INTERNATIONAL

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Standard Test Method for Measuring Heat Transfer Rate Using a Thin-Skin Calorimeter[1]

This standard is issued under the fixed designation E459; 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.

1. Scope

1.1 This test method covers the design and use of a thin metallic calorimeter for measuring heat transfer rate (also called heat flux). Thermocouples are attached to the unexposed surface of the calorimeter. A one-dimensional heat flow analysis is used for calculating the heat transfer rate from the temperature measurements. Applications include aerodynamic heating, laser and radiation power measurements, and fire safety testing.

1.2 *Advantages:*

1.2.1 *Simplicity of Construction*—The calorimeter may be constructed from a number of materials. The size and shape can often be made to match the actual application. Thermocouples may be attached to the metal by spot, electron beam, or laser welding.

1.2.2 Heat transfer rate distributions may be obtained if metals with low thermal conductivity, such as some stainless ~~steels,~~ steels or Inconel 600, are used.

1.2.3 The calorimeters can be fabricated with smooth surfaces, without insulators or plugs and the attendant temperature discontinuities, to provide more realistic flow conditions for aerodynamic heating measurements.

1.2.4 The calorimeters described in this test method are relatively inexpensive. If necessary, they may be operated to burn-out to obtain heat transfer information.

1.3 *Limitations:*

1.3.1 At higher heat flux levels, short test times are necessary to ensure calorimeter survival.

1.3.2 For applications in wind tunnels or arc-jet facilities, the calorimeter must be operated at pressures and temperatures such that the thin-skin does not distort under pressure loads. Distortion of the surface will introduce measurement errors.

1.3.3 Interpretation of the heat flux estimated may require additional analysis if the thin-skin calorimeter configuration is different from the test specimen.

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] 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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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:*[2]

E176 Terminology of Fire Standards
E230 Specification for Temperature-Electromotive Force (emf) Tables for Standardized Thermocouples
E235 Specification for Type K and Type N Mineral-Insulated, Metal-Sheathed Thermocouples for Nuclear or for Other High-Reliability Applications
E456 Terminology Relating to Quality and Statistics
E3057 Test Method for Measuring Heat Flux Using Directional Flame Thermometers with Advanced Data Analysis Techniques
E457 Test Method for Measuring Heat-Transfer Rate Using a Thermal Capacitance (Slug) Calorimeter

3. Terminology

3.1 *Definitions*—Refer to Terminologies E176 and E456 for definitions of terms used in this test method.

3.2 *Definitions of Terms Specific to This Standard:*

3.2.1 *absorbed heat flux, n*—incident radiative heat flux less the reflected radiative flux, W/m^2.

3.2.2 *convective heat flux, n*—the addition or loss of energy per unit area into the sensing surface due to convection, = $h*(T_{fs}-T_s)$, W/m^2.

3.2.3 *control volume, n*—user defined volume over which an energy balance is determined.

3.2.4 *emitted heat flux, n*—energy per unit area emitted from a hot surface – $\varepsilon*\sigma*T^4$, W/m^2.

3.2.5 *incident radiative heat flux (irradiance; $q_{inc,r}$), n*—radiative heat flux (energy per unit area) impinging on the surface of the calorimeter from an external environment, W/m^2.

3.2.6 *heat flux, n*—energy per unit area, W/m^2.

3.2.7 *lumped heat flux, n*—the energy stored in the metal plate divided by the surface area of the sensing surface, W/m^2.

3.2.8 *net heat flux, n*—net energy divided by the sensing surface area transferred to the calorimeter face; it is equal to the [absorbed radiative heat flux + convective heat flux] – [re-radiation from the exposed surface].

3.2.9 *reflected heat flux, n*—that part of the incident radiative flux that is not absorbed by or transmitted into the surface of the calorimeter, W/m^2.

3.2.10 *verified, n*—the process of checking that a data acquisition channel correctly measures an input value, to a pre-set, acceptable level condition defined by the user.

3.3 *Symbols Specific to This Standard:*

A—sensing surface area of calorimeter, m^2

[2] 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.

Cp—specific heat at constant pressure of metal as a function of temperature, J/(kg-K)
h—convective heat transfer coefficient, W/m^2-K
k—thermal conductivity of metal as a function of temperature, W/(m-K)
ρ—density of metal, kg/m^3
q—heat flux, W/m^2
$\dot{q}$—MW/m^2 (Figs. 2 and 3 only)
q_{lumped}—energy per unit area stored in the metal calorimeter, W/m^2
t —time, sec
T—temperature, K
T_{fs}—free stream fluid temperature, K
T_s—surface temperature of thin-skin calorimeter, K
δ—metal thickness, m
ε—emissivity of sensing surface
σ—Stefan-Boltzmann constant, 5.67E-08 W/m^2-K^4
τ_r—initial response time, sec

3.4 *Abbreviations:*

3.4.1 B_T—total bias uncertainty

3.4.2 *DOF*—degrees of freedom

3.4.3 *ms*—milliseconds

3.4.4 *OD*—outer diameter

3.4.5 S_T—total systematic or precision uncertainty

3.4.6 *TC*—thermocouple

3.4.7 t_{95}—"Students t"

3.4.8 U_{95}—total uncertainty to 95 % confidence

4. Summary of Test Method

4.1 This test method for measuring the heat transfer rate to a metal calorimeter of finite thickness is based on the assumption of one-dimensional heat flow, known metal properties (density and specific heat), heat as functions of temperature), known metal thickness, and measurement of the rate of temperature rise of the back (or unexposed) surface of the calorimeter.

4.2 After an initial transient, the response of the calorimeter is approximated by a lumped parameter analysis:

$$q = \rho C_p \delta \frac{dT}{d\tau} \tag{1}$$

$$q_{lumped} = \rho C_p \delta \left(\frac{dT}{dt}\right) \tag{1}$$

where:

q_{lumped} = heat transfer rate, W/m^2, stored in the metal calorimeter,
ρ = metal density, kg/m^3,
δ = metal thickness, m,
C_p = metal specific heat, J/kg·K, and
$dT/d\tau$ = back surface temperature rise rate, K/s.
dT/dt = back surface temperature rise rate, K/s.

Use of Eq 1 assumes that the user understands the limitations of how the heat flux is interpreted. See Appendix X1 for more discussion related to this topic.

5. Significance and Use

5.1 This test method may be used to measure the net heat transfer rate to a metallic or coated metallic surface for a variety of applications, including:

5.1.1 Measurements of aerodynamic heating when the calorimeter is placed into a flow environment, such as a wind tunnel or an arc jet; the calorimeters can be designed to have the same size and shape as the actual test specimens to minimize heat transfer corrections;

5.1.2 Heat transfer measurements in fires and fire safety testing;

5.1.3 Laser power and laser absorption measurements; as well as,

5.1.4 X-ray and particle beam (electrons or ions) dosimetry measurements.

5.2 The thin-skin calorimeter is one of many concepts used to measure heat transfer rates. It may be used to measure convective, radiative, or combinations of convective and radiative (usually called mixed or total) heat transfer rates. However, when the calorimeter is used to measure radiative or mixed heat transfer rates, the absorptivity and reflectivity of the surface should be measured over the expected radiation wavelength region of the ~~source.~~source, and as functions of temperature if possible.

5.3 In ~~4.6~~6.6 and ~~4.7~~6.7, it is demonstrated that lateral heat conduction effects on a local measurement can be minimized by using a calorimeter material with a low thermal conductivity. Alternatively, a distribution of the heat transfer rate may be obtained by placing a number of thermocouples along the back surface of the calorimeter.

5.4 In high temperature or high heat transfer rate applications, the principal drawback to the use of thin-skin calorimeters is the short exposure time necessary to ensure survival of the calorimeter such that repeat measurements can be made with the same sensor. When operation to burnout is necessary to obtain the desired heat flux measurements, thin-skin calorimeters are often a good choice because they are relatively inexpensive to fabricate.

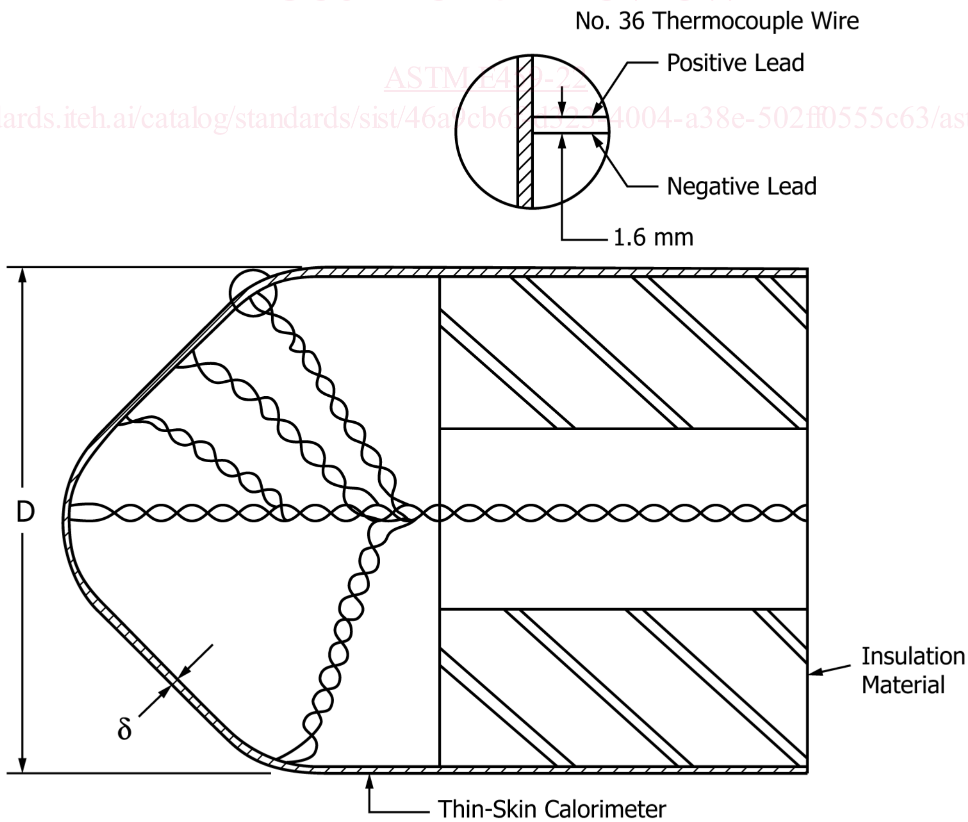

FIG. 1 Typical Thin-Skin Calorimeter for Heat Transfer Measurement

5.5 It is important to understand that the calorimeter design (that is, that shown in Fig. 1) will measure the "net" heat flux into the thin-skin calorimeter. This configuration may or may not be the same as the test specimen of interest. If it is the same configuration, then the results from use of Eq 1 can be used directly. But if the configuration is different, then some additional analysis should be performed. For example, if the actual test specimen has an insulated layer on the inside surface of the thin-skin, but the thin-skin calorimeter does not, then the net heat flux from Eq 1 will not be the same as the response of the test specimen. Refer to Appendix X1 for further discussion of this topic.

6. Apparatus

6.1 *Calorimeter Design*—Typical details of a thin-skin calorimeter used for measuring aerodynamic heat transfer rates are shown in Fig. 1. (See also E457.) The thermocouple wires ~~(0.127 mm OD, 0.005 in., 36 gage)~~ are individually welded to the back surface of the calorimeter using spot, electron beam, or laser techniques. This type of thermocouple joint (called an intrinsic thermocouple) has been found to provide superior transient response as compared to a peened joint or a beaded thermocouple that is soldered to the surface (**1, 2**).[3] The wires should be positioned approximately ~~1.6 mm~~ 1.6 mm apart along an expected isotherm. The use of a small thermocouple (for example, 0.127 mm (0.005 in.) OD, 36 gage) wire minimizes heat conduction into the wire but the calorimeter should still be rugged enough for repeated measurements. However, when the thickness of the calorimeter is ~~on the order of the~~ less than the wire diameter ~~to~~(to obtain the necessary response ~~characteristics, the~~ characteristics), it is possible that the presence of the TC will locally depress the temperature of the thin-skin. As a general rule of thumb, one should size the TC wire diameter no larger than the thickness of the calorimeter (δ). Further information on this topic is provided in the recommendations of Sobolik, et al. [1989], Burnett [1961], and Kidd [1985] (**2-4**~~)~~). ~~should be followed.~~

6.2 When heating starts, the response of the back (unheated) surface of the calorimeter lags behind that of the front (heated) surface. For a step change in the heat transfer rate, the initial response time of the calorimeter is the time required for the temperature rise rate of the unheated surface to approach the temperature rise rate of the front surface within 1 %. If conduction heat transfer into the thermocouple wire is ignored, the initial response time is generally defined as:

$$\tau_r = 0.5\,\frac{\rho C_p \delta^2}{k} \quad (2)$$

$$\tau_r = 0.5 * \left(\frac{\rho C_p \delta^2}{k}\right) \quad (2)$$

where:

τ_r = initial response time, s, and
k = thermal conductivity, W/m·K.

As an example, the 0.76 mm (0.030 in.) thick, 300 series stainless steel calorimeter analyzed in Ref (**4**) has an initial response time of 72 ms. Eq 2 can be rearranged to show that the initial response time also corresponds to a Fourier Number (a dimensionless time) of 0.5.

6.3 Conduction heat transfer into the thermocouple wire delays the time predicted by Eq 2 for which the measured back face temperature rise rate accurately follows (that is, within 1 %) the undisturbed back face temperature rise rate. For a 0.127 mm (0.005 in.) OD, Type K intrinsic thermocouple on a 0.76 mm (0.030 in.) thick, 300 series stainless steel calorimeter, the analysis in Ref (**4**) indicates the measured temperature rise rate is within 2 % of the undisturbed temperature rise rate in approximately 500 ms. An estimate of the measured temperature rise rate error (or slope error) can be obtained from Ref (**1**) for different material combinations:

$$\frac{dT_C}{dt} - \frac{dT_{TC}}{dt} = C_1 \exp\left(C_2^2 \frac{\alpha t}{R^2}\right) erfc\left(C_2 \sqrt{\frac{\alpha t}{R^2}}\right) \quad (3)$$

$$\frac{dT_C}{dt} - \frac{dT_{TC}}{dt} = C_1 \exp\left(\frac{C_2^2 \alpha t}{R^2}\right) * erfc\left(C_2 \sqrt{\frac{\alpha t}{R^2}}\right) \quad (3)$$

where:

T_C = calorimeter temperature,

[3] The boldface numbers in parentheses refer to the list of references at the end of this standard.

T_{TC} = measured temperature (that is, thermocouple output),
C_1 = $\beta/(8/\pi^2 + \beta)$ and $C_2 = 4/(8/\pi + \beta\pi)$,
α = $k/\rho C_p$ (thermal diffusivity of the calorimeter material),
β = $K/\sqrt{A}$,
K = k of thermocouple wire/k of calorimeter,
A = α of thermocouple wire/α of calorimeter,
R = radius of the thermocouple wire, and
t = time.

Using thermal property values given in Ref **(4)** for the Alumel (negative) leg of the Type K thermocouple on 300 Series stainless steel (K = 1.73, A = 1.56, β = 1.39), Eq 3 can be used to show that the measured rate of temperature change (that is, the slope) is within 5 % of the actual rate of temperature change in approximately 150 ms. For this case, the time for a 1 % error in the measured temperature rise rate is roughly 50 times as long as the initial response time predicted by Eq 2; this ratio depends on the thermophysical properties of the calorimeter and thermocouple materials (see Table 1).

6.3.1 When the heat transfer rate varies with time, the thin-skin calorimeter should be designed so the response times defined using Eq 2 and 3 are smaller than the time for significant variations in the heat transfer rate. If this is not possible, methods for unfolding the dynamic measurement errors **(1, 5)** should be used to compensate the temperature measurements before calculating the heat flux using Eq 1.

6.4 Determine the maximum exposure time **(6)** by setting a maximum allowable temperature for the front surface as follows:

$$\tau_{max} = \left(\frac{\rho C_p \delta^2}{k}\right) * \left[\left(\frac{k(T_{max} - T_0)}{q\delta}\right) - \left(\frac{1}{3}\right)\right] \quad (4)$$

where:

τ_{max} = maximum exposure time, s,
T_0 = initial temperature, K, and
T_{max} = maximum allowable temperature, K.

6.4.1 In order to have time available for the heat transfer rate measurement, τ_{max} must be greater ~~than τ~~than τ_{r}, which requires that:

$$\frac{k(T_{max} - T_0)}{q\delta} > \frac{5}{6} \quad (5)$$

6.4.2 Determine an optimum thickness that maximizes ($\tau_{max} - \tau_{r}$) **(7)** as follows:

~~$$\delta_{opt} = \left(\frac{3}{5}\right) \frac{k(T_{max} - T_0)}{q} \quad (6)$$~~

$$\delta_{opt} = \left(\frac{3}{5}\right) * \frac{k(T_{max} - T_0)}{q} \quad (6)$$

6.4.3 Then calculate the maximum exposure time using the optimum thickness as follows:

~~$$\tau_{maxopt} = 0.48 \rho C_p k \left[\frac{T_{max} - T_0}{q}\right]^2 \quad (7)$$~~

$$\tau_{maxopt} = 0.48 \rho C_p k * \left[\frac{T_{max} - T_0}{q}\right]^2 \quad (7)$$

6.4.4 When it is desirable for a calorimeter to cover a range of heat transfer rates without being operated to burn-out, design the

TABLE 1 Time Required for Different Error Levels in the Unexposed Surface Temperature Rise Rate

Error Level Due to Heat Conduction into Thermocouple	10 %	5 %	2 %	1 %
Negative Leg (Alumel) of Type K on 304 Stainless	35 ms	150 ms	945 ms	3.8 s
Negative Leg (Constantan) of Type T on Copper	<1 ms	<1 ms	1 ms	4 ms

calorimeter around the largest ~~heat-transfer~~ heat transfer rate. This gives the thinnest calorimeter with the shortest initial response time (Eq 2); however, Refs **(2, 3, 8, 9)** all show the time to a given error level between the measured and undisturbed temperature rise rates (left hand side of Eq 3) increases as the thickness of the calorimeter decreases relative to the thermocouple wire diameter.

6.5 In most applications, the value of T_{max} should be well below the melting temperature to obtain a satisfactory design. Limiting the maximum temperature to 700 K will keep radiation losses below 15 kW/m^2. For a maximum temperature rise ($T_{max} - T_0$) of 400 K, Fig. 2 shows the optimum thickness of copper and stainless steel calorimeters as a function of the ~~heat-transfer~~ heat transfer rate. The maximum exposure time of an optimum thickness calorimeter for a 400 K temperature rise is shown as a function of the ~~heat-transfer~~ heat transfer rate in Fig. 3.

6.6 The one-dimensional heat flow assumption used in ~~2.2~~4.2 and ~~4.3~~6.3–~~4.4~~6.4 is valid for a uniform ~~heat-transfer~~ heat transfer rate; however, in practice, the calorimeter will generally have a ~~heat-transfer~~ heat transfer rate distribution over the surface. Refs (**9, 10**) both consider the effects of lateral heat conduction in a hemispherical calorimeter on heat transfer measurements in a supersonic stream. For a cosine shaped heat flux distribution at the stagnation-point of the hemisphere, Starner **(10)** gives the lateral conduction error relative to the surface heating as

$$E_{C_L} = \frac{2\alpha t}{R^2} = \frac{8kt}{\rho C_p D^2} \quad (8)$$

$$E_{C\,L} = \frac{2\alpha t}{R^2} = \frac{8kt}{\rho C_p D^2} \quad (8)$$

where:

~~E = relative heat-transfer rate ratio,~~
~~R = radius of curvature of the body (D/2), and~~
~~t = exposure time.~~

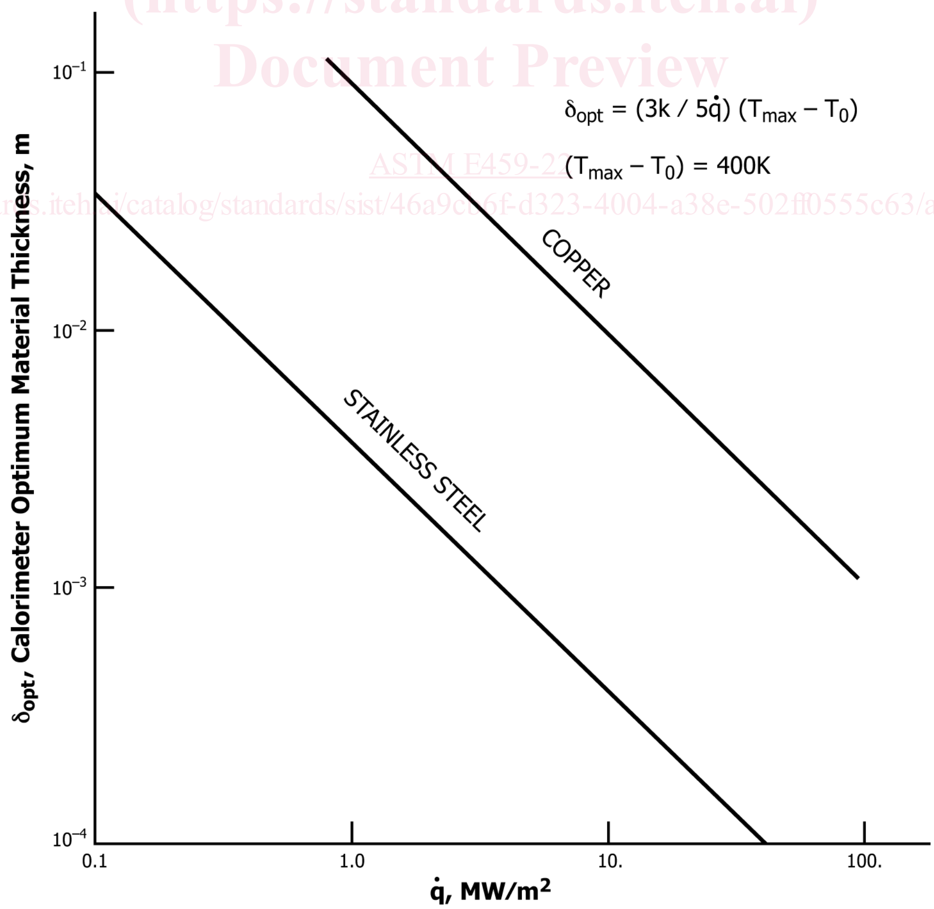

FIG. 2 Calorimeter Optimum Material Thickness as a Function of Heat Transfer Rate and Material