INVESTIGATION ON CALIBRATION SYSTEM FOR CONDUCTIVE HEAT FLUX GAGES

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ABSTRACT

Nowadays, heat flux gages are used more commonly than before, and heat flux gage calibration becomes more and more important. A heat flux gage calibration system is described in detail in this paper and three heat flux gages are calibrated using this approach. Then the coefficients of them are calculated and compared with those supplied by the manufacturer. The difference of each gage is 9.76%、6.30% and 3.59% respectively. Problems encountered during the experiment have been analyzed carefully and suggestions on how to improve this system are provided. Through the experiment, conclusions can be drawn that this calibration system has its advantages and reliability on conductive heat flux gage calibrating.

1. INTRODUCTION

With development of modern science and technology, especially the use of heat transfer in aviation、energy management and so on, it is not sufficient to take the temperature as the only signal of heat transfer. Then, technologies of heat transfer measurement got great development and heat flux gages appeared.

Because each kind of heat flux gages is produced by different materials and technology, characteristics of each gage are different even in the same kind. Therefore heat flux gages must be calibrated before they are used. When heat flux gages are calibrating, there must be a one-dimensional heat flux whose value is known. It means that there must be a standard heat flux producer, which can produce a known heat flux and its surface is isothermal. Normally, calibration methods are divided into two categories: relative method and absolute method.

Individuals have been very innovative in designing methods suitable for their gages and applications. Many calibration methods have been used for their gages. All of the heat transfer modes have been utilized: radiation, convection and conduction. Radiation has been used most, usually because it is easier to establish a known heat flux level and the available heat flux range is so wide [1].

Different calibration methods may give different results, particularly if radiation methods are compared with convection or conduction methods [2]. Nowadays, all of the current calibration facilities are designed to calibrate gages at room temperature. Because many of the applications involve hot walls, calibrations with the gage at high temperature are important and becoming more, so temperature limits are increased.

Because heat flux gage calibration involves factors of radiation, convection and conduction, it isn't an

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easy work to determine coefficients of the heat flux gages [3]. Forms of heat transfer are composed of radiation, convection, and conduction. Each of these forms of energy transfer affects the sensor differently. Radiation is defined in terms of wavelength、spectrum、intensity and angular distribution. Any given sensor absorbs, reflects and transmits heat flux according to its own surface properties which may not match those of the surrounding surface. In addition, radiation is not actually absorbed at the surface, but within the first micrometer of the surface [4], which is on the order of the thickness of thin-film heat flux gages. This could significantly affect measurements of radiative heat flux for these sensors [5].

The results of the calibrations could be fit as a linear equation of this form:

$$\mathrm{Y}=a+b\mathrm{X} \tag{1}$$

where "Y" is the applied heat flux (W/m^2), "X" is the voltage output for the gage in mV, "*a*" and "*b*" are the intercept and slope for the line. The square root of the coefficient of determination, R, is used as a measure for the goodness of the fit [6].

2. FACILITY DESCRIPTION

The heat source consists of a commercial radiant heater. The radiant heater incorporates a 2000W tungsten-halogen filament lamp. A spare lamp is available. The lamp is located in a large ellipsoidal reflector, with the lamp placed at one of the foci and the entrance to the kaleidoscope flux redistributor (Fig.1) at the other. The lamp is placed inside the ellipsoidal mirror through a hole in the lower rear of one side. A metal housing surrounds the half of the ellipsoidal mirror containing the lamp. The mirror passes through the wall of the housing and extends 10cm before being cut off short of the second focus of ellipse.

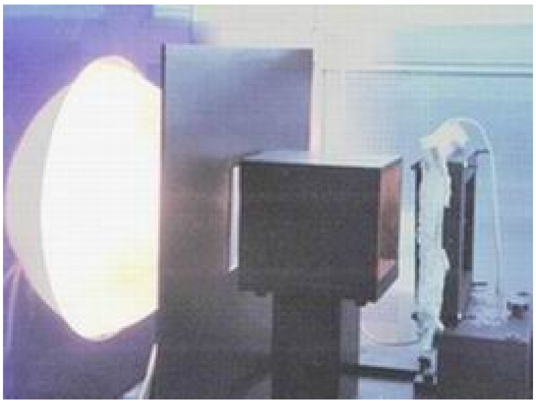

Figure 1. Heat flux redistributor

A blackened radiation shield with a square cut out centered on the mirror axis is positioned 2.5cm from the mirror. A small box open at both ends is attached over the radiation shield cut out on the side opposite to the lamp. This box was designed to improve the uniformity of the heat flux spatial distribution reaching the gage [7]. When its entrance is placed at the focal point of an optical system, internal reflections of light within the box redistribute the energy flux by forming and superimposing multiple images such that the flux distribution becomes more uniform at the exit [8].

The heat flux gage to be exposed is placed in a specially machined metal holder, on which there is a square cut hole. Either the gage itself or a machined holder with inserted heat flux gage is placed in this holder such that the heat flux gage surface is flush with the mount side facing the lamp. A setscrew is used to lock the gage or mount in place.

The gage holder is clamped to a mount base with two slots on either side of the lamp axis. The mount and gage holder are secured with bolts to a pedestal equipped with two slotted bars attached to its top surface such that they form a slide for the gage mount. This arrangement allows the distance between the gage surface and the kaleidoscope flux redistributor to be adjusted along the system's horizontal axis. In addition to the heat flux gage mount, the kaleidoscope flux redistributor and radiation shield are attached to the pedestal. A specially constructed mount is attached to the pedestal to hold the kaleidoscope flux redistributor in place.

Both the radiant heat source and the pedestal are attached to a metal base. This base is equipped with legs. The lamp housing is mounted with threaded rods that allow the height of the lamp to be varied relative to the base. The lower side of the pedestal is slotted along the lamp-axis direction so that the pedestal can be positioned before being bolted securely to the base (the whole system can be seen in Fig.2).

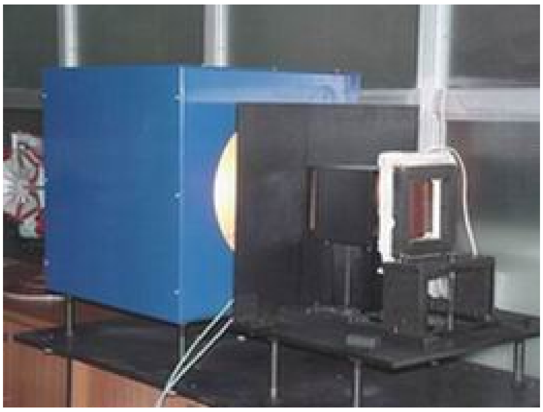

Figure 2. Calibration System

The lamp is powered by a YF630 transducer that is produced by Special Power System Co., LTD in Taiwan. This transducer can change the voltage and current from 0V to 220V and 0A to 27A respectively, and can show the numerical values of the current、voltage、frequency and power. The voltage outputs of the heat flux gage are recorded with an HP 34970A data collector using a 60s averaging period with two readings per second.

3. CALIBRATION PROCEDURE

The procedure for calibration is composed of the next steps:
1. Plug in data collector.
2. Place standard gage in holder.
3. Turn on the power supply (some nominal setting 5A, 25V), allow coming to equilibrium.
4. Record outputs of standard sensor and reference sensor at varying irradiances.
5. Plot data.
6. Determine reference sensor calibration factor from curve slope.
7. Turn off power supply.

In order to perform a heat flux gage calibration, an arbitrary heat flux level is initially set by adjusting the lamp power supply voltage and current. A sufficient period (generally 20 min) is allowed for the lamp intensity to stabilize. After the lamp intensity is stabilized, the secondary-standard heat flux gage is positioned in the holder and connected to the data collector. The voltage generated by gage is then recorded. Generally, five or more 30s readings are recorded to ensure that the radiant flux is not changing. At this point a 60s average is recorded that is taken as the gage response to the imposed heat flux. The corresponding heat flux at the gage location is determined using the calibration value from the secondary standard.

Following the characterization of the heat flux, the standard gage is immediately replaced with the gage to be calibrated, and a 60s average voltage is recorded, taken to be the response of the gage to the imposed heat flux. If more than one gage is to be calibrated, the measurement is repeated until the response of each gage to be calibrated has been recorded for the current applied heat flux.

Generally, gage response is characterized at three or more flux levels. Once a calibration cycle is completed, the lamp output is readjusted to another flux level, and following a stabilization period, the entire measurement procedure is repeated [9].

During the test, lamp currents of approximately 3A、3.2A、3.4A、3.6A and 3.8A were used to generate heat flux levels at the gage on the order of 19.62W/m^2、24.55W/m^2、29.43 W/m^2、34.47 W/m^2 and 44.16 W/m^2. Current practice is to limit maximum heat flux values to no more than 2kW/m^2 in order to protect the secondary-standard gage and the lamp.

Following the completion of a calibration the results are plotted as imposed heat flux (W/m^2) versus the corresponding gage output readings in mV. Generally a linear least square curve is employed to fit the experimental data points, and the result is reported in terms of W/m^2 per millivolt.

The calibrated heat flux gages that produced by Chinese Center for Disease Control and Prevention are bought from the market, and the type is NWP-4. There are three kinds of heat flux gages of this type among which WYP (Dimension: 110×110×2.5mm. Test temperature range : ≤100℃. Coefficient of heat flux gage: 11.6 W/m^2·mV. Error of calibration: <5%) and WTR (Dimension: 110×55×4mm. Test temperature range: ≤200℃. Coefficient of heat flux gage: 116 W/m^2·mV. Error of calibration: <5%) are used.

A higher precision heat flux gage which is produced by Kyoto Electronics Manufacturing Co., LTD is used as the secondary-standard gage to calibrate the other three, including one WYP and two WYR heat flux gages. During experiment, the laboratory must be kept as dark as possible to reduce the influence of the radiation. At the same time, airflow should be reduced to keep the precision of calibration.

4. RESULTS AND DISCUSSION

Through changing the voltage and current of the tungsten-halogen, different heat fluxes were got. The results of calibrations are summarized in the following four tables. Gage surface temperatures recorded by the standard heat flux gage are included in table 1.

Table 1: Experimental Data of Standard Heat Flux Gage

Times	Voltage (V)	Current (A)	Heat flux (W/㎡)	Temperature (℃)
1	28.8	3	19.6	24.8
2	32.7	3.2	24.5	25.2
3	36.6	3.4	29.4	25.5
4	40.7	3.6	34.4	26.0
5	44.8	3.8	44.1	27.7

Table 2: Experimental Data of WYP Heat Flux Gage

Times	Voltage (V)	Current (A)	Heat flux (W/㎡)	Voltage reading (mV)
1	28.8	3	19.6	1.58
2	32.7	3.2	24.5	2.07
3	36.6	3.4	29.4	2.33
4	40.7	3.6	34.4	2.79
5	44.8	3.8	44.1	3.52

Table 3: Experimental Data of WYR Heat Flux Gage A

Times	Voltage (V)	Current (A)	Heat flux (W/㎡)	Voltage reading (mV)
1	28.8	3	19.6	0.176
2	32.7	3.2	24.5	0.213
3	36.6	3.4	29.4	0.239
4	40.7	3.6	34.4	0.286
5	44.8	3.8	44.1	0.373

Table 4: Experimental Data of WYR Heat Flux Gage B

Times	Voltage (V)	Current (A)	Heat flux (W/㎡)	Voltage reading (mV)
1	28.8	3	19.6	0.164
2	32.7	3.2	24.5	0.208
3	36.6	3.4	29.4	0.237
4	40.7	3.6	34.4	0.284
5	44.8	3.8	44.1	0.374

Heat flux gage's coefficient can be determined by calculating the slope of the fitting line. All coefficients of these gages were calculated using software Origin6.0. The analysis also returns values of the errors for "a" and "b", which are denoted as "Δa" and "Δb", respectively. The square roots of the coefficients of determination R also included in the fitting line figures. All results are summarized in table 5 and fitting lines of each gage are plotted in Figure 3, Figure 4 and Figure 5.

Table 5: Results of Calibration

Heat flux gage	a	Δa	b	Δb	R
WYP	-0.978	0.237	12.765	0.4861	0.99782
WYR A	-1.418	0.722	123.61	4.468	0.99592
WYR B	0.699	0.215	120.48	4.616	0.99768

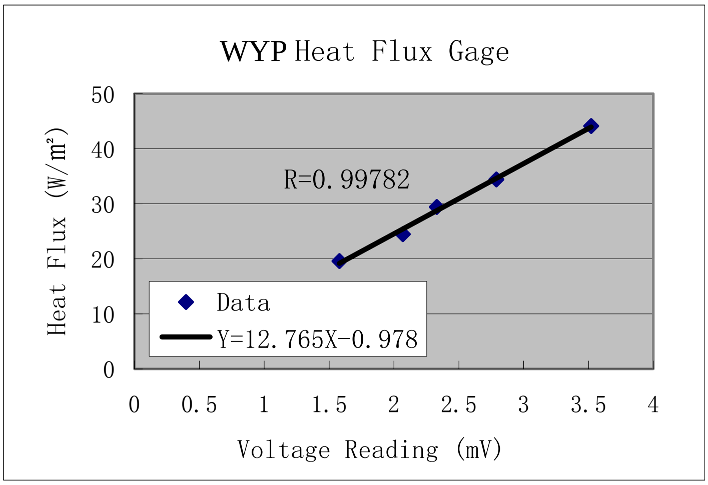

Figure 3: Fitting line of WYP heat flux gage

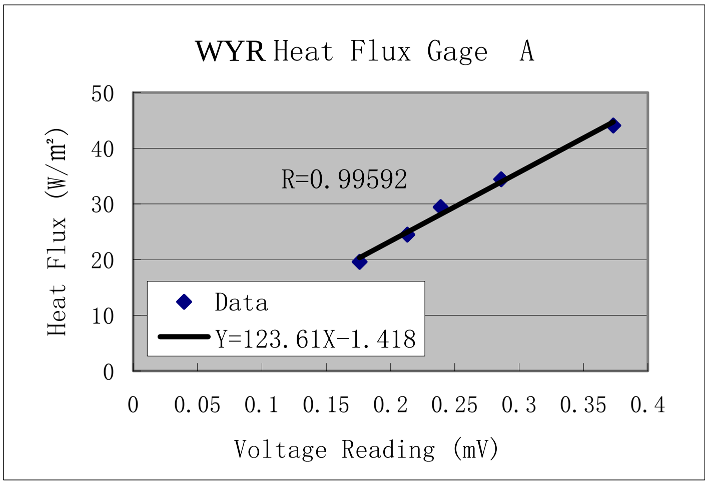

Figure 4: Fitting line of WYR heat flux gage A

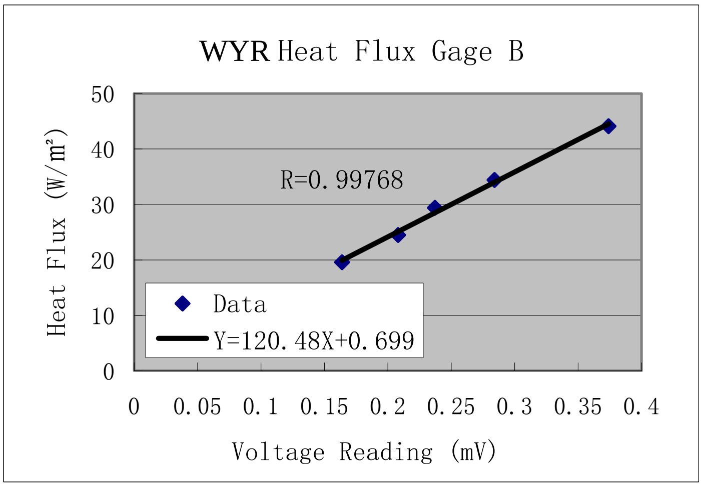

Figure 5: Fitting line of WYR heat flux gage B

Through analysis of the experimental data, coefficients of the heat flux gages were calculated. Compared them with coefficients supplied by the manufacturer, another table was got:

Table 6: Comparison of the Coefficients

Heat flux gage	Coefficient calculated from calibration （W/㎡・mV）	Coefficient supplied by manufacturer （W/㎡・mV）	Difference （%）
WYP	12.765	11.63	+9.76
WYR A	123.6	116.3	+6.3
WYR B	120.48	116.3	+3.59

Through the comparison, we can see that the difference of type WYP heat flux gage is larger, which is +9.76%. Difference of type WYR is relative smaller. The difference is +6.3% and +3.59% respectively. The higher difference of the WYP gage is partly because of its higher precision and higher reflectivity.

5. MEASUERMENT UNCERTAINTIES

There are so many reasons leading to calibration errors and they are summarized as follows:

a) Outside disturbance. During calibration, outside disturbance can cause the changing of the heat flow fields and heat fluxes near the surface of the calibrated gages. It means that the heat flux read from secondary-standard gage isn't the same as that reaching the calibrated gages under the same current. This is a main reason that leads to the calibration errors. Under normal condition, this error could not be eliminated completely. But this error can be partly reduced by calibrating gages in vacuum. Through this way, errors caused by air turbulent can be eliminated and the heat fields near the calibrated gages could be steadier. This conclusion needs to be testified by farther experiments.

b) Unsteady of the heat flux. With time passed, heat produced by the lamp in the metal housing cannot be diffused timely which caused the heat flux reaching the gage surface became higher and higher under the same current. Gages could not be calibrated under a steady heat flux, and then errors appeared. To eliminate this error, length of the calibration time should be controlled. If calibration time lasts too long, temperature and heat flux may be changed. But if time lasts too short, heat flux could not be steady enough to calibrate gages. So, during calibration, we must change the calibrated gages (after their readings are steady) as quickly as possible when the heat fluxes are relatively steady. By this way, we can reduce the influence of the temperature and heat flux increasing caused by the metal housing.

c) Errors of measurement [10]. Because the precision of the calibrated gages is limited, errors of measurement are inevitable. As to the heat flux gage, the response time of these gages is relatively longer and a little long time is needed to get to the steady state. Known from above that the calibration time should not last too long, and then confliction appeared. During calibration, readings of these heat flux gages may not be the true value some times. The differences of these readings cause calibration errors. To reduce these errors, time control is important. A suitable time is needed to balance this confliction during calibration. Otherwise, a higher sensitive secondary-standard gage is necessary too.

d) With the increase of the heat flux, outside disturbance become more and more obvious and its influence increased too. This causes the increasing of the calibration errors at the end of the experiment.

e) Different reflectivity of each gage. As we can see from table 6, all differences of coefficients are positive. It's mainly because of the different reflectivity of each gage. Heat flux was partly reflected by the surface of these gages and heat passed through them is smaller then the true values. That is why the calculated coefficients are higher than those supplied by the manufacturer. Because reflectivity of each heat flux gage is different, so there are calibration errors.

6. CONCLUSIONS

Calibration is a necessary step in the use of the heat flux gages. Therefore, calibration facility is very important. A new calibration facility is described in detail. Through the calibration experiment analysis, conclusions can be drawn that this calibration system has its advantages and reliability on heat flux gage calibrating. It can calibrate different kinds of conductive heat flux gages and has its precision. Using radiation, heat flux applied to gages can be changed easily by changing voltage and current supply of the lamp, which makes the calibration more simple and convenient. Through analysis of the calibration result, suggestions on how to improve calibration precision are given. Because the errors caused by outside disturbance are relatively obvious, this calibration system still needs to be improved and there's still much work to do.

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ABSTRACT

Nowadays, heat flux gages are used more commonly than before, and heat flux gage calibration becomes more and more important. Because each form of energy transfer affects a sensor differently, it is difficult to calibrate a heat flux gage accurately. This paper describes a heat flux gage calibration system and how to use it to calibrate heat flux gages in detail. The system consists of a radiant heater incorporating a lamp, a metal housing and a blackened radiation shield. A small box, open at both ends, is attached over the radiation shield, which was designed to improve the uniformity of the heat flux spatial distribution reaching the gage. The gage is positioned on the far side of the box.

Calibrations are performed using a secondary-standard heat flux gage. An arbitrary heat flux level is set, and after a stable period, response of this gage is recorded. Then replace it with the gage to be calibrated and the response is again recorded. Generally, gage response is characterized at three or more flux levels. The calibration results are fit to a straight line and a linear equation.

Three heat flux gages were calibrated using this approach. Then coefficients of them were calculated and compared with those supplied by the manufacturer. The difference of each gage is 9.76%、6.30% and 3.59% respectively. There are many reasons causing errors. For example, heat flux reaching the gage isn't steady enough because of the environment disturbance. With the time passed, heat produced by the lamp in the metal housing can't be diffused timely which caused the heat reaching the gage's surface became higher and higher under the same current and so on. Each of them can lead to calibration errors. Problems encountered during the experiment have been analyzed carefully and suggestions on how to improve this system are provided. Through the experiment, conclusions can be drawn that this calibration system has its advantages and reliability on conductive heat flux gages calibrating.

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