probe up to 0.5 A did not make a significant contribution to the heat transfer rate measurement; however, small currents will cause instrumentation error. Larger current values will give larger heat transfer values with correspondingly large errors in enthalpy computations.

4.7.4 Depending upon exact arc heater and tunnel configurations and power circuits, some modifications and precautions may be required over the simple circuit shown.

4.8 *Catalytic Effects:*

4.8.1 The catalytic reaction-rate constants for most metals are large and it is generally common practice to assume that the models are fully catalytic for atom recombination. However, metallic oxides inhibit the recombination reaction (~~12~~13) and should be removed before each use by using a procedure such as that described in Ref (~~13~~14) and summarized as: The metallic calorimeter surface should be chemically cleaned and the calorimeter placed in a nonoxidizing or vacuum environment until used.

4.8.2 A noncatalytic surface does not promote atomic recombination; thus, the energy invested in dissociation of the molecules may not contribute to the heat transfer. A heat transfer metallic surface may be made noncatalytic by vacuum-depositing silicon monoxide or spraying with tetrafluoroethylene solids suspended in a fluorocarbon propellant. The reader may obtain a better understanding of heat transfer to catalytic, noncatalytic surfaces in frozen dissociated flows from Refs (~~13~~14 and ~~14~~15).

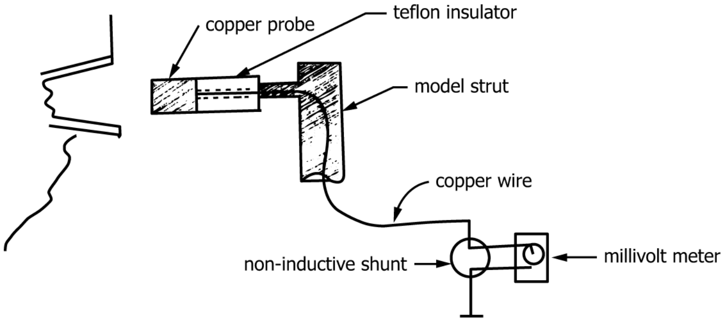


FIG. 9 Sketch of Set-Up to Measure Current-to-Metal Models in Arc-Heated Streams

5. Procedure

5.1 Calculate the stagnation enthalpy by use of Eq 2 with the proper constants for the Mach number, shape factor, and test gas.

6. Report

6.1 In reporting the results of the enthalpy computation, the following data should be reported:

6.1.1 Test gas,

6.1.2 Nozzle area ratio,

6.1.3 Model stagnation pressure,

6.1.4 Calorimeter size and shape,

6.1.5 Calorimeter material,

6.1.6 Calorimeter surface condition,

6.1.7 Nondimensional stagnation-point velocity gradient,

6.1.8 Calorimeter type,

6.1.9 Calculated heat transfer rate,

6.1.10 Mach number,

6.1.11 Calculated enthalpy, and

6.1.12 Appropriate Reynolds number or numbers.

7. Measurement Uncertainty

7.1 The application of this test method requires measurement of stagnation pressure and stagnation-point heat transfer rate. The uncertainty of those measurements must be characterized to produce a meaningful analysis with this test method. There are a number of methods that can be used for the determination of measurement uncertainty. A recent summary of the various uncertainty analysis methods is provided in Ref (~~15~~16). The American Society of Mechanical Engineers' (ASME's) earlier performance test code PTC 19.1-1985 (~~16~~17) has been revised and was replaced by Ref (~~17~~18) in ~~1998.~~2018. In Refs (~~16~~17) and (~~17~~18), uncertainties were separated into two types: "bias" or "systematic" uncertainties (B) and "random" or "precision" uncertainties (S). Systematic uncertainties (Type B) are often (but not always) constant for the duration of the experiment. Random uncertainties are not constant and are characterized via the standard deviation of the random measurements, thus the abbreviation 'S.'

7.2 ASME's ~~new~~ PTC 19.1 standard (~~17~~18) proposes use of the following model:

~~$U_{95} = \pm t_{95}\left[(\mathrm{B}_\mathrm{T}/2)^2+(\mathrm{S}_\mathrm{T})^2\right]^{\frac{1}{2}}$ (10)~~

$$U_{95} = \pm t_{95}\left[(B_T/2)^2+(S_T)^2\right]^{\frac{1}{2}} \quad (10)$$

where t_{95} is determined from the number of degrees of freedom (DOF) in the data provided. For large DOF (that is, 30 or larger) t_{95} is almost 2. B_T is the total bias or systematic uncertainty of the result, S_T is the total random uncertainty or precision of the result, and t_{95} is "Student's t" at 95 % for the appropriate degrees of freedom (DOF).

8. Keywords

8.1 enthalpy distribution; enthalpy profile; local enthalpy; stagnation enthalpy