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Standard Test Method for Measuring Heat Flux Using Directional Flame Thermometers with Advanced Data Analysis Techniques[1]

This standard is issued under the fixed designation E3057; 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

This test method describes a technique for measuring the net heat flux to one or both surfaces of a sensor called a Directional Flame Thermometer. The sensor covered by this standard uses measurements of the temperature response of two metal plates along with a thermal model of the sensor to determine the net heat flux. These measurements can be used to estimate the total heat flux (also known as thermal exposure) and bi-directional heat fluxes for use in CFD thermal models.

The development of Directional Flame Thermometers (DFTs) as a device for measuring heat flux originated because commercially available, water-cooled heat flux gauges (for example, Gardon and Schmidt-Boelter gauges) did not work as desired in large fire tests. Because the Gardon and Schmidt-Boelter (S-B) gauges are water cooled, condensation and soot deposition can occur during fire testing or in furnaces. Both foul the sensing surface which in turn changes the sensitivity (calibration) of the gauge. This results in an error during data reduction. Therefore, a different type of sensor was needed; one such sensor is a DFT. DFTs are not cooled so condensation and soot deposition are minimized or eliminated.

Additionally, a body of work has shown that for both Gardon and Schmidt-Boelter gauges the sensitivity coefficients determined through the calibration process, which uses a radiative heat source, are not the same as the sensitivity coefficients determined if a purely convective source is used for calibration [Test Method E511-07; Keltner and Wildin, 1975 (**1, 2**); Borell, G. J., and Diller, T. E., 1987 (**3**); Gifford, A., et al., 2010 (**4**); Gritzo, L. A., et al., 1995 (**5**); Young, M. F., 1984 (**6**); Sobolik, et al., 1987 (**7**); Kuo and Kulkarni, 1991 (**8**); Keltner, 1995 (**9**); Gifford, et al., 2010 (**10**); Nakos, J. T., and Brown, A. L., 2011 (**11**)].[2] As a result, one can incur significant bias errors when reducing data in tests where there may be a non-negligible convective component because the only sensitivity coefficient available is for a radiation calibration. It was desired to reduce/eliminate these potential sources of error by designing a gauge that does not depend on a radiation only calibration. DFTs have this characteristic.

A sensor, also called a Directional Flame Thermometer, was developed to help estimate flame thickness in pool fire tests of hazardous material shipping containers [Burgess, M. H., 1986 (**12**); Fry, C. J., 1989 (**13**); Burgess, M. H., et al., 1990 (**14**); and Fry, C. J., 1992 (**15**)]. As originally designed, DFTs were quasi-equilibrium sensors that used a thin metal plate with a single thermocouple attached and backed by multiple radiation shields. To make a sensor suitable for continuous transient heat flux measurements, this basic design was modified to use two instrumented plates, with a layer of insulation in between.

For the Directional Flame Thermometers described in this standard, the net heat flux is calculated using transient temperature measurements of the two plates and temperature dependent material properties for the plates and the insulation. Three methods are described in this standard to calculate the net heat flux. The most accurate method for calculating the net heat flux is believed to be the 1-dimensional, nonlinear inverse heat conduction analysis, which uses the IHCP1D code. This is based on uncertainty analyses and comparisons with measurements made with Schmidt-Boelter and Gardon gauges, which have NIST traceable calibrations. The second method uses transient energy balances on the DFT. As will be shown below, the energy balance method compares very well with the inverse method, again based on uncertainty analyses. The third method uses sets of linearized, convolution digital filters based on IHCP1D. These allow a near real-time calculation of the net heat flux [Keltner, N. R., 2007 (**16**); Keltner, N. R., et al., 2010 (**17**)]. See Section 1 for more detailed information on each analysis technique. Additional information is given in the Annexes and Appendices.

Various DFT designs have been used in a variety of applications including very large pool fires, LNG spill fires, marine fire safety testing, automobile fires, to study rocket launch accident fires, and in research of forest and wild-land fires. Appendix X1 provides a comprehensive list of applications where DFTs have been successfully used.

Advantages of DFTs are their relatively low cost, ease of construction, they require no calibration (see later), and require no cooling. They are robust and can survive intense fire environments without failure. Disadvantages include most are large compared with Gardon and S-B heat flux gauges and because they are not calibrated, one cannot reference the measurements to a NIST standard. Because no calibration is required, one must quantify the uncertainties present in the temperature measurements and the data reduction methods used to calculate the heat flux. Also, DFTs measure net heat flux; for a direct comparison with Gardon and S-B gauges, which are calibrated to incident (or "cold wall") flux, one must use a thermal model to estimate the incident flux.

The best applications for DFTs are where Gardon and S-B gauges cannot be used (for example, due to high temperatures, lack of cooling, soot deposition, fouling, and so forth), or when long life and overall costs are a consideration. Gardon and Schmidt-Boelter gauges are recommended in non-sooty environments, when it is possible to mount the gauges and cooling lines, and in predominantly radiative environments with a small convective contribution.

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[1] This test method was jointly developed by 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 at the end of this standard.

1. Scope

1.1 This test method describes the continuous measurement of the hemispherical heat flux to one or both surfaces of an uncooled sensor called a "Directional Flame Thermometer" (DFT).

1.2 DFTs consist of two heavily oxidized, Inconel 600 plates with mineral insulated, metal-sheathed (MIMS) thermocouples (TCs, type K) attached to the unexposed faces and a layer of ceramic fiber insulation placed between the plates.

1.3 Post-test calculations of the net heat flux can be made using several methods. The most accurate method uses an inverse heat conduction code. Nonlinear inverse heat conduction analysis uses a thermal model of the DFT with temperature dependent thermal properties along with the two plate temperature measurement histories. The code provides transient heat flux on both exposed faces, temperature histories within the DFT as well as statistical information on the quality of the analysis.

1.4 A second method uses a transient energy balance on the DFT sensing surface and insulation, which uses the same temperature measurements as in the inverse calculations to estimate the net heat flux.

1.5 A third method uses Inverse Filter Functions (IFFs) to provide a near real time estimate of the net flux. The heat flux history for the "front face" (either surface exposed to the heat source) of a DFT can be calculated in real-time using a convolution type of digital filter algorithm.

1.6 Although developed for use in fires and fire safety testing, this measurement method is quite broad in potential fields of application because of the size of the DFTs and their construction. It has been used to measure heat flux levels above 300 kW/m^2 in high temperature environments, up to about 1250 °C, which is the generally accepted upper limit of Type K or N thermocouples.

1.7 The transient response of the DFTs is limited by the response of the MIMS TCs. The larger the thermocouple the slower the transient response. Response times of approximately 1 to 2 s are typical for 1.6 mm diameter MIMS TCs attached to 1.6 mm thick plates. The response time can be improved by using a differential compensator.

1.8 The values stated in SI units are to be regarded as standard. The values given in parentheses after SI units are provided for information only and are not considered standard.

1.9 *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, health, and environmental practices and determine the applicability of regulatory limitations prior to use.*

1.10 *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]

C177 Test Method for Steady-State Heat Flux Measurements and Thermal Transmission Properties by Means of

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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.

the Guarded-Hot-Plate Apparatus

E119 Test Methods for Fire Tests of Building Construction and Materials

E176 Terminology of Fire Standards

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

E511 Test Method for Measuring Heat Flux Using a Copper-Constantan Circular Foil, Heat-Flux Transducer

E1529 Test Methods for Determining Effects of Large Hydrocarbon Pool Fires on Structural Members and Assemblies

E2683 Test Method for Measuring Heat Flux Using Flush-Mounted Insert Temperature-Gradient Gages

2.2 *Other Standards:*

ISO 834-11:2014 Fire Resistance Tests—Elements of Building Construction—Part 11: Specific Requirements for the Assessment of Fire Protection to Structural Steel Elements[4]

IMO A754 Fire Resistance Tests: Fire Safety Onboard Ships[5]

2.3 *Other ASTM Document:*[6]

MNL12-4th Manual on the Use of Thermocouples in Temperature Measurement, Fourth Edition, 1993, Sponsored by ASTM Committee E20 on Temperature Measurement

3. Terminology

3.1 *Definitions*—Refer to Terminology E176 for definitions of some terms used in these test methods.

3.2 *Definitions of Terms Specific to This Standard:*

3.2.1 *incident radiative heat flux (irradiance; $q_{inc,r}$), n*—radiative heat flux impinging on the surface of the DFT or the unit under test.

3.2.2 *net heat flux, n*—storage in the DFT front plate + transmission (in other words, loss) to insulation layer. It is equal to the [absorbed radiative heat flux + convective heat flux] – [re-radiation from the exposed surface].

3.2.3 *total absorbed heat flux, n*—absorbed radiative heat flux + convective flux.

3.2.4 *total cold wall heat flux, n*—the heat flux that would be transferred by means of convection and radiation to an object whose temperature is 21 °C (70 °F).

3.2.5 *total heat flux (thermal exposure), n*—incident radiative heat flux + convective heat flux.

4. Summary of Test Method

4.1 This test method provides techniques for measurement of the net heat flux to a surface. Because Directional Flame Thermometers are un-cooled devices, they are minimally affected by soot deposition or condensation. Calibration factors or sensitivity coefficients are not required because alternate methods of data reduction are used. DFTs are simple to fabricate and use, but are more complicated when reducing the data. Gardon and Schmidt-Boelter gauges have relatively linear outputs with heat flux and only require a single sensitivity coefficient (for example, xx mv/unit of flux) to convert the output to an incident heat flux. DFTs have two thermocouple outputs as a function of time. Those outputs along with temperature dependent thermal properties and advanced analysis techniques are used with a thermal model to calculate the net heat flux. The net heat flux (with an energy balance) can be used to estimate the total cold wall heat flux, which is same as the measurement made by Gardon or S-B gauges [Janssens, 2007 (**18**)].

5. Significance and Use

5.1 *Need for Heat Flux Measurements:*

5.1.1 Independent measurements of temperature and heat flux support the development and validation of engineering models of fires and other high environments, such as furnaces. For tests of fire protection materials and structural assemblies, temperature and heat flux are necessary to fully specify the boundary conditions, also known as the thermal exposure. Temperature measurements alone cannot provide a complete set of boundary conditions.

5.1.2 Temperature is a scalar variable and a *primary variable*. Heat Flux is a vector quantity, and it is a *derived variable*. As a result, they should be measured separately just as current and voltage are in electrical systems. For steady-state or quasi-steady state conditions, analysis basically uses a thermal analog of Ohm's Law. The thermal circuit uses the temperature difference instead of voltage drop, the heat flux in place of the current and thermal resistance in place of electrical resistance. As with electrical systems, the thermal performance is not fully specified without knowing at least two of these three parameters (temperature drop, heat flux, or thermal resistance). For dynamic thermal experiments like fires or fire safety tests, the electrical capacitance is replaced by the volumetric heat capacity.

5.1.3 The net heat flux, which is measured by a DFT, is likely different than the heat flux into the test item of interest because of different surface temperatures. An alternative measurement is the total cold wall heat flux which is measured by water-cooled Gardon or S-B gauges. The incident radiative flux can be estimated from either measurement by use of an energy balance [Keltner, 2007 and 2008 (**16, 17**)]. The convective flux can be estimated from gas temperatures and the convective heat transfer coefficient, *h* [Janssens, 2007 (**18**)]. Assuming the sensor is physically close to the test item of interest; one can use the incident radiative and convective fluxes from the sensor as boundary conditions into the test item of interest.

5.1.4 In standardized fire resistance tests such as Test Methods E119 and E1529, or ISO 834 or IMO A754, the furnace temperature is controlled to a standard time-temperature curve. In all but Test Methods E1529, implicit assumptions have been made that the thermal exposure can be described solely by the measured furnace temperature history and that it will be repeatable from time to time and place to

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[4] Available from American National Standards Institute (ANSI), 25 W. 43rd St., 4th Floor, New York, NY 10036, http://www.ansi.org.

[5] Available from International Maritime Organization (IMO), 4, Albert Embankment, London SE1 7SR, United Kingdom, http://www.imo.org.

[6] Available from the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org.