



Designation: E 422 – 99

Standard Test Method for Measuring Heat Flux Using a Water-Cooled Calorimeter¹

This standard is issued under the fixed designation E 422; 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 approval. 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 *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 235 Specification for Thermocouples, Sheathed, Type K, for Nuclear or for Other High-Reliability Applications²

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:

$$E_{\text{CAL}} = [mC_p(\Delta T_0 - \Delta T_1)]/A \quad (1)$$

where:

- E_{CAL} = energy flux transferred to calorimeter face, $W \cdot m^{-2}$
- m = mass flow rate of coolant water, $kg \cdot s^{-1}$
- C_p = water specific heat, $J \cdot kg^{-1} \cdot K^{-1}$,
- ΔT_0 = $T_{0_2} - T_{0_1}$ = calorimeter water bulk temperature rise during operation, K,
- ΔT_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, 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 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

¹ This test method is under the jurisdiction of ASTM Committee E-21 on Space Simulation and Applications of Space Technology and is the direct responsibility of Subcommittee E21.08 on Thermal Protection.

Current edition approved Oct. 10, 1999. Published February 2000. Originally published as E 422 – 71. Last previous edition E 422 – 83(1994).

² Annual Book of ASTM Standards, Vol 14.03.

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

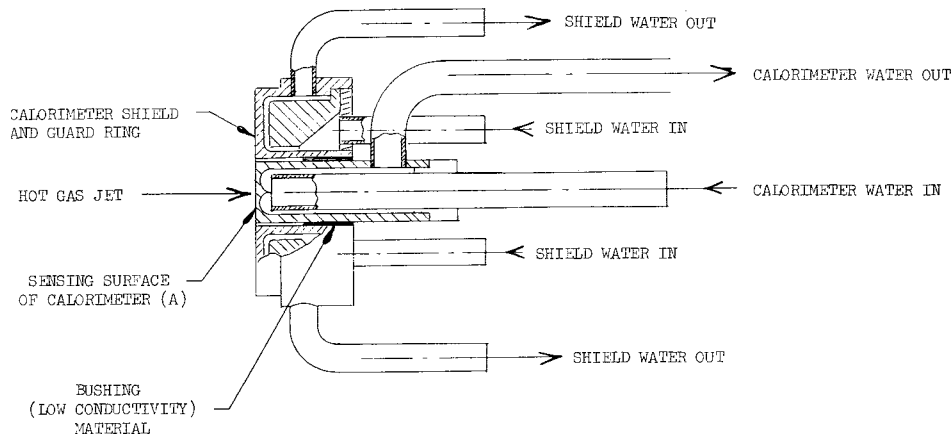


FIG. 1 Steady-State Water-Cooled Calorimeter.

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/m² to 60 MW/m².

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 $\pm 2\%$. 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 E 235, 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