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# Standard Test Method for Measuring Heat Flux Using a Water-Cooled Calorimeter[1]

This standard is issued under the fixed designation E422; 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 a steady heat flux to a given water-cooled surface by means of a system energy balance.

1.2 The values stated in SI units are to be regarded as standard. No other units of measurement are included in this standard.

1.3 *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:*[2]

E235 Specification for Thermocouples, Sheathed, Type K and Type N, for Nuclear or for Other High-Reliability Applications

## 3. Summary of Test Method

3.1 A measure of the heat flux to a given water-cooled surface is based upon the following measurements: (*1*) the water mass flow rate and (*2*) the temperature rise of coolant water. The heat flux is determined numerically by multiplying the water coolant flow rate by the specific heat and rise in temperature of the water and dividing this value by the surface area across which heat has been transferred.

3.2 The apparatus for measuring heat flux by the energy-balance technique is illustrated schematically in Fig. 1. It is a typical constant-flow water calorimeter used to measure stagnation region heat flux to a flat-faced specimen. Other calorimeter shapes can also be easily used. The heat flux is measured using the central circular sensing area, shown in Fig. 1. The water-cooled annular guard ring serves the purpose of preventing heat transfer to the sides of the calorimeter and establishes flat-plate flow. An energy balance on the system (the centrally located calorimeter in Fig. 1) requires that the energy crossing the sensing surface (*A*, in Fig. 1) of the calorimeter be equated to the energy absorbed by the calorimeter cooling water. Interpretation of the data obtained is not within the scope of this discussion; consequently, such effects as recombination efficiency of the surface and thermochemical state of the boundary layer are outside the scope of this test method. It should be noted that recombination effects at low pressures can cause serious discrepancies in heat flux measurements (such as discussed in Ref (**1**))[3] depending upon the surface material on the calorimeter.

3.3 For the particular control volume cited, the energy balance can be written as follows:

$$E_{\mathrm{CAL}} = \left[mC_p(\Delta \mathrm{T}_0 - \Delta \mathrm{T}_1)\right]/A \qquad (1)$$

where:

$E_{\mathrm{CAL}}$ = energy flux transferred to calorimeter face, $W \cdot m^{-2}$
$m$ = mass flow rate of coolant water, $\mathrm{kg} \cdot \mathrm{s}^{-1}$
$C_p$ = water specific heat, $\mathrm{J} \cdot \mathrm{kg}^{-1} \cdot \mathrm{K}^{-1}$,
$\Delta T_0$ = $T_{0_2}$ — $T_{0_1}$ calorimeter water bulk temperature rise during operation, K,
$\Delta T_1$ = $T_2$ — $T_1$ = calorimeter water apparent bulk temperature rise before operation, K,
$T_{0_2}$ = water exhaust bulk temperature during operation, K,
$T_{0_1}$ = water inlet bulk temperature during operation, K,
$T_2$ = water exhaust bulk temperature before operation, K,
$T_1$ = water inlet bulk temperature before operation, K, and
$A$ = sensing surface area of calorimeter, $\mathrm{m}^2$.

3.4 An examination of Eq 1 shows that to obtain a value of the energy transferred to the calorimeter, measurements must be made of the water coolant flow rate, the temperature rise of the coolant, and the surface area across which heat is transferred. With regard to the latter quantity it is assumed that the surface area to which heat is transferred is well defined. As is indicated in Fig. 1, the design of the calorimeter is such that the heat transfer area is confined by design to the front or directly heated surface. To minimize side heating or side heat losses, a

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[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] 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.

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

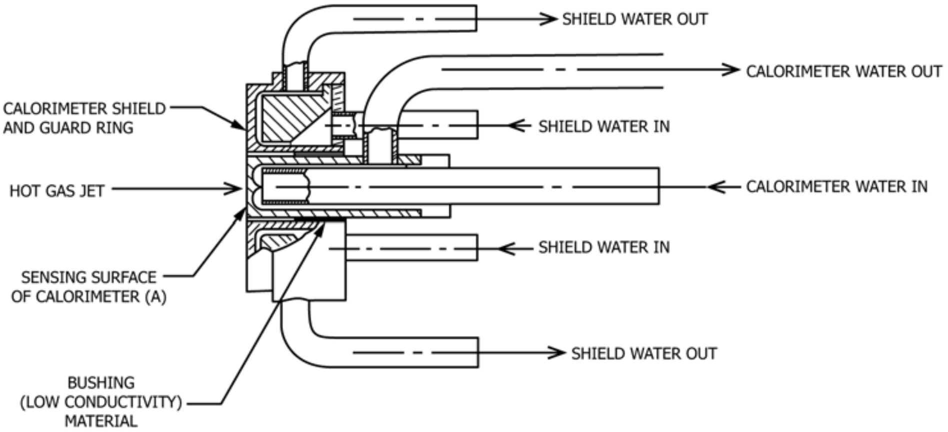

FIG. 1 Steady-State Water-Cooled Calorimeter.

water-cooled guard ring or shroud is utilized and is separated physically from the calorimeter by means of an air gap and low conductivity bushing such as nylon. The air gap is recommended to be no more than 0.5 mm on the radius. Thus, if severe pressure variations exist across the face of the calorimeter, side heating caused by flow into and out of the air gap will be minimized. Also, since the water-cooled calorimeter and guard ring operate at low surface temperatures (usually lower than 100°C) heat losses across the gap by radiant interchange are negligible and consequently no special calorimeter surface gap finishes are necessary. Depending upon the size of the calorimeter surface, large variations in heat flux may exist across the face of the calorimeter. Consequently, the measured heat flux represents an average heat flux over the surface area of the water-cooled calorimeter. The water-cooled calorimeter can be used to measure heat-flux levels over a range from 10 kW/m$^2$ to 60 MW/m$^2$.

## 4. Significance and Use

4.1 The purpose of this test method is to measure the heat flux to a water-cooled surface for purposes of calibration of the thermal environment into which test specimens are placed for evaluation. If the calorimeter and holder size, shape, and surface finish are identical to that of the test specimen, the measured heat flux to the calorimeter is presumed to be the same as that to the sample's heated surface. The measured heat flux is one of the important parameters for correlating the behavior of materials.

4.2 The water-cooled calorimeter is one of several calorimeter concepts used to measure heat flux. The prime drawback is its long response time, that is, the time required to achieve steady-state operation. To calculate energy added to the coolant water, accurate measurements of the rise in coolant temperature are needed, all energy losses should be minimized, and steady-state conditions must exist both in the thermal environment and fluid flow of the calorimeter.

4.3 Regardless of the source of energy input to the water-cooled calorimeter surface (radiative, convective, or combinations thereof) the measurement is averaged over the surface active area of the calorimeter. If the water-cooled calorimeter is used to measure only radiative flux or combined convective-radiative heat-flux rates, then the surface reflectivity of the calorimeter shall be measured over the wavelength region of interest (depending on the source of radiant energy). If non-uniformities exist in the gas stream, a large surface area water-cooled calorimeter would tend to smooth or average any variations. Consequently, it is advisable that the size of the calorimeter be limited to relatively small surface areas and applied to where the heat-flux is uniform. Where large samples are tested it is recommended that a number of smaller diameter water-cooled calorimeters be used (rather than one large unit). These shall be located across the heated surface such that a heat-flux distribution can be described. With this, a more detailed heat-flux measurement can be applied to the specimen test and more information can be deduced from the test.

## 5. Apparatus

5.1 *General*—The apparatus shall consist of a water-cooled calorimeter and the necessary instrumentation to measure the heat transferred to the calorimeter. Although the recommended instrumentation accuracies are state-of-the-art values, more rugged and higher accuracy instrumentation may be required for high pressure and high heat-flux applications. A number of materials can be used to fabricate the calorimeter, but OFHC (oxygen free high conductivity) copper is often preferred because of its superior thermal properties.

5.2 *Coolant Flow Measurement*—The water flow rate to each component of the calorimeter shall be chosen to cool the apparatus adequately and to ensure accurately measurable rise in water temperature. The error in water flow rate measurement shall be not more than ±2 %. Suitable equipment that can be used is listed in Ref (2) and includes turbine flowmeters, variable area flowmeters, etc. Care must be exercised in the use of all these devices. In particular, it is recommended that appropriate filters be placed in all water inlet lines to prevent particles or unnecessary deposits from being carried to the water-cooling passages, pipe, and meter walls. Water flow rates and pressure shall be adjusted to ensure that no bubbles are formed (no boiling). If practical, the water flowmeters shall be placed upstream of the calorimeter in straight portions of the piping. The flowmeter device shall be checked and calibrated periodically. Pressure gages, if required, shall be used in accordance with the manufacturer's instructions and calibration charts.

5.3 *Coolant Temperature Measurement*—The method of temperature measurement must be sufficiently sensitive and reliable to ensure accurate measurement of the coolant water temperature rise. Procedures similar to those given in Specification E235, Type K, and Ref (**3**) should be followed in the calibration and preparation of temperature sensors. The bulk or average temperature of the coolant shall be measured at the inlet and outlet lines of each cooled unit. The error in measurement of temperature difference between inlet and outlet shall be not more than ±1 %. The water temperature indicating devices shall be placed as close as practical to the calorimeter's heated surface in the inlet and outlet lines. However, care must be exercised so as not to place the temperature sensors where there is energy exchange between the incoming (cold) water and the outgoing (heated) water. This occurs most readily at flow dividers and at the calorimeter sensing surface. No additional apparatus shall be placed in the line between the temperature sensor and the heat source. The temperature measurements shall be recorded continuously to verify that steady-state operation has been achieved. Reference (**2**) lists a variety of commercially available temperature sensors. Temperature sensors which are applicable include liquid-in-glass thermometers, thermopiles, thermocouples, and thermistors. During operation of the heat source, care should be taken to minimize deposits on the temperature sensors and to eliminate any possibility of sensor heating because of specimen radiation to the sensor. In addition, all water lines should be shielded from direct-flow impingement or radiation from the test environment.

5.3.1 If at all practical a thermocouple shall be placed on the water-cooled side of the heated calorimeter surface. Although this surface temperature (water side) measurement is not used directly in the calculation of heat flux it is necessary for the calculation of the surface temperature (front face) used in the correction of the measured heat flux to walls of different temperatures.

5.4 *Recording Means:*

5.4.1 Since measurement of the energy transfer requires that the calorimeter operate as a steady state device, all calculations will use only measurements taken after it has been established that the device has achieved steady operating levels. To assure steady flow or operating conditions the above mentioned parameters shall be continuously recorded such that instantaneous measurements are available to establish a measure of steady-state operation. Wherever possible it is highly desirable that the differential temperature (ΔT) be made of the desired parameters rather than absolute measurements.

5.4.2 In all cases, parameters of interest, such as water flow rates and cooling water temperature rises should be automatically recorded throughout the measurement period. Recording speed or sampling frequency will depend on the variations of the parameters being recorded. When a strip chart recorder is used, the response time of the recorder shall be 1 s or less for full-scale deflection. Timing marks should be an integral part of the recorder with a minimum requirement of 1/s.

## 6. Procedure

6.1 It is essential that the environment be at steady-state conditions prior to testing if the water-cooled calorimeter is to give a representative measure of the heat flux.

6.2 After a sufficient length of time has elapsed to assure constant mass flow of water as well as constant inlet and outlet water temperature, place the system into the heat-source environment. Steady-state operation has been assured if the inlet and exhaust water temperature, and water flow rates are steady and not changing with time. In particular the water flow rates should not change during operation. After removing the calorimeter from the environment, record the inlet water temperature and flow rates so that they can be compared with pretest values. Changes between pre- and post-test water temperature rise may indicate deposit buildups on the calorimeter backface or cooling passages which may alter the results of the measurement of energy transfer.

6.3 To ensure consistent heat-flux data, it is recommended that measurements be repeated with the same apparatus. A further check on the measurement of heat flux using a water-cooled calorimeter would be to use a different mass flow of water through the calorimeter for different test runs. No significant difference in heat-flux measurements should be noted with the change in water flow rate for different test runs.

## 7. Heat-Flux Calculation

7.1 The quantities as defined by Eq 1 shall be calculated based on the bulk or average temperature rise of the coolant water for each water-cooled section of the calorimeter. The choice of units shall be consistent with the measured quantities.

7.2 Variance analyses of heat-source conditions shall provide a sound basis for estimation of the reproducibility of the thermal environment. Refs (**4**) and (**5**) may provide a basis for error analysis of the measurements.

## 8. Report

8.1 In reporting the results of the measurement tests, the following steady-state data shall be reported:

8.1.1 Dimensions of the calorimeter configuration active surface and guard ring,

8.1.2 Calorimeter coolant water flow rate,

8.1.3 Temperature rise of calorimeter coolant water,

8.1.4 Calculated heat flux,

8.1.5 Front surface temperature (if measured or calculated), and

8.1.6 Variance of results.

## 9. Measurement Uncertainty

9.1 There are a number of methods that can be used for the determination of measurement uncertainty. A recent summary of the various uncertainty analysis methods is provided in Ref (**6**). The American Society of Mechanical Engineers' (ASME's) earlier performance test code PTC 19.1-1985 (**7**) has been revised and was replaced by Ref (**8**) in 1998. In Refs (**7**) and (**8**), uncertainties were separated into two types: "bias" or "systematic" uncertainties (B) and "random" or "precision" uncertainties (S). Systematic uncertainties (Type B) are often (but not always) constant for the duration of the experiment. Random uncertainties are not constant and are characterized via the standard deviation of the random measurements, thus the abbreviation 'S.'

9.2 ASME's new standard (**8**) proposes use of the following model:

$$U_{95} = \pm t_{95}\left[(B_T/2)^2 + (S_T)^2\right]^{\frac{1}{2}} \qquad (2)$$

where $t_{95}$ is determined from the number of degrees of freedom (DOF) in the data provided. For large DOF (that is, 30 or larger) $t_{95}$ is almost 2. $B_T$ is the total bias or systematic uncertainty of the result, $S_T$ is the total random uncertainty or precision of the result, and $t_{95}$ is "Student's t" at 95 % for the appropriate degrees of freedom (DOF).

9.3 This test method requires the measurement of water flow rate, temperature difference, and sensing surface area. The water flow rate measurement can be made with fundamentally different methods such as differential pressure across an orifice or an in-line turbine correlating vane velocity to flow rate. The successful application of this test method requires the user to perform an uncertainty analysis on the specific steady state water flow rate instrument used ((**9**, **10**). In the case of sensing surface area, length measurement techniques with their uncertainties are well documented (**10**).

9.4 In the case of a temperature measurement ((**9**, **11**)) with a thermocouple, types of systematic uncertainties are mounting errors, non-linearity, and gain. Less commonly discussed systematic uncertainties are those that result from the sensor design (that is, TC junction type) and coupling with the environment. Types of random uncertainty are common mode and normal mode noise.

9.5 To quantify the total uncertainty of a measurement, the entire measurement system must be examined. For a thermocouple measurement the following uncertainty sources must be considered:

9.5.1 Thermocouple wire accuracy.
9.5.2 Thermocouple connectors.
9.5.3 Thermocouple extension cable.
9.5.4 Thermocouple mounting error (transient and steady).
9.5.5 Data acquisition system (DAS).
9.5.6 Conversion equation (mV to temperature).
9.5.7 Positioning errors.
9.5.8 Angular errors.

9.6 Additional uncertainty can be attributed to the engineering application of the thermocouple transducer to the environment, or material, of interest. Specific examples include:

9.6.1 Contact between a thermocouple and its environment, or thermal contact conductance between the bead and material. The contact conductance must be characterized to analyze the bead transient response versus the environment.

9.6.2 Radiation versus convective heat transfer of the environment versus heat transferred to the bead. The bead emissivity must be known or estimated for incident radiative environment calculations.

9.6.3 Time response of the thermocouple bead (or probe) versus the estimated transient thermal environment to be measured to ensure the TC is not too slow to measure gradients of interest.

9.6.4 Position location uncertainty of the TC junction must be known to perform material response analysis. The uncertainty of temperature measurement location will propagate error into material response calculations.

9.6.5 When using mineral-insulated, metal-sheathed thermocouples, the TC wires are surrounded with the metal sheath to keep the TC wires from shorting, melting, and so forth. But in doing so, the TC measuring junction is insulated from the environment being measured, and the measurement will have some thermal lag. The TC thermal lag is increasingly worse as the transient environment becomes faster.

9.7 It is important to realize that any transducer has finite mass and heat transfer characteristics. Therefore, the thermocouple (for example) will read a temperature different from the surface you are measuring. In a well-designed experimental system the difference between the "true" temperature and the TC reading can be reduced to acceptable values. Errors are not zero or negligible, but acceptable from an uncertainty budget perspective. The main point is uncertainty exists, and, it must be quantified to produce meaningful data.

## 10. Keywords

10.1 calorimeter; heat flux; heat transfer rate

## REFERENCES

**(1)** Pope, R. B., *Stagnation-Point Convective Heat Transfer in Frozen Boundary Layers*, AIAA Journal, Vol g, No. 4, April 1968, pp. 619–626.

**(2)** *ISA Transducer Compendium*, A Publication of Instrument Society of America, Plenum Press, 1963.

**(3)** Considine, D. M., *Process Instruments and Controls Handbook*, McGraw-Hill Book Co., Inc., 1957.

**(4)** Brownlee, K. A., *Statistical Theory and Methodology in Science and Engineering*, John Wiley and Sons, Inc., New York, NY, 1960.

**(5)** Hald, A., *Statistical Theory with Engineering Applications*, John Wiley and Sons, Inc., New York, NY, 1952.

**(6)** Dieck, R. H., "Measurement Uncertainty Models," *ISA Transactions*, Vol. 36, No.1, 1997, pp. 29–35.

**(7)** ANSI/ASME PTC 19.1-1985, "Part 1, Measurement Uncertainty, Instruments and Apparatus," Supplement to the ASME Performance Test Codes, reaffirmed 1990.

**(8)** ASME PTC 19.1-1998, "Test Uncertainty, Instruments and Apparatus," Supplement to the ASME Performance Test Codes, 1998.

**(9)** Doebelin, E. O., *Measurement Systems Application and Design*, McGraw-Hill, 1983.

**(10)** Holman, J.P., *Experimental Methods for Engineers*, McGraw-Hill, 1978.

**(11)** *Manual on the Use of Thermocouples in Temperature Measurement, ASTM Manual Series: MNL 12, Revision of Special Technical Publication (STP) 470B*, ASTM International, 1993.

**(12)** Coleman, H. W. and Steele, W. G., "Engineering Application of Experimental Uncertainty Analysis," *AIAA Journal*, Vol. 33, No. 10, October 1995, pp. 1888–1896.

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