Standard Practice for Measuring Plasma Arc Gas Enthalpy by Energy Balance[1]

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1. Scope

1.1 This practice covers the measurement of total gas enthalpy of an electric-arc-heated gas stream by means of an overall system energy balance. This is sometimes referred to as a bulk enthalpy and represents an average energy content of the test stream which may differ from local values in the test stream.

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. Summary of Test Method

2.1 A measure of the total or stagnation gas enthalpy of plasma-arc heated gases (nonreacting) is based upon the following measurements:

2.1.1 Energy input to the plasma arc,

2.1.2 Energy losses to the plasma arc hardware and cooling water, and

2.1.3 Gas mass flow.

2.2 The gas enthalpy is determined numerically by dividing the gas mass flow into the net power input to the plasma arc (power to plasma arc minus the energy losses).

2.3 The technique for performing the overall energy balance is illustrated schematically in Fig. 1. The control volume for the energy balance can be represented by the entire envelope of this drawing. Gas enters at an initial temperature, or enthalpy, and emerges at a higher enthalpy. Water or other coolant enters the control volume at an initial temperature and emerges at a higher temperature. Across the arc, electrical energy is dissipated by virtue of the resistance and current in the arc itself. A heat balance of the system requires that the energy gained by the gas must be defined by the difference between the incoming energy (electrical input) and total coolant and external losses. This is a direct application of the First Law of Thermodynamics and, for the particular control volume cited here, can be written as follows:

$$\text{Energy In} - \text{Energy Out} = \text{Energy to Gas} \quad (1)$$

$$\overline{EI} - Q_{CR} - \sum_{i=1}^{n} W_{H_2O_i} C_p \left(\Delta T_0 - \Delta T_1\right)_{H_2O_i} - \sum_{j=1}^{p} M_j H_j = W_g\left(H_g - H_{in}\right)$$

where:

C_p	=	water, specific heat,
E	=	plasma arc voltage,
H_g	=	exhaust gas enthalpy,
H_{in}	=	inlet gas enthalpy,
H_j	=	heat of vaporization corresponding to the material M_j,
I	=	plasma arc current,
M_j	=	mass loss rate of electrode insulator, interior metal surface, etc.
Q_{CR}	=	energy convected and radiated from external surface of plasma generator,
$\Delta T_{0_{H2O}}$	=	$T_{0_2} - T_{0_1}$ = water temperature rise during plasma arc operation,
$\Delta T_{1_{H2O}}$	=	$T_2 - T_1$ = water temperature rise before plasma arc operation,
T_{0_2}	=	water exhaust temperature during plasma arc operation,
T_{0_1}	=	inlet water temperature during plasma arc operation,
T_2	=	water exhaust temperature before plasma arc operation,
T_1	=	inlet water temperature before plasma arc operation,
W_g	=	gas flow rate,
W_{H_2O}	=	mass flow rate of coolant water, and
$\overline{EI}$	=	average of the product of voltage, E, and current, I.

2.4 An examination of Eq 1 shows that, in order to obtain an evaluation of the energy content of the plasma for a specified set of operating conditions, measurements must be made of the voltage and current, the mass-flow rate and temperature rise of the coolant, the mass-flow rate and inlet ambient temperature of the test gas, and the external surface temperature and housing of the arc chamber. For all practical purposes, the external surface temperature of the water-cooled plasma arc is

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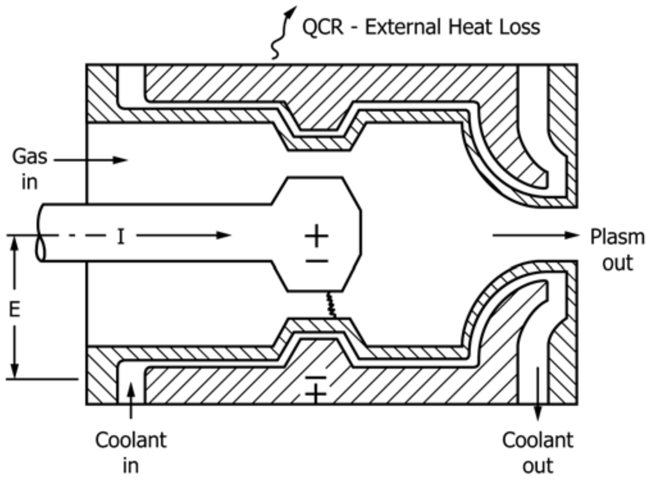

FIG. 1 Schematic Energy Balance Method for Determining Gas Enthalpy

minimum. Consequently, it will be assumed throughout this discussion that negligible energy (compared to the input energy) is lost from the external plasma generator surface by convective or radiative mechanisms and that the internal loss of electrode or plasma generator material is small compared with the energy input. In addition, as some plasma generators utilize magnetic fields in their design, the magnetic field coil electrical power and ohmic-heating dissipation should be included in the over-all heat balance. Precautions should be taken to assure that only a negligible portion of magnetic energy is being dissipated in hardware not within the heat balance circuit. For the purposes of this discussion, the magnetic field power input and loss aspects have been omitted because of their unique applicability to specific plasma generator designs.

2.5 The energy balance is given by Eq 2 when these factors are taken into account:

$$\overline{EI} - \sum_{i=1}^{n} W_{H_2O_i} C_p (\Delta T_0 - \Delta T_1)_{H_2O_i} = W_g (H_g - H_{in}) \tag{2}$$

The exhaust enthalpy, H_g, of the effluent as defined by Eq 1 and 2 is a measure of the average total (stagnation) enthalpy at the nozzle exit plane of the plasma-arc heater. This enthalpy does not necessarily apply to the plasma downstream of the nozzle exit plane.

3. Significance and Use

3.1 The purpose of this practice is to measure the total or stagnation gas enthalpy of a plasma-arc gas stream in which nonreactive gases are heated by passage through an electrical discharge device during calibration tests of the system.

3.2 The plasma arc represents one heat source for determining the performance of high temperature materials under simulated hyperthermal conditions. As such the total or stagnation enthalpy is one of the important parameters for correlating the behavior of ablation materials.

3.3 The most direct method for obtaining a measure of total enthalpy, and one which can be performed simultaneously with each material test, if desired, is to perform an energy balance on the arc chamber. In addition, in making the energy balance, accurate measurements are needed since the efficiencies of some plasma generators are low (as low as 15 to 20 % or less in which case the enthalpy depends upon the difference of two quantities of nearly equal magnitude). Therefore, the accuracy of the measurements of the primary variables must be high, all energy losses must be correctly taken into account, and steady-state conditions must exist both in plasma performance and fluid flow.

3.4 In particular it is noted that total enthalpy as determined by the energy balance technique is most useful if the plasma generator design minimizes coring effects. If nonuniformity exists the enthalpy determined by energy balance gives only the average for the entire plasma stream, whereas the local enthalpy experienced by a model in the core of the stream may be much higher. More precise methods are needed to measure local variations in total enthalpy.

4. Apparatus

4.1 *General*—The apparatus shall consist of the plasma-arc facility and the necessary instrumentation to measure the power input to the arc, gas stream and coolant flow rates, inlet gas temperature and net coolant temperature rise of the plasma generator hardware. Although the recommended instrumentation accuracies are state-of-the-art values, higher accuracy instruments (than those recommended) may be required for low efficiency plasma generators.

4.2 *Input Energy Measurements*—The energy input term, *EI*, to a large degree may be time dependent. Fluctuations in the power input can produce errors as large as 50 % under certain conditions. The magnitude of the error will depend on the amplitude of the unsteady compared with the steady portion of the current and voltage and also on the instantaneous phase relationship between current and voltage. The power input portion term should be written:

$$\overline{EI} = 1/t \int_0^t EI \, dt \quad (3)$$

As a consequence each plasma generator should make use of oscilloscopic voltage-current traces during operation in order to ascertain the time variation of the voltage-current input. If these traces show significant unsteadiness it is recommended that additional methods of input power measurements be pursued, such as an integrating device if available. In order to measure power directly, a wattmeter as cited by Dawes (**1**)[2] can be employed. As a precaution in the use of the wattmeter, reversed readings of current and voltage should be taken and the average of the two readings used. For those plasma generator facilities which operate under known and steady input power the use of a voltmeter and ammeter is recommended owing to their high degree of accuracy.

4.2.1 *Voltage Measurement*—The determination of power input to the plasma generator requires the measurement of the voltage across the circuit. Suitable instruments for such voltage measurements are presented by the Instrument Society of America (ISA) (**2**). The measurement techniques to be used can be either a voltage divider network or a direct reading instrument. It is highly desirable to be able to record the voltage such that time variations are a part of the test data. Accuracy of the voltage measurements shall be within ±1 %. The voltage measurement shall be taken at the electrode terminals of the plasma generator circuit.

4.2.2 *Current Measurement*—The measurement of plasma arc current shall be accomplished with an ammeter equipped with a precision shunt and the reading shall be within ±1 %. Ref (**2**) lists other instruments suitable for measuring arc current. If a precision shunt is utilized, the temperature across the shunt shall be constant and within the stated limits as given by the manufacturer. Arc current shall be measured taking into account any losses in the lead lines from the metering shunt to the ammeter recorder. It is highly desirable to be able to record the plasma-arc current so that time variations are a part of the test data.

4.3 *Coolant Energy Loss Measurements:*

4.3.1 *Coolant Flow Measurement*—The discussion that follows assumes that water is the coolant used in most plasma arcs. The water flow rate to each water-cooled component of the plasma arc shall be measured. The error in measurement techniques shall be not more than ±2 %. Suitable equipment that can be used is listed in Ref (**2**) and includes turbine flowmeters, heat flowmeters, area flowmeters, etc. Care must be exercised in the use of all of 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 shall be properly adjusted in such a way that bubbles are eliminated and that water vapor formation is not present. If practical, the water flowmeters shall be placed upstream of the plasma generator in straight portions of the piping. The flowmeter device shall be checked and calibrated periodically.

4.3.2 *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 the *Annual Book of ASTM Standards*, Part 44, and Ref (**3**) should be adhered to in the calibration and preparation of temperature sensors. The bulk or average temperature of the coolant shall be measured at the inlet and output 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 plasma arc in the inlet and outlet lines. No additional apparatus shall be between the temperature sensor and the plasma arc. The temperature measurements shall be recorded continuously. Ref (**2**) lists a variety of commercially available temperature sensors. During the course of operation of the plasma arc, care should be taken to minimize deposits on the 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 radiation from the test specimen.

4.3.3 *Coolant Flow Pressure Gages*—If apparatus such as flowmeters require the use of pressure gages, they shall be used in accordance with the manufacturer's instructions and calibration charts that are furnished with the flowmeters.

4.4 *Gas Stream Measurements:*

4.4.1 *General*—Inasmuch as single or multiple gas inlets may be used in the plasma arc the following pertains to each gas supply system in use. In particular, for each gas supply system the measurements shall include inlet gas temperature and gas flow rate.

4.4.2 *Gas Stream Flow Rate*—The flow rate of each gas entering the plasma generator shall be measured and the error shall be no greater than ±4.0 %. Ref (**2**) gives suitable commercially available gas flowmeters. For most applications, the orifice or rotameter will suffice. Pressure and temperature measurements shall be made in accordance with manufacturer's instructions and calibration charts that are furnished with the flowmeters. The flowmeter should be placed in that portion of the gas line where disturbances are at a minimum. In all cases the flowmeter device shall be checked and calibrated periodically.

4.4.3 *Gas Stream Temperature Measurement*—Inasmuch as the inlet gas temperature will not differ substantially from room temperature, it will usually have negligible effects on the calculation of total enthalpy. However, if it is practical, a thermal sensor such as those commercially available in Ref (**2**) shall be installed in an inlet section where the gas flow is free of disturbances. Preferably the temperature of the inlet gas stream shall be measured in a settling or plenum chamber where the gas velocity has been minimized. The error in measurement shall not be greater than ±1 %.

4.5 *Recording Means:*

4.5.1 Since the energy balance technique requires that the plasma generator 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

[2] The boldface numbers in parentheses refer to the list of references appended to this practice.

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 separate measurements be made of the desired parameters.

4.5.2 In all cases, parameters of interests, such as arc voltage, arc current, gas and water flow rates, and cooling water temperature rises shall be automatically recorded throughout the calibration period. Recording speed will depend on the variations of the parameters being recorded. The response time of the recorder shall be 1 s or less for full scale deflection. Timing marks shall be an integral part of the recorder with a minimum requirement of 1/s.

5. Procedure

5.1 It is essential, if the energy balance technique is to give a representative measure of the exhaust gas enthalpy, that the plasma arc must operate at steady state conditions prior to and during data taking. Therefore, the cooling system shall be operating at steady-state conditions prior to arc start up. Automatically record measurements of gas inlet and cooling water inlet and outlet temperature throughout the calibration period.

5.2 After a sufficient length of time has elapsed to assure constant mass flow of water and gas, as well as constant inlet and outlet water temperature, initiate the plasma arc. After making the necessary control adjustments, operate the plasma generator for a sufficient length of time to assure that steady state operation has been achieved. Steady-state operation assumes that the exhaust water temperature, arc current and voltage, gas and water flow rates are steady and not changing with time. In particular, the water flow rate should not change during arc operation. After arc shut off, record the gas inlet and water temperature and flow rates, respectively, so that they can be compared with pre-arc ignition values. Changes between pre- and post-arc test water temperature may indicate deposit buildups in the plasma generator proper or cooling passages which may alter the results of the energy balance.

6. Enthalpy Calculations

6.1 The quantities as defined by Eq 2 shall be calculated based on the bulk or average temperature rise of the coolant water for each water cooled section of the plasma generator. Consequently, rearranging Eq 2 the total or stagnation enthalpy becomes:

$$H_g = \frac{\overline{EI} - \sum_{i=1}^{n} W_{H_2O_i} C_p (\Delta T_0 - \Delta T_1)_{H_2O_i}}{W_g} + H_{in} \tag{4}$$

Note that when multiple gas supplies are used (see 4.4.1), W_g and H_{in} are made up of the summation over the multiple gas supplies k according to equations:

$$W_g = \sum_{k=1}^{m} W_{gk} \tag{5}$$

$$H_{in} = \frac{\sum_{k=1}^{m} W_{gk} H_{ink}}{W_g} \tag{6}$$

The choice of units shall be consistent with the measured quantities (see 2.2 for identification of above symbols).

6.2 An uncertainty analysis shall be performed according to the standard of Ref (4). Both Type A and Type B uncertainties shall be included in the analysis. The plasma enthalpy result shall be reported with its total uncertainty at a stated confidence level. Values that went into the uncertainty analysis, including those derived from calibration reports and manufacturers' specifications, as well as any assumptions or estimates, shall be documented.

7. Report

7.1 In reporting the results of the calibration tests the following steady state measurements shall be reported:

7.1.1 Arc voltage,

7.1.2 Arc current,

7.1.3 Coolant water flow rate,

7.1.4 Temperature rise of coolant water,

7.1.5 Mass flow rate of gas,

7.1.6 Calculated exhaust gas enthalpy, and

7.1.7 Uncertainty of results.

8. Keywords

8.1 bulk enthalpy; energy balance; gas enthalpy

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