Designation: E 598 – 96

Standard Test Method for Measuring Extreme Heat-Transfer Rates from High-Energy Environments Using a Transient, Null-Point Calorimeter[1]

This standard is issued under the fixed designation E 598; 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 measurement of the heat-transfer rate or the heat flux to the surface of a solid body (test sample) using the measured transient temperature rise of a thermocouple located at the null point of a calorimeter that is installed in the body and is configured to simulate a semi-infinite solid. By definition the null point is a unique position on the axial centerline of a disturbed body which experiences the same transient temperature history as that on the surface of a solid body in the absence of the physical disturbance (hole) for the same heat-flux input.

1.2 Null-point calorimeters have been used to measure high convective or radiant heat-transfer rates to bodies immersed in both flowing and static environments of air, nitrogen, carbon dioxide, helium, hydrogen, and mixtures of these and other gases. Flow velocities have ranged from zero (static) through subsonic to hypersonic, total flow enthalpies from 1.16 to greater than 4.65×10^1 MJ/kg (5×10^2 to greater than 2×10^4 Btu/lb.), and body pressures from 10^5 to greater than 1.5×10^7 Pa (atmospheric to greater than 1.5×10^2 atm). Measured heat-transfer rates have ranged from 5.68 to 2.84×10^2 MW/m^2 (5×10^2 to 2.5×10^4 Btu/ft^2-sec).

1.3 The most common use of null-point calorimeters is to measure heat-transfer rates at the stagnation point of a solid body that is immersed in a high pressure, high enthalpy flowing gas stream, with the body axis usually oriented parallel to the flow axis (zero angle-of-attack). Use of null-point calorimeters at off-stagnation point locations and for angle-of-attack testing may pose special problems of calorimeter design and data interpretation.

1.4 *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:*

E 422 Test Method for Measuring Heat Flux Using a Water-Cooled Calorimeter[2]

E 511 Test Method for Measuring Heat Flux Using a Copper-Constantan Circular Foil, Heat-Flux Gage[2]

3. Terminology

3.1 *Symbols:*

a	=	Radius of null-point cavity, m (in.)
b	=	Distance from front surface of null-point calorimeter to the null-point cavity, m (in.)
C_p	=	Specific heat capacity, J/kg–K (Btu/lb-°F)
d	=	Diameter of null-point cavity, m (in.)
k	=	Thermal conductivity, W/m–K (Btu/in.-sec-°F)
L	=	Length of null-point calorimeter, m (in.)
q	=	Calculated or measured heat flux or heat-transfer-rate, W/m^2 (Btu/ft^2-sec)
q_0	=	Constant heat flux or heat-transfer-rate, W/m^2 (Btu/ft^2-sec)
R	=	Radial distance from axial centerline of TRAX analytical model, m (in.)
r	=	Radial distance from axial centerline of null-point cavity, m (in.)
T	=	Temperature, K (°F)
T_b	=	Temperature on axial centerline of null point, K (°F)
T_s	=	Temperature on surface of null-point calorimeter, K (°F)
t	=	Time, sec
Z	=	Distance in axial direction of TRAX analytical model, m (in.)
α	=	Thermal diffusivity, m^2/sec (in.^{2}/sec)
ρ	=	Density, kg/m^3 (lb/in.^{3})

4. History of Test Method

4.1 From literature reviews it appears that Masters and Stein **(1)**[3] were the first to document the results of an analytical study of the temperature effects of axial cavities drilled from the backside of a wall which is heated on the front surface (see Fig. 1). These investigators were primarily concerned with the deviation of the temperature measured in the bottom of the cavity from the undisturbed temperature on the heated surface. Since they were not in possession of either the computing

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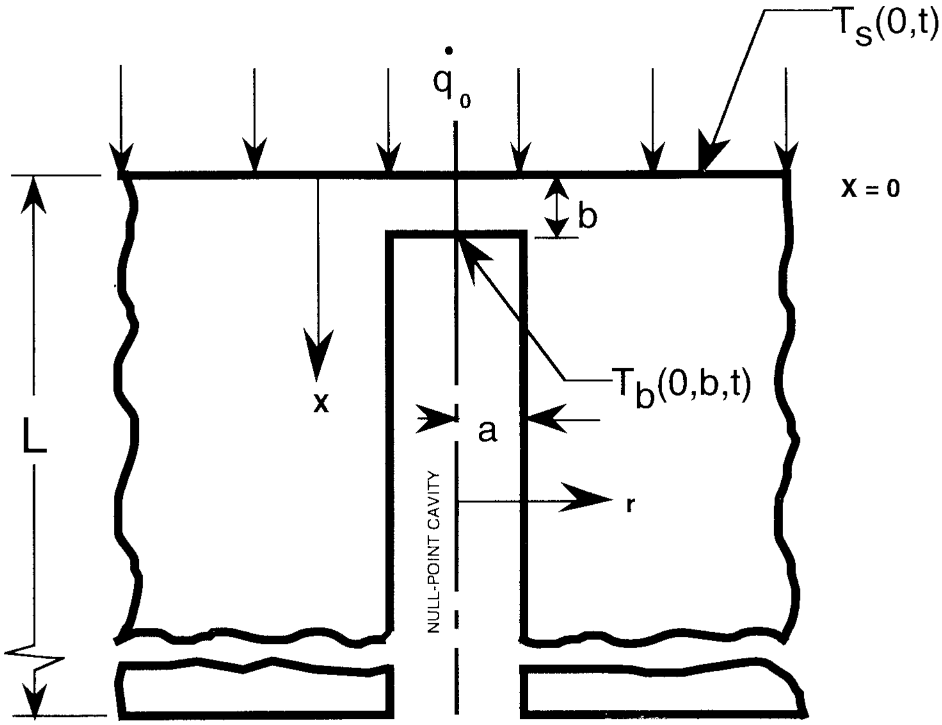
[2] *Annual Book of ASTM Standards*, Vol 15.03.

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



NOTE 1—1-T_s (0,t) = Surface temperature (x = 0) of a solid, semi-infinite slab at some time, t.

NOTE 2—2-T_b (0,b,t) = Temperature at r = 0, x = b of a slab with a cylindrical cavity at some time, t, heat flux, q, the same in both cases.

FIG. 1 Semi-infinite Slab with Cylindrical Cavity

power or the numerical heat conduction codes now available to the analyst, Masters and Stein performed a rigorous mathematical treatment of the deviation of the transient temperature, T_b, on the bottom centerline of the cavity of radius, *a*, and thickness, *b*, from the surface temperature T_s. The results of Masters and Stein indicated that the error in temperature measurement on the bottom centerline of the cavity would decrease with increasing values of *a/b* and also decrease with increasing values of the dimensionless time, $\alpha t/b^2$, where α is the thermal diffusity of the wall material. They also concluded that the most important factor in the error in temperature measurement was the ratio *a/b* and the error was independent of the level of heat flux. The conclusions of Masters and Stein may appear to be somewhat elementary compared with our knowledge of the null-point concept today. However, the identification and documentation of the measurement concept was a major step in leading others to adapt this concept to the transient measurement of high heat fluxes in ground test facilities.

4.2 Beck and Hurwicz **(2)** expanded the analysis of Masters and Stein to include steady-state solutions and were the first to label the method of measurement "the null-point concept." They effectively used a digital computer to generate relatively large quantities of analytical data from numerical methods. Beck and Hurwicz computed errors due to relatively large thermocouple wires in the axial cavity and were able to suggest that the optimum placement of the thermocouple in the cavity occurred when the ratio *a/b* was equal to 1.1. However, their analysis like that of Masters and Stein was only concerned with the deviation of the temperature in the axial cavity and did not address the error in measured heat flux.

4.3 Howey and DeCristina **(3)** were the first to perform an actual thermal analysis of this measurement concept. Although the explanation of modeling techniques is somewhat ambiguous in their paper, it is obvious that they used a finite element, two dimensional axisymmetric model to produce temperature profiles in a geometry simulating the null-point calorimeter. Temperature histories at time intervals down to 0.010 sec were obtained for a high heat-flux level on the surface of the analytical model. Although the analytical results are not presented in a format which would help the user/designer optimize the sensor design, the authors did make significant general conclusions about null point calorimeters. These include: 1) "..., thermocouple outputs can yield deceivingly fast response rates and erroneously high heating rates (+ 18 %) when misused in inverse one-dimensional conduction solutions." 2) "The prime reason for holding the thermocouple depth at *R/E* = 1.1 is to maximize thermocouple response at high heating rates for the minimum cavity depth..." (Note: *R* and *E* as used by Howey and DeChristina are the same terms as *a* and *b* which are defined in 4.1 and are used throughout this document.) 3) A finite length null-point calorimeter body may be considered semi-infinite for:

$$\frac{(\alpha t)}{L^2} \leq 0.3$$

4.4 Powers, Kennedy, and Rindal **(4 and 5)** were the first to document using null point calorimeters in the swept mode. This method which is now used in almost all arc facilities has the advantages of 1) measuring the radial distributions across the arc jet, and 2) preserving the probe/sensor structural integrity for repeated measurements. This technique involves