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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, 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] and the pressure rise method (**3**). 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**).

## 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.

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] 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.

1.3.10 *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 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 and health practices and determine the applicability of regulatory limitations prior to use.*

## 2. Referenced Documents

2.1 *ASTM Standards:*[3]

E341 Practice for Measuring Plasma Arc Gas Enthalpy by Energy Balance
E422 Test Method for Measuring 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 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**):

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



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 $M_{oo}$ <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:

[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.

**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 | $3.905 \times 10^{-4}$ (0.0461) | 2561 (21.69) |
| Argon | $5.513 \times 10^{-4}$ (0.0651) | 1814 (15.36) |
| Carbon dioxide | $4.337 \times 10^{-4}$ (0.0512) | 2306 (19.53) |
| Hydrogen | $1.287 \times 10^{-4}$ (0.0152) | 7768 (65.78) |
| Nitrogen | $3.650 \times 10^{-4}$ (0.0431) | 2740 (23.20) |

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

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

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

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

where:

| | | |
|---|---|---|
| $\beta$ | = | stagnation-point velocity gradient, $s^{-1}$, |
| $D$ | = | hemispherical diameter, m (or ft), |
| $U_\infty$ | = | freestream velocity, m/s (or ft/s), |
| $(\beta D/U_\infty)_{x=0}$ | = | dimensionless stagnation velocity gradient, |
| $K_M$ | = | enthalpy computation constant, $(N^{1/2}\cdot m^{1/2}\cdot s)/kg$ or $(ft^{3/2}\cdot atm^{1/2}\cdot s)/lb$, and |
| $M\infty$ | = | the freestream Mach number. |

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

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

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)** as follows:

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

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

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

and thus, since $\gamma$, 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)**.



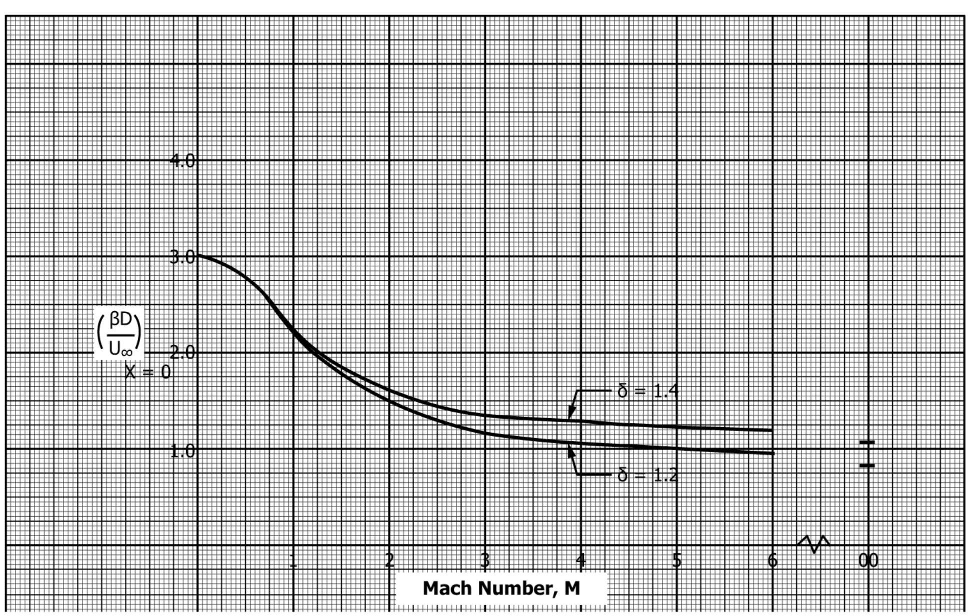



**FIG. 1 Dimensionless Velocity Gradient as a Function of Mach Number and Ratio of Specific Heats**

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**) 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**).*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:

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

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 $U/U_\infty$ 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**). 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**).

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.



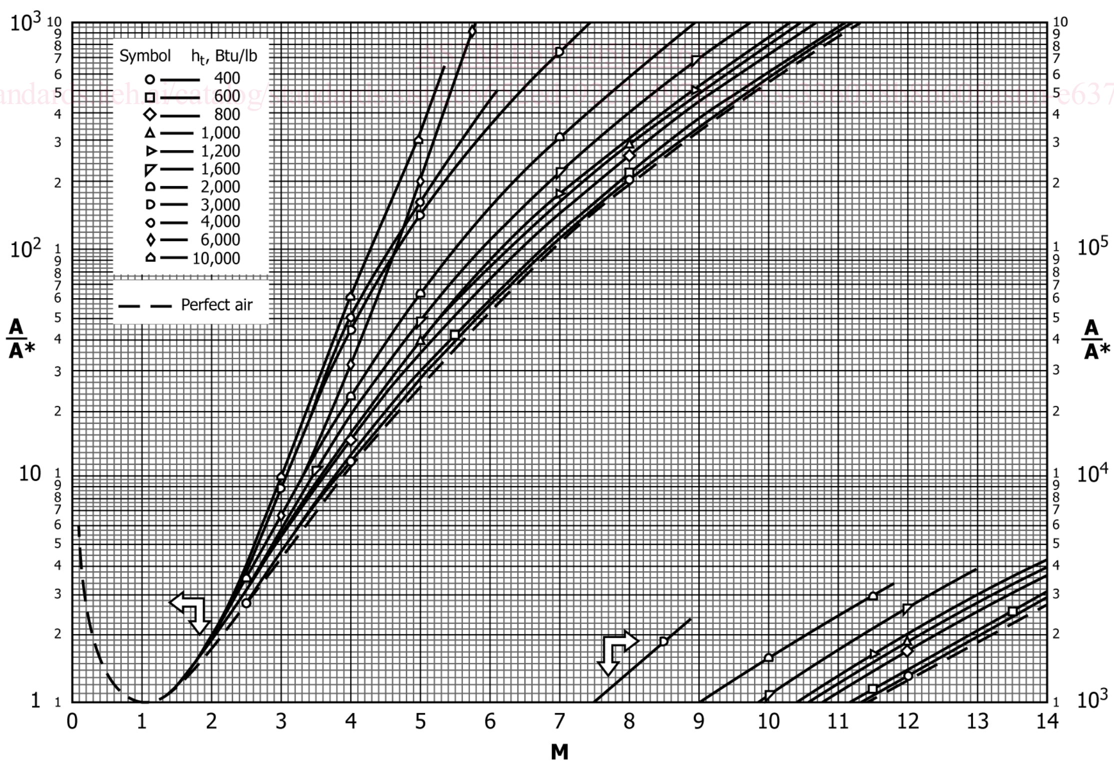
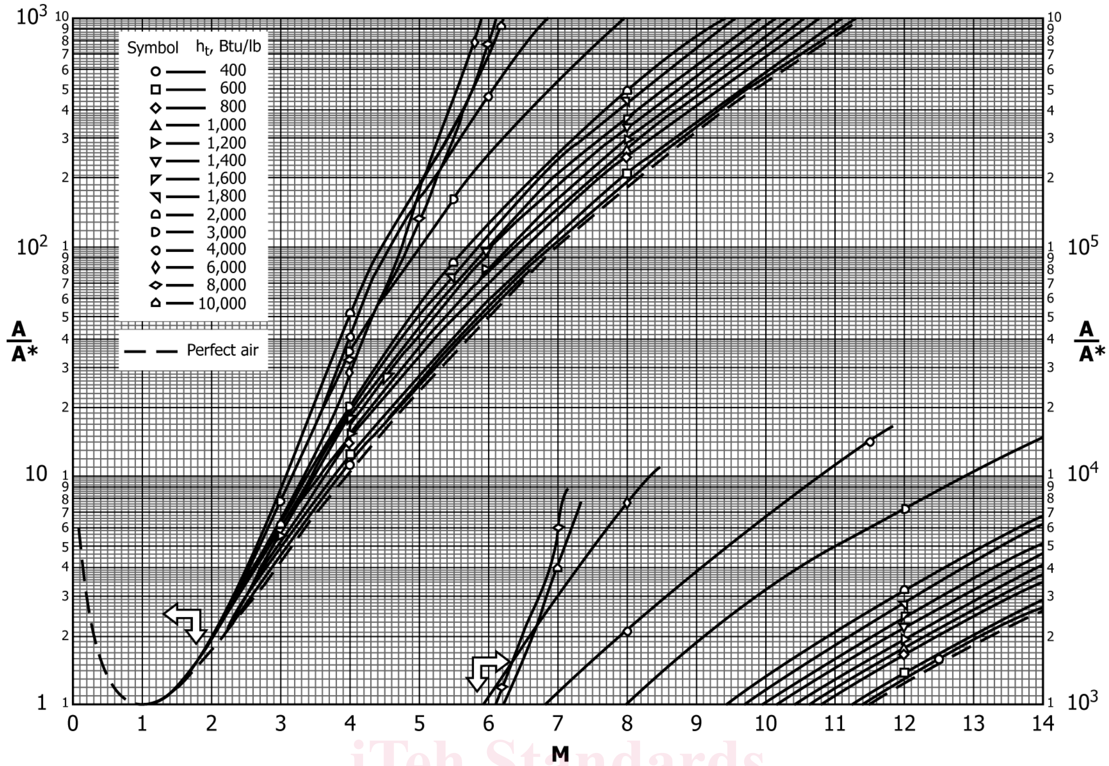



**FIG. 2 (a) Variation of Area Ratio with Mach Numbers**




**(b)** $p_t$ = 10 atm

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



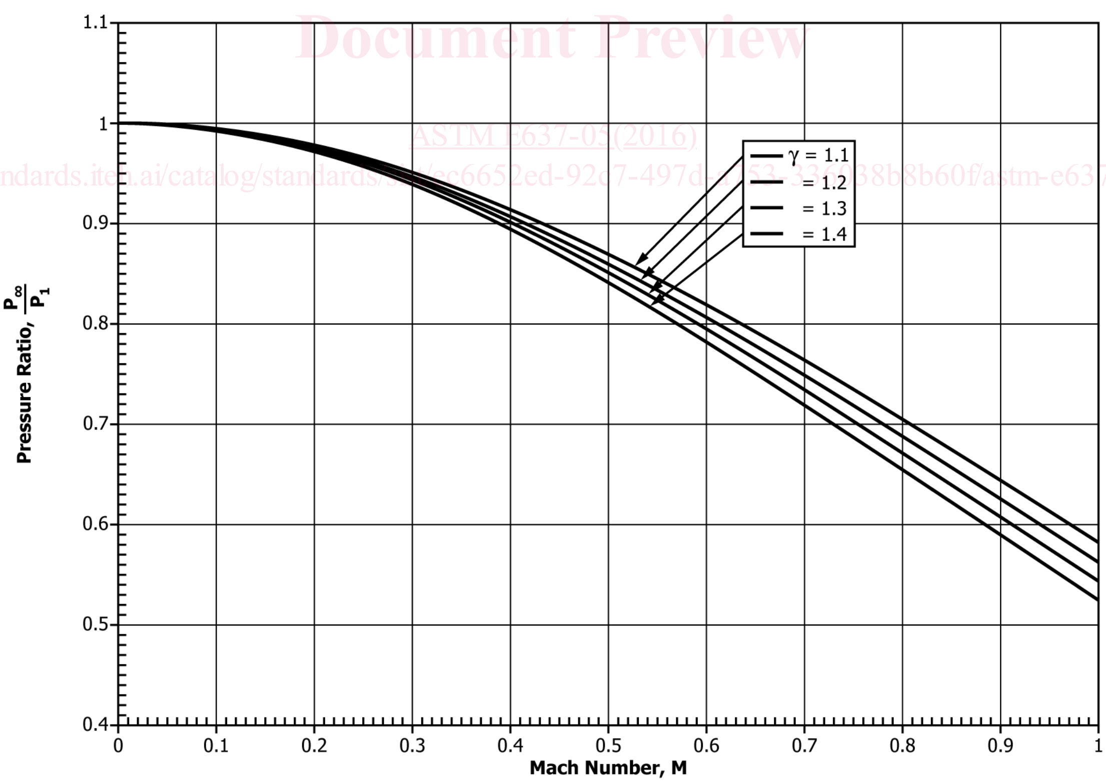



**FIG. 3 Subsonic Pressure Ratio as a Function of Mach Number and γ**

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

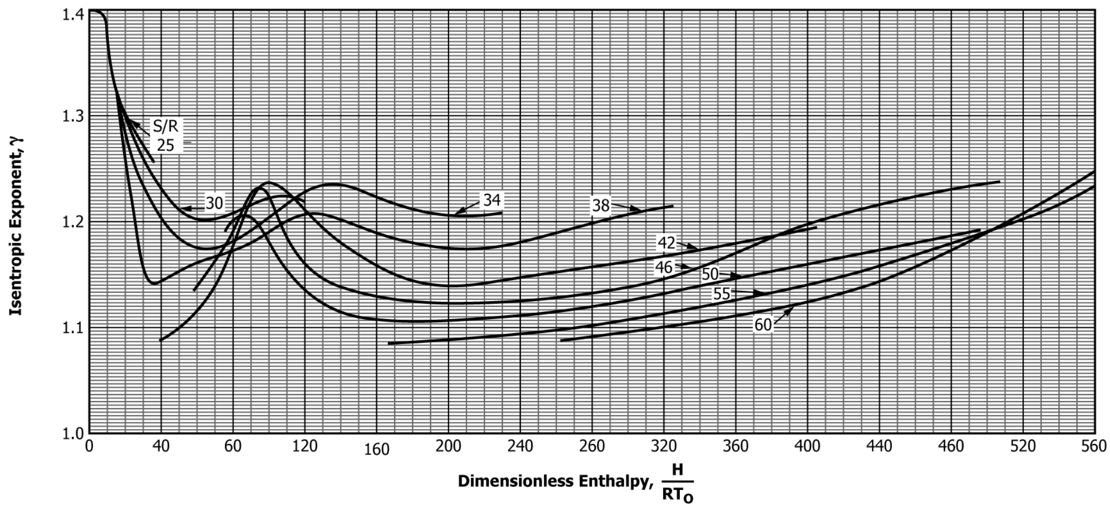



**FIG. 4 Isentropic Exponent for Air in Equilibrium**

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:



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

where:

$\dot{q}_{r_1}$ = radiant transfer at stagnation point,
$\dot{q}_{r_2}$ = radiant transfer at bottom of cavity (measured),
$\alpha_2$ = absorptance of sensor surface, and
$F_{12}$ = configuration factor.

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

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