Workshop on Laboratory Use of Heat Flux Transducers—*F. J. Powell and B. G. Rennex*

There were 14 attendees at the workshop, primarily laboratory representatives. The scope of the discussion included 1) calibration in a laboratory setting and 2) the use of heat flux transducers (HFTs) as part of a research apparatus.

The following specific topics were discussed in depth:

(*a*) the definition of calibration—for the ideally guarded, for the embedded, and for the *in situ* case,
(*b*) pros and cons of various calibration techniques,
(*c*) estimates of uncertainties for various calibration techniques,
(*d*) the "zero offset" in a heat flow meter apparatus, and
(*e*) the parameters that may affect a calibration.

Definition of HFT Calibration

The HFT is used to measure the heat flux, Q/A, immediately below the HFT. The heat flux is assumed to flow in a one-dimensional (1-d) direction, perpendicular to the surface of the wall specimen being measured. The measurement principle is that the HFT thermopile voltage is proportional to the HFT Q/A, which is equal to the specimen Q/A (in the 1-d condition). However, this condition is almost never met, and this leads to a somewhat complicated picture for HFT calibration. A second assumption is that the change in thermal resistance resulting from the placement of the HFT in the system to be measured is negligible or incalculable.

The following discussion describes a hierarchy of calibration methods defined by the extent to which the 1-d assumption is met. The three calibration methods are the 1-d, the embedded, and the *in situ* methods.

The 1-d Calibration Method

In this case, all possible precautions have been made to ensure 1-d heat flow. This means that a guard with a similar construction and the same thickness and the same *R*-value surrounds the HFT. This guard must be of sufficient width to ensure 1-d heat flow in the HFT area. The most accurate method to achieve a 1-d calibration is to use a guarded hot plate (GHP) and put the HFT and guard layer in the center of a stack of insulation chosen for uniformity. This minimizes the edge loss to the ambient air. It should be possible to know the Q/A for the apparatus to within 0.1%. Depending on the care with which the guard matches the HFT, it should be possible to know that the HFT Q/A is equal to the apparatus Q/A within 0.1 to 1%.

A word of caution is in order. This calibration [namely, the correspondence of the voltage (HFT) to apparatus Q/A] applies only to the extent to which the subsequent HFT application ensures the 1-d assumption. Or, this calibration can be used as the basis for a model correction to the said calibration, which would be appropriate to the conditions of subsequent application.

The Embedded Calibration Method

In this case, the HFT is tested with the same guard, or lack of guard, as will be used in its application. It is embedded in a uniform insulation medium (the embedding medium) for the cases of both the calibration and the subsequent application. In this method, the calibration will depend on the thermal conductivity, k-value, of the embedding medium. Care must be taken to know this k-value well for both the calibration and the application. The safest policy is to bracket the range of application k-values with a range of calibration points. Models, such as those presented in this volume by van der Graaf and by Apthorp and Bligh, can be used in conjunction with one or more calibration data points (for varying k-values) to predict the application calibration more accurately. This method promises the greatest accuracy, perhaps as good as within 1 or 2%.

The In Situ *Calibration Method*

This method applies to surface-mounted HFTs, and it takes into account the fact that the environment around the locality of the HFT may cause some lateral heat flow. This means that the wall Q/A will differ from the HFT Q/A or, equivalently, that the 1-d condition is met.

The idea with the *in situ* calibration is to simulate the environmental conditions in the calibration test that will pertain in the subsequent application.

The apparatus Q/A measured in the calibration test will correspond to the wall Q/A in the subsequent application, and it will not matter that the HFT Q/A is not known (that is, that the 1-d condition is not met).

The problem with this method is that it will probably be difficult to quantify all of the environmental parameters (such as emittance or wind velocity) in the application, and many calibration points may be necessary to cover the possible combinations of these parameters.

For the most part, the discussion of *in situ* calibration will be left to the other special workshops on applications.

Discussion of Various Calibration Techniques

Guarded Hot Plate

The pros of this technique are as follows:

1. It provides accurate knowledge of Q/A.
2. It provides accurate knowledge of the HFT temperature.
3. It is an absolute method.

The cons are as follows:

1. It cannot be used for *in situ* calibration.
2. Material variability of stack material occurs.
3. It is expensive.

Secondary Methods

Secondary methods include the heat flow meter apparatus or the Massachusetts Institute of Technology (MIT) apparatus described by Bligh in this workshop.

The pros are as follows:

1. They are inexpensive and easy to make.
2. They are portable.

The cons are as follows:

1. The apparatus are limited to a fixed temperature.
2. Edge loss occurs.
3. Lead loss occurs.
4. Material variability of the calibration sample occurs.
5. Long-term change of the calibration sample occurs.

Radiant Method

The pros of this method are as follows:

1. It works with high flux.
2. It is fast.
3. It works at high temperatures.

The cons are as follows:

1. Convection causes errors.
2. Its overall uncertainty is not well understood.

Hot Box

The advantage of this method is the possibility for *in situ* calibration. The disadvantage is that it provides poor knowledge of Q/A.

Estimates of Uncertainties for Various Calibration Techniques

Common Uncertainties

The following uncertainties are common to all techniques: (1) The *readout* uncertainty of the *HFT voltage* is on the order of *0.2%*, assuming a 500-μV signal with a 1-μV accuracy. (2) The uncertainty due to a *change* in *thermocouple sensitivity* with *temperature* is larger if the calibration is done at only one temperature or if one must extrapolate. Based on data presented in this workshop by Rennex, this uncertainty might be as large as *15%*. When sufficient calibration points are made to ensure interpolation, this uncertainty can be as small as about *0.2%*. (3) There is the uncertainty due to *material variability* of the insulation material in the stack used for the calibration testing. This uncertainty is probably of the order of *2* to *10%*. A study of material variability is necessary to estimate this uncertainty. This could be accomplished using a set of data to make a k-value versus density curve, in conjunction with a study of the variation of density over the sample area. Unfortunately, this procedure would be rather time-consuming. Thus, the common uncertainties add up to between 2.4 and 25%.

This uncertainty must then be added to the uncertainty in Q/A, which varies from 0.2 to 0.5% for the guarded hot plate, from 2 to 4% for secondary methods, from 2 to 15% for the hot box, and from 5 to 25% for the radiant method.

Zero Offset

The term *zero offset* refers to the phenomenon often found in the heat flow meter apparatus in which the HFT voltage has a nonzero value, the so-called zero offset, when the apparatus hot and cold plate temperatures are equal. The workshop discussion dealt with possible explanations of this phenomenon. One explanation advanced was that the thermopile might somehow be generating a voltage even when no temperature difference exists, perhaps as a result of moisture in the HFT causing an electrolytic voltage. It was then pointed out that this zero offset was found to go to zero (at the National Bureau of Standards) when steps were taken to ensure a uniform temperature within the entire HFT apparatus. This was accomplished by bringing the hot and cold plates in contact, turning off the heating and cooling units, insulating the entire plate area, and waiting until all temperature gradients had disappeared. Another hypothesis was then advanced that the zero offset was in fact a result of edge heat flow within the plate stack. It was also pointed out that this edge flow would not necessarily be constant as the plate temperatures change. Thus, the common practice of measuring the zero offset (that is, the HFT voltage when the plate temperature difference is zero) and subtracting out this voltage when tests are made with the plates at different temperatures is not justified. There is no reason to suppose that the lateral heat flows are the same in these two cases.

Calibration Parameters

It is possible that the HFT can depend on the following parameters: heat flux, temperature, pressure on the surface of the HFT, thermal conductivity of surrounding material, surface air velocity, emittance of HFT and of surrounding material, moisture, radiative environment, surface mounting technique, and test time.

Conclusions

There was general agreement on the part of the participants on a considerable need for research to assess systematically the order of magnitude of the calibration errors. Other suggestions were projects to write calibration procedures for the 1-d, the embedded, and the *in situ* cases, to run a round-robin test, and to encourage manufacturers to obtain and make available information on their products' limitations of use.