LOW HEAT-FLUX MEASUREMENTS: SOME PRECAUTIONS

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Low Heat-flux Measurements: Some Precautions

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ABSTRACT

Simple experiments are described for the purpose of illustrating measurement errors and their avoidance during use of Gardon or Schmidt–Boelter total heat flux sensors. These errors can assume serious proportions of the observed signal at flux levels below about 15 kW/m^2. *They result from two sources, both a consequence of the flux gage's temperature relative to its surroundings: firstly, convective heating of the gage by the boundary layer from hot surfaces surrounding it and second, heat exchange with the ambient environment by radiation and convection. Some proposals are made for standardizing measurement methods, but it seems unlikely that errors in measurement can be completely eliminated. It thus becomes important for users of experimentally derived data to understand the limitations which may exist in the data reported.*

1 INTRODUCTION

The problem of errors in low-flux radiation measurements has been examined here in the context of a particular test where such measurements are critical; the lessons learned here are more broadly applicable, however.

The International Maritime Organization (IMO) surface flammability test method for deck and bulkhead finish materials[1,2] measures the lateral flame-spread behavior of rectangular slabs of material subjected to a spatially varying incident radiant flux from a

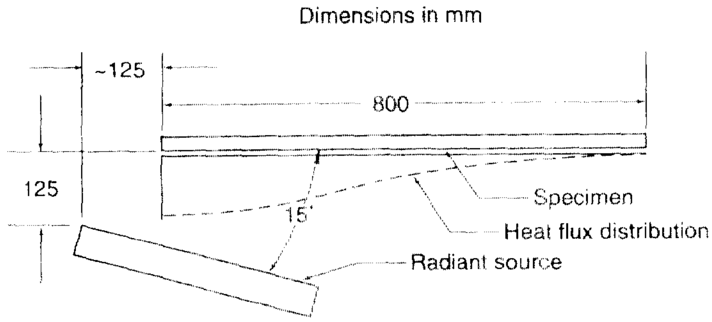

Fig. 1. Schematic of sample and radiant panel arrangement for the IMO surface flammability test showing the flux distribution on the sample surface.

gas-fired radiant panel. Test specimens of 155 mm width, 800 mm length and varying thickness are mounted in a frame-like holder; the sample orientation is typically vertical (with the long axis horizontal) and this is the case considered here. The incident flux decays monotonically along the horizontal length of the sample face due to the angled orientation of the radiant panel source, Fig. 1. One seeks the quantitative behavior of the flame-spread process as a function of the incident radiant heat flux.

Results from the first inter-laboratory study of this test showed excellent agreement of ignition and flame-spread data at flux levels above 15 kW/m^2. However, the data did not correlate as closely at the low end of the flux scale. Since the fluxmeters used in the different laboratories to define the flux gradient along the specimen were neither identical nor used in exactly the same way, it seemed possible that either differences in the calibration or method of use of the gages might be responsible for the variations observed.

Two types of total heat fluxmeter are commercially available. One is the Gardon gage which, through radial heat flow in a metallic foil, develops a temperature difference between the foil's center, usually the hot junction, and the other peripheral junction with the water-cooled gage body, Fig. 2(a). The other fluxmeter type, also named after its developers, is the Schmidt–Boelter meter, Fig. 2(b). This makes use of a thermopile, the signal being developed as a result of a temperature differential across a thin wafer of thermally stable material located between the sensing surface and the gage body. For the same voltage signal level, a Schmidt–Boelter gage requires a lesser temperature

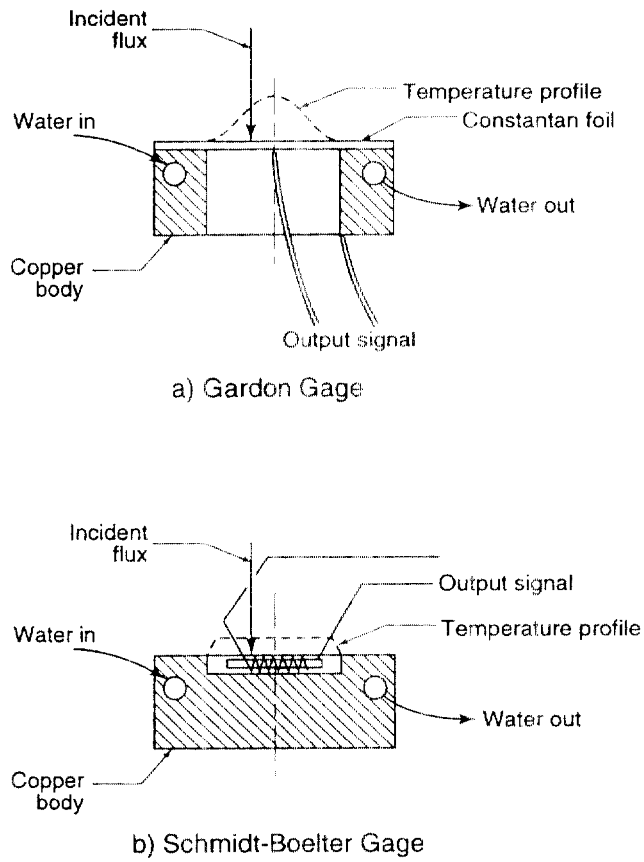

Fig. 2. Schematic cross-sections of the most commonly used flux gages.

differential; thus the gage surface temperature is better defined in that it is closer to the cooling water's temperature.

The electrical circuit of a Schmidt–Boelter gage is insulated from the water-cooled body. This fact is useful since, on casual inspection, the two types of gage are difficult to distinguish. An electrical low-voltage continuity test, with a high sensitivity meter, between a signal output lead and the gage body should permit correct classification. (Note that these gages may contain very fine wires subject to ohmic heating if more than a volt or so is used for this type of test.)

It has been considered that since the calibration curves of both gages are remarkably linear, the electrical output signal is independent of body temperature and is simply proportional to the imposed heat flux; this is not the case, as will be illustrated here.

2 THE MEASUREMENT APPLICATION UNDER CONSIDERATION

In the IMO application, one measures the flame-spread rate as a function of the incident local radiant flux, as well as the minimum incident flux at which spread is possible. Thus it is critical to carefully characterize the spatially variant incident flux profile. Calibration of this profile in the IMO test was originally to be inferred by mounting fluxmeters with their sensing surfaces flush with the heat-exposed surface of a refractory board dummy specimen (e.g. Marinite*) of 800 ± 100 kg/m^3 density and about 20 mm thickness. This places the several possible positions of the fluxmeters' centerlines in a horizontal plane and, since this plane is located at the mid-height of the 155 mm specimen dimension, the fluxmeter will sense not only irradiance but also any effect of convective heat transfer due to the buoyant boundary layer developed on the dummy specimen.

3 PRELIMINARY TESTS IN THE UK

The Fire Research Station (FRS) in the UK assisted in the early stages of this study, by examining the effect of flux gage diameter on the observed flux. Tests were run with water-cooled, Gardon-type fluxmeters having exposed faces of both 25 and 75 mm diameter at 5 and 25 kW/m^2 irradiance levels. These flux levels were based on measurements with the gages alone, without a simulated specimen or surround, such as is shown in Fig. 3. The change in the gage's electrical signal was then observed following the placement of a board surround with its exposed face flush with the gage's sensing surface, and the board being allowed to heat up. It was found that the surround always tended to increase the gage signal. Moreover, the percentage signal change was greater for the smaller diameter gage. Additionally, the signal change was found to be inversely related to the irradiance level.

It was concluded by the FRS that the smaller gages provided less cooling of the convective boundary layer before it contacted the sensing area and thus yielded higher signals.[3]

It is worth noting, parenthetically, that Gardon gages have been shown to have differing sensitivities to convective and radiative heat

* Mention of specific products is for clarity only; it does not imply any endorsement by NIST, nor does it mean that they are necessarily best for the application described.

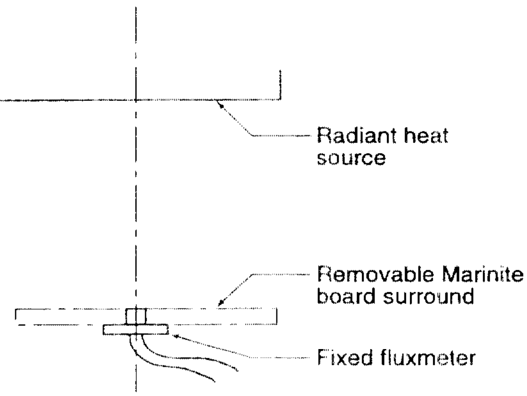

Fig. 3. Arrangement tested by H. Wraight of the Fire Research Station.

fluxes.[4] This arises because these gages have a spatially non-constant surface temperature, unlike the Schmidt–Boelter gages used in the work described below. In any event, as discussed below, measurement of the convective component is not a goal here; rather, it is to be minimized so that the radiative flux is more accurately measured.

4 BASIS OF THE CURRENT TESTS

One might at first infer from the above results obtained by the FRS that the smaller diameter gage is more correctly measuring the total heat flux (convective plus radiative), since it has a lesser effect on the boundary layer from the surround. However, it must be realized that the convective component of the flux being measured in the above tests, and in the original IMO flux calibration configuration, is an unwanted signal resulting from the low gage temperature. It adds to the radiant flux because the boundary layer arising from the hot surround is above the gage temperature. If one were to attempt to measure the total flux felt by the hot surround itself (or in the IMO test, the hot specimen surface), one would find that the convective component counters the radiant flux because ambient air is cooling the specimen. Measurement of this total flux is problematical and is typically not attempted. Thus the goal remains a precise measurement of incident radiant flux alone.

A second source of sensitivity of the flux gage's response to gage temperature derives from the fact that, even in the absence of a hot surrounding surface, the gage will exchange heat with its ambient environment if their temperatures differ.

5 EXPERIMENTAL RESULTS

Recognition of the sensitivity of the observed flux gage signal to gage temperature and thus cooling water temperature prompted further study of this issue and a search for ways in which errors of the above types could be reduced.

Schmidt–Boelter gages were used because of their more ready availability, but there is reason to believe that the results would be similarly applicable to Gardon gages. They were supplied with cooling water from a laboratory sink faucet of the mixing type. Most of the experiments were conducted with water at either about 12 or 50°C and at flux levels varying from about 30 down to 1·5 kW/m^2. Emphasis was placed on the lower range of fluxes because errors caused by uncontrolled thermal changes would be expected to represent a larger fraction of the desired signal.

The initial tests were similar to those performed at the FRS, but made use of the configuration geometry required by the IMO procedure. The regular specimen holder was not used, but a refractory board dummy specimen of 370 mm length and 155 mm width was fixed in the position normally occupied by the hot end of the specimen. The fluxmeter used was then mounted in a fixed position about 495 mm from the hot end, beyond the end of the dummy specimen board. A short length of similar board or surround of 150 mm × 130 mm dimensions was prepared with a hole at the center of the face allowing it to be placed snugly over the fluxmeter. When this was done, the exposed surfaces of the surround, shortened dummy specimen and fluxmeter were all coplanar and occupied the same position as a normally mounted test specimen. Figure 4 shows data secured with this test arrangement; the figure is a scan of the original chart recorder trace. In this figure, the removable surround is referred to as B. (Note that time increases from right to left.)

Inspection of Fig. 4 shows two relevant signals as a function of time. The lower trace is that of a radiation pyrometer which follows source radiance, and thus fluxmeter irradiance, as conditions at the flux gage are changed. The pyrometer was focused on a large fraction of the face of the radiant panel. It is important to note that its signal remained essentially constant (corresponding to 30 kW/m^2) even though addition/removal of the flux gage surround somewhat changes the

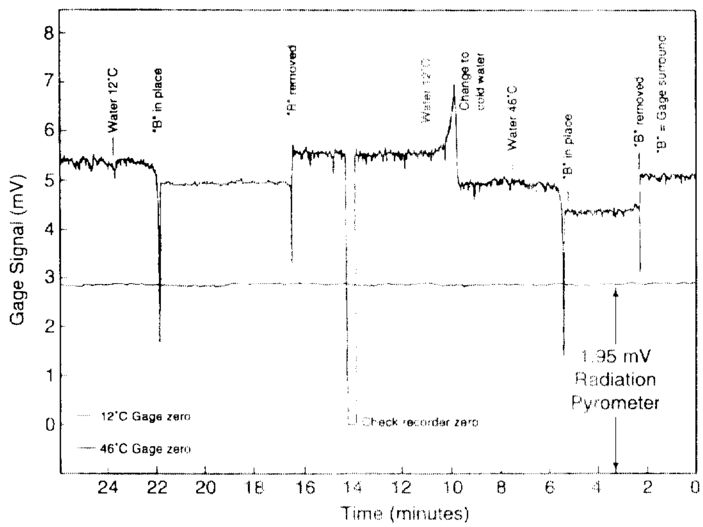

Fig. 4. Heat flux gage trace showing the effect of surround and cooling water temperature on the observed signal for a constant incident radiant panel flux.

radiative interaction of the gas-fired radiant panel with its surroundings.*

To minimize this, the surround, when removed from the specimen holder, was placed in the panel's radiation field in such a position as to keep the temperature of the surround nearly constant; this also minimized the time needed for stabilization of the temperature of the surround when it was returned to its position around the flux gage. The upper trace in Fig. 4 records the output of the fluxmeter during the constant irradiance from the gas-fired panel, as the temperature of the gage cooling water was changed and the surround was applied or removed. During this experiment, the cooling water temperature was initially 46°C and then was changed to 12°C, as indicated in Fig. 4.

Following this experiment, when the radiant source had cooled to room temperature and the radiation pyrometer signal had dropped to zero, the fluxmeter signals were measured with gage temperatures of 12 and 47°C. Under these conditions, fluxmeter signals of +0·2 and −0·4

* The radiant panel in the IMO test is run as a constant power input device, which typically will have reached a steady temperature based on a balance of heat input with heat losses. There is no feedback loop to control the temperature of the radiating surface and thus a change in the radiative interaction with the surroundings can lead to a change in the steady temperature of the radiator. Even systems which have active temperature control, such as the conical heater in the cone calorimeter, can experience significant transient changes in radiator temperature if the control loop is unable to quickly adjust to altered radiative exchange conditions.

mV, respectively, were observed. These two signal levels are shown in the lower left corner of Fig. 4. They represent the 'zero' flux signal for these two flux gage temperature levels. These bias error signals of −0·2 and −0·4 mV represent heat exchange between the gage and the ambient environment. Obviously, heat is lost to the ambient environment when the gage is above its temperature and conversely; thus this source of error should vanish if the gage temperature matches that of the ambient environment. One can readily estimate that this heat exchange is approximately equally proportioned between radiation and convection. Note that this particular convection component is present even though the surround is absent; it is due to the buoyant boundary layer on the face of the gage itself.

Since, for all practical purposes, the millivolt signal generated by the fluxmeters is directly proportional to the net flux exchange between the gage and its surroundings, rounding errors can be reduced by comparing millivolt signals directly as an indication of heat exchange. In most instances, this procedure will be used in the paper.

Table 1 presents an analysis of a portion of the data obtained during this test. More data are shown than can be derived from Fig. 4, since the latter represents only a portion of a longer chart. This table shows individual signals and averages of both corrected and uncorrected gage signals from the bare gage (i.e. with surround B removed) for the two temperatures used. The close agreement of the two average corrected signals (within 1%) as compared with the uncorrected signals shows the improvement that can be made in consistency of flux measurement when corrections are made for heat exchange between the bare gage

TABLE 1

Analysis of the Errors in the Bare Gage Signal Data Shown in Fig. 4 with Water Temperatures of 12 and 46°C for a Corrected Bare Gage Flux of 5·9 kW/m²

Fluxmeter cooling temperature and signal bias	*Observed signal from gage* (mV)	*Corrected signal* (mV)	*Error in bare gage measurement*
12°C, +0·20 mV	4·90	4·70	
12°C, +0·20 mV	4·90	4·70	
12°C, +0·20 mV	4·85	4·65	
Average	4·88	4·68	+ 4·3%
46°C, −0·40 mV	4·30	4·70	
46°C, −0·40 mV	4·35	4·75	
Average	4·32	4·72	− 8·5%

TABLE 2

Analysis of Convection Error Signals During Tests of a Schmidt–Boelter Fluxmeter Arising from a Refractory Board Surround Flush with the Sensing Surface of the Gage. Data are from Fig. 4 and are all corrected for Gage Temperature Signal Bias

Fluxmeter cooling temperature and signal bias	*Signal without surround on gage* (mV)	*Signal with surround on gage* (mV)	*Convective component*	*Measurement error*
12°C, +0·20 mV	4·70	5·30		
12°C, +0·20 mV	4·70	5·35		
12°C, +0·20 mV	4·65	5·25		
Average	4·68	5·30	− 0·62 mV	+ 13·2%
46°C, +0·40 mV	4·7	5·30		
46°C, +0·40 mV	4·75	5·40		
Average	4·72	5·35	− 0·63 mV	− 13·3%

and its ambient environment. Using these data, one can calculate the additional convection errors that occur when flux measurements are made with a surround mounted on the gage operated at these two temperatures. Table 2 shows such a calculation.

The data analyzed in Table 2 have all been corrected for the zero bias of the gage, discussed above. The first two columns are duplicates of the bare gage data shown in Table 1. The data in the third column were derived from fluxmeter signals when a surround was in place. Since zero bias corrections have been applied to the data in both the second and third columns, the average signals for the two water coolant temperatures used should show close agreement. This is indeed the case, the agreement being within about 1%. However, there are significant differences between the averages of the bare gage readings and those when the surround was in place. Since source radiance was unaffected, the observed signal difference must be attributed to the convective flux the gage receives from the hot boundary layer rising from the lower half of the surround.* This convective component is shown in column 4 and reported as a percentage in column 5. The latter is calculated on the basis that the average of the bare gage data (corrected for zero bias) represents the best estimate of incident radiant flux from the gas-fired panel.

* One might suppose that the difference is to some extent affected by the fact that the surround shades the lateral (cylindrical) surface of the flux gage when it is in place. These gages are designed to be as insensitive as possible to such effects, however, as long as the rate of water supply is adequate.

TABLE 3

Comparison of Low and High Flux Bias Errors; Schmidt–Boelter Gage Rated at 50 kW/m^2 Located 50mm from Cold End and then 50mm from Hot End, Flush with Face of the IMO Dummy Specimen

Data treatment	*Flux signal at gage temperature* (mV)		*Apparent errors**		*Error span*
	12°C	47°C	12°C	47°C	12–47°C
Cold end (1·24 kW/m^2)					
Apparent signal	0·29	0·16	+12·4%	−38·0%	50·4%
Correction	−0·025	+0·09			
Corrected signal	0·265	0·25			
Average	0·258				
Hot end (30·8 kW/m^2)					
Apparent signal	6·65	6·40	+1·7%	−2·1%	3·8%
Correction	−0·044	+0·08			
Corrected signal	6·606	6·48			
Average	6·54				

* Calculated relative to the signal corrected for bias error; the actual incident radiant flux is somewhat less than the bias-corrected signal indicates because it is not corrected for the additional effect of buoyant convective heating of the gage by the hot dummy specimen.

Table 3 presents the results of further experiments with a Schmidt–Boelter fluxmeter mounted in the previously described IMO dummy specimen. The assembly was mounted in a specimen holder, first with the gage near the cold end, yielding the data shown in Fig. 5, and then at the hot end of the specimen, yielding the data shown in Fig. 6. Note the differing ordinate scales in the two figures. In both tests, the fluxmeter sensing surface was in the plane of the irradiated specimen surface and 50 mm from the end of the specimen. It is evident from Table 3 that, for a fixed cooling water temperature, there is a much larger percentage measurement error at the low flux position. This develops because, at this location, the flux measurement bias errors become comparable with the flux signal being measured (which is, in the case of Table 3, the incident radiation plus convection from the hot dummy specimen surface). While the convective error caused by the hot dummy specimen surface will be larger at the hot end, the much greater irradiance signal makes this of less importance.

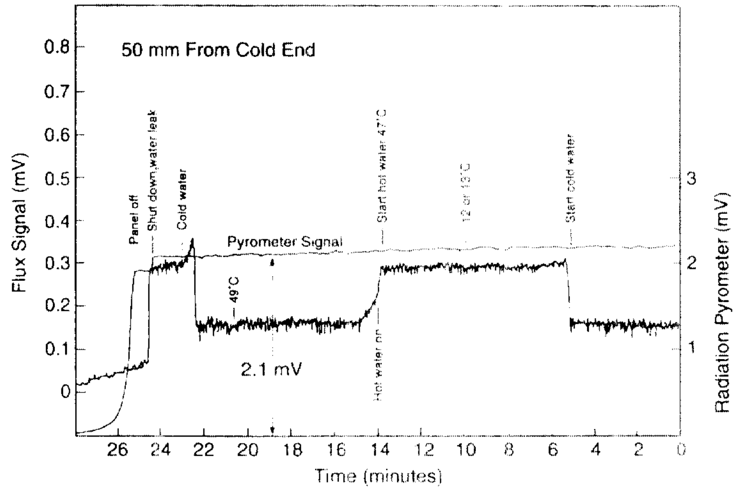

Fig. 5. Heat flux gage trace showing the effect of coolant temperature on gage signal when the gage is near the low radiant flux end of the sample.

6 REDUCING THE CONVECTIVE ERROR DUE TO THE HOT SURROUNDING SURFACE

It seemed likely that a reduction of this convective error could be achieved by permitting the gage to project beyond the surface of the dummy specimen. Thus, an experiment was performed in much the

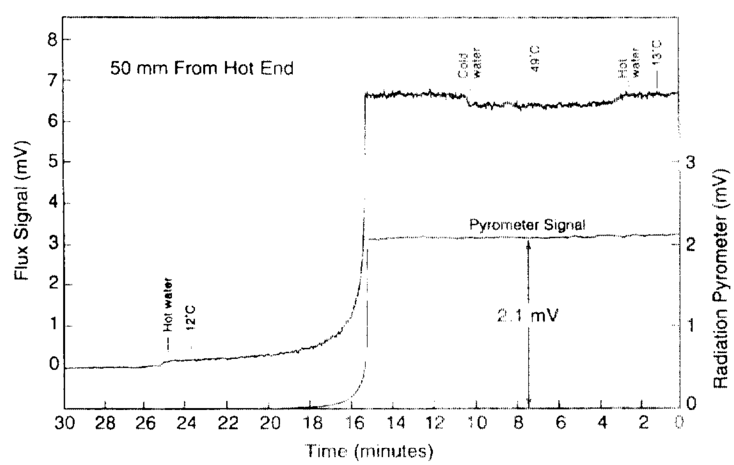

Fig. 6. Heat flux gage trace showing the effect of coolant temperature when the gage is near the high radiant flux end of the sample.

TABLE 4
Reduction of Hot Surface Buoyant Convection Error by Gage Projection. Bare Gage Flux of 7·8 kW/m² (6·24 mV)

Gage projection beyond surround	*Bias corrected signals* (mV)	*Average signal*	*Error (% of bare gage reading)*
No Surround	6·28, 6·20	6·24	0·0
10 mm	6·5, 6·75, 6·5	6·58	+5·4
3 mm	6·85, 6·80	6·82	+9·3
0 mm	7·1, 7·2, 7·2, 7·1	7·15	+14·6

same fashion as those previously described, but with a surround of only 10 mm thickness. The fluxmeter was fixed in position and cooling water temperatures of 12 and 47°C were again used. Since the surround was thinner than before, it could be mounted in such a way that the fluxmeter sensing surface would project by as much as 10 mm beyond its heated face. Measurements of gage signals were made with the fluxmeter in the following positions: flush, and extending 3 and 10 mm beyond the surround face, as well as with the surround removed. This last configuration presumably provides minimum buoyant convective flux from below the gage's location. (As in the previous tests, when the surround was removed, it was placed in a position in the radiation field such that its heated face did not change significantly in temperature. This minimized test equilibration time and also helped assure a constant irradiance from the panel.)

Table 4 presents the results of an analysis of the data from the above measurements. The data shown have all been corrected for the zero signal gage bias. The errors listed are with reference to the bare gage, i.e. no surround, measurement. The error with a 10 mm gage projection has been reduced by about 60% below that with the flush-mounted gage. This is about the maximum projection practical with the gages commonly in use. On the basis of these measurements, a new dummy calibration specimen was developed for use in flux distribution measurements with the IMO apparatus. This is illustrated in Fig. 7. It provides for a 10 mm projection of the fluxmeter beyond the face of the refractory board at the 512 and 662 mm positions from the hot exposed end of the dummy. Such a projection does not seem necessary at positions nearer the hot end because the larger configuration factor between the gage and the radiating source yields substantially higher radiant fluxes, greatly reducing the percentage error due to the convective boundary layer on the dummy specimen.

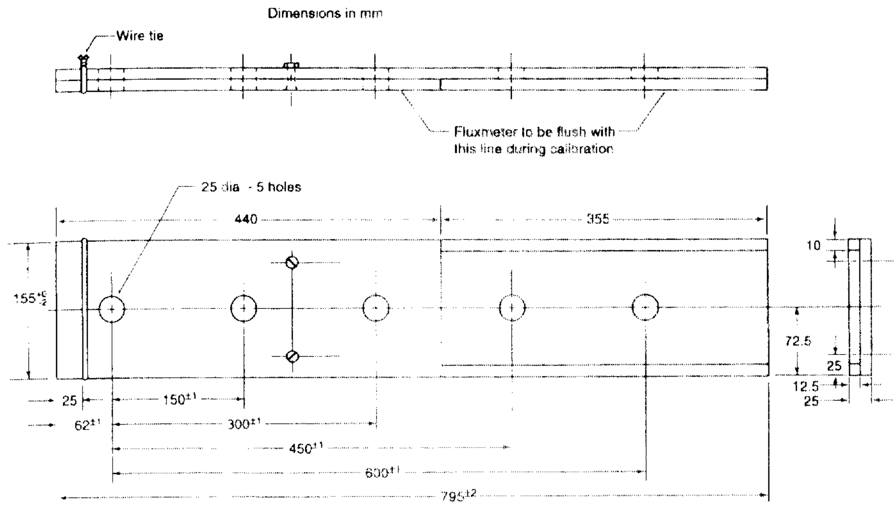

Fig. 7. Dummy specimen for holding the flux gage during the IMO flux distribution calibration. The holes denote gage locations. Note that the gage surface protrudes 12·5 mm from the two holes on the right (the low flux end). Note also that the current version of this calibration board in the IMO surface flammability test uses ten evenly-spaced gage holes rather than the five shown here.)

Table 5 provides both theoretical and effective configuration factors derived from calibration of the incident flux using the dummy specimen shown in Fig. 7 in the NIST IMO device. Here, the theoretical and effective configuration factors were taken to be equal at the 50 mm point on the dummy specimen. The effective factor at other points was inferred from the actual measured incident flux (with the bias error eliminated by using room temperature cooling water) and that expected on the basis of the theoretical configuration factor (for the given geometry of Fig. 1 and the radiant panel size). This theoretical factor assumes that the radiator is uniform in temperature and unbiased with respect to radiation as a function of angle relative to its surface (i.e. it is a diffuse radiator). The departures from this ideal profile shown in Table 5, reflect the less than perfect behavior of the particular panel used (due to temperature non-uniformities and non-diffuse radiation).

7 SUMMARY

The relatively simple experiments performed shed light on possible sources of error in flux measurements with water-cooled fluxmeters of Gardon- or Schmidt–Boelter-type construction.

TABLE 5
Measured Flux Distribution Along Specimen With Theoretical and Effective Geometric Configuration Factors

Position on the dummy specimen from the hot end (mm)	*Geometric configuration factor*		*Measured incident flux* (kW/m^2)
	Theoretical	*Effective**	
50	0·496	0·496	50·5
150	0·442	0·463	47·1
250	0·347	0·371	37·8
350	0·274	0·235	23·9
450	0·194	0·130	13·2
500	0·153	0·090	9·2
550	0·190	0·061	6·2
650	0·064	0·030	3·1
750	0·030	0·015	1·5

* See text for definition.

1. Even a bare flux gage will exchange heat with its surroundings, by both radiation and buoyant convection, if its surface temperature differs from that of the surroundings. The radiative component of this unwanted exchange is lessened if the view factor to the surroundings is reduced and that to the radiant source of interest maximized. The convective component is unaffected by such changes, however. The combined convective/radiative signal, referred to here as a bias error signal, can be minimized by matching the gage surface temperature to the temperature of the experimental surroundings as closely as possible. (In experiments which involve large heat sources, one needs to be aware of the fact that the temperature of the surroundings may change during a test, thus shifting the bias error.) Since the user only has control of the gage cooling water temperature, setting this equal to the room temperature and using a Schmidt–Boelter type gage, with its small temperature differential, appears to be the best way to minimize this bias error.*

* Note that there are circumstances when one deliberately raises the gage temperature well above that of the ambient environment. This is done, for example, when making flux measurements in situations (e.g. inside a flame) which may provide a false heat flux component due to liquid condensation on the cool gage surface. Typically, in such circumstances, the gage is calibrated at this elevated temperature. Caution is indicated when applying such a calibration to a low flux situation where the offset is significant since the exchange with the surroundings may not match that during calibration.

2. If the measuring surface of the fluxmeter is in the same plane as the surface on which irradiance is desired, convection over that irradiated surface may cause errors. The measurements reported here involved natural convection over a dummy specimen lying in a vertical plane and the desired flux is just that due to incident radiation. The buoyant flow over the specimen will be at a temperature below that of the heated specimen's surface but above that of the flux gage's surface. This will result in an erroneous measure of the irradiance because of the added convective input. This type of error can be reduced, but not eliminated, by allowing the fluxmeter to extend beyond the specimen's surface. It is shown that this convection error can be a very large fraction of the signal measured at low flux levels. In applications where the radiant source is temperature-controlled, and thus not affected by the temperature of objects in its field of view, it should be possible to eliminate this source of error by eliminating any surface in the radiation field which can transfer heat to the flux gage by buoyant convection.

   If the specimen lies in a horizontal plane, irradiated on its top surface, buoyant convective interference with radiant flux measurements is still to be expected. However, the flow may be less stable and harder to envision, particularly for large-aspect-ratio specimens such as that used in the IMO test discussed above. Thus there may be a variability in the 'hot surround' convective error that is more complex than with a vertical surface. The aspect ratio becomes unity (for a square sample) in the cone calorimeter (ASTM E-1354); a simple radial inward then upward flow is induced both by the heated specimen surface and the cone-shaped heater above it. Wraight[5] reports measurements of the effect of various draft conditions on the time for specimen ignition in this type of configuration. His findings fail to suggest any major affect of draft conditions on specimen ignition time. This implies that radial air flow is unlikely to change the net flux level (radiative input minus convective loss) near the center of the specimen surface but may have some effect on observed flux levels near the edge of the specimen during calibration of flux levels of 2 kW/m^2 or less.

It must be emphasized that the methods described in this paper can only serve to provide a means of systematizing incident radiant flux measurements and minimizing the errors in this process. They do not address the problem of the measurement of combined flux in environments where both convection and radiation are of interest since that requires the fluxmeter's thermal properties to be matched to those of the specimen being heated.[6,7]

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