Designation: E637 – 22

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 (**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 (**2, 3**),[2] and the pressure rise method (**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 (**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.

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*

[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.

responsibility of the user of this standard to establish appropriate safety, health, and 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 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 **(6)**:

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

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 $M_\infty < 2$. 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:

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

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

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

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

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,
M_∞ = the freestream Mach number, and
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 **(7)** as follows:

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

[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	3.905×10^{-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)