UNIVERSITY OF ALBERTA

Department of Mechanical Engineering

4-9 Mechanical Engineering Building
Edmonton, Alberta, Canada T6G 2G8

www.engineering.ualberta.ca/mece

Tel: 780.492.3598
Fax: 780.492.2200

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Mr. Ray Ault
Wildland Fire Operations Research Group
1176 Switzer Drive
Hinton, Alberta T7V 1V3

Dear Mr. Ault:

Please find enclosed a hard copy of Progress Report 3 that pertains to our collaborative research project on "Quantification of Energy Transfer from Wildland/urban Interface Fires".

Our next report that presents results from the in-house radiant panel burning of treated vegetative fuel will follow in the next few weeks.

Sincerely,

André G. McDonald, Ph.D., P.Eng.
Associate Professor

ERROR REDUCTION IN THE HEAT FLUX SENSOR

"THERMAL CUBE" USED IN FOREST FIRES

PROGRESS REPORT 3

AUGUST 27th, 2014

PREPARED FOR FPINNOVATIONS

MR. RAZIM REFAI

MR. SHAMMAWI ANDERSON

DR. ANDRÉ MCDONALD

EXECUTIVE SUMMARY

This project focuses on reducing the amount of error in the estimates of heat fluxes that are obtained from the heat flux sensor "Thermal Cube" that was modelled and developed by Erik Sullivan. The original model that accompanied the heat flux sensor produced very high errors for low heat fluxes and lesser, but still significant, errors for high heat fluxes, which are unacceptable in common engineering practice based on experimental results [1].

The percentages of error produced in both the low and high heat flux scenarios were measured by assessing the propagation of uncertainties. The largest error was a result of the errors in the thermocouple (based on the manufacturer's data) for each temperature measurement [1]. The method to reduce the errors that was explored was to measure the temperature difference directly by wiring the thermocouples to read only a temperature difference rather than two individual temperatures. Incorporating this method, it is possible that the error can be reduced by approximately 40% in the case of low heat flux and by approximately 10% in the high heat flux scenario, based on uncertainty percentage calculations.

In an attempt to reduce the error further, other methods were also considered and have been included as recommendations in this report.

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1.0 SYNOPSIS

Due to various factors such as increases in temperature, variability in moisture, and increased encroachment of human population into wildland areas, the frequency of forest fires have increased [1]. Quantifying the energy released from these forest fires to its surroundings is crucial to firefighting safety as well as in the effort to supress wildfires [1]. Thus, a simple heat flux sensor was built and estimates of heat flux from high heat load sources were based on a one-dimensional heat transfer model. However, the heat flux sensor produced significant errors in the estimates of heat fluxes. The purpose of this study was to investigate how to reduce the errors obtained in the heat flux values that were calculated with data from the sensor.

Note: In this report, the data used for the calculations was obtained from [E. Sullivan, Measuring Energy Transfer from Wildland Forest Fires, University of Alberta, M.Sc. Thesis, 2014].

2.0 EXPERIMENTAL PROCEDURE

2.1 Identification of Errors

The initial step to reduce the error in the heat flux sensor was the identification of the source of the errors. The model used to calculate the heat flux was developed by Sullivan [1], and was used as the basis to determine the uncertainties. The model can be seen in Eq. (1) below:

$$q''_{\text{incident}}(t) = \frac{1}{\varepsilon}\left(\frac{k[T(d,t) - T_1(t)]}{(L-d)} + \sigma\varepsilon\left[T(d,t)^4 + T_1(t)^4 - 2T_\infty^4\right]\right), \qquad (1)$$

where

t is time, k is thermal conductivity, ε is emissivity, σ is the Stefan-Boltzmann constant, L is the thickness of the cube, d is the depth into the cube, T_∞ is the surrounding ambient temperature, T_1(t) is the backside temperature, and $T(d,t)$ is the temperature at location d in the cube.

From Eq. (1), it is observed that there are several variables that could be sources of error. In particular,

- The errors in the emissivity and thermal conductivity of the aluminium block were assumed to be zero even though in practice, there would be error in those properties [1].
- The error in the Stefan-Boltzmann constant was taken as zero since its value is well-documented [1].
- The error in the value of the ambient temperature was assumed to be zero [1].
- The positions of the thermocouples (*L* and *d*) were measured by using a tape measure, which has an accuracy of up to 1 mm [1].

- As for the two temperature measurements, the values were taken using two J-type thermocouples. These thermocouples have an error value of 1.1°C, as specified by the manufacturer [1].

The errors associated with the corresponding variables were documented by Sullivan [1], and are shown in Table 1 below.

Variable	ε	k	σ	T_∞ (°C)	$T(d,t)$ (°C)	$T_l(t)$ (°C)	L (in)	d (in)
Error	0	0	0	0	1.1	1.1	0.0394	0.0394

Table 1: Errors Associated with Corresponding Variables [1]

2.2 Methodology

Given that the thermocouples had the largest error amongst all the variables that were taken into consideration, the focus was to change the thermocouple arrangement in an attempt to reduce the errors. The idea employed was to obtain the differential temperature between the front face and the back face of the thermal cube, rather than measuring the individual temperatures of the front face and back face and using them in the heat flux model.

The original thermocouple arrangement is shown in Fig. 1 and it was designed using the J-Type Thermocouple:

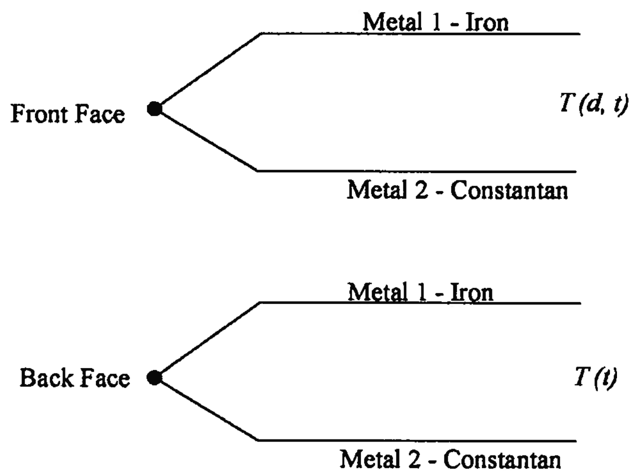

Figure 1: Original Thermocouple Arrangement (J-Type Thermocouple)

To obtain the differential temperature, the two identical metals (constantan) were joined together while the two iron ends were fixed to the thermocouple connector. The cold junction compensation was internally included within the circuit and hence, no external cold junction compensation was required. This specification must not be overlooked as it was crucial in order to attain the correct value of the differential temperature. The voltage difference between the two iron ends corresponds to the temperature difference between the two thermocouple junctions, which represented the differential temperature that was required. This wiring arrangement was tested by using an ice bath and room temperature. This circuit can be used for other thermocouple types as well.

Shown in Fig. 2 is the wiring for the new thermocouple circuit:

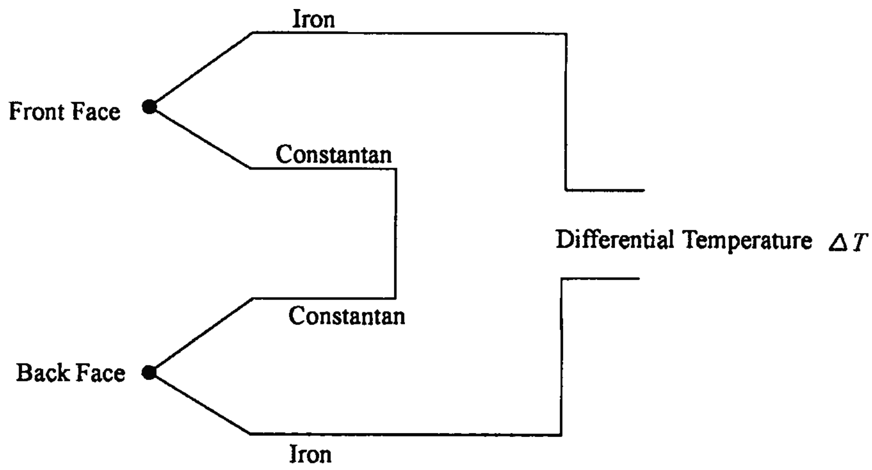

Figure 2: New Thermocouple Arrangement

Most data acquisition systems have built-in cold junction compensation. An option to input a specified value of cold junction compensation was also present. By setting this value as zero, the cold junction compensation was removed. This had to be done so that the cold junction compensation that was present within the new circuit could be applied in the system.

3.0 PROPAGATION OF UNCERTAINTIES

The propagation of uncertainties was determined by Sullivan [1] using the following equation:

$$\left(\frac{\omega_{\dot{q}_{net}''}}{\dot{q}_{net}''}\right)^2 = \left(\frac{\left[(\omega_{T_1(t)})^2 + (\omega_{T(d,t)})^2\right]^{1/2}}{T_1(t) - T(d,t)}\right)^2 + \left(\frac{\left[(\omega_L)^2 + (\omega_d)^2\right]^{1/2}}{(L-d)}\right)^2 + 8\left(\frac{\omega_{T_1(t)}}{T_1(t)}\right)^2 + 8\left(\frac{\omega_{T(d,t)}}{T(d,t)}\right)^2 \qquad (2)$$

The data from a mass loss cone calorimeter test (see Table 2) performed by Sullivan [1] was used in Eq. (2) to estimate the value of uncertainty in the original sensor.

Test	High Heat Flux (64.2 kW-m^{-2})	Low Heat Flux (12.7 kW-m^{-2})
t (s)	67	29
$T(d, t)$ (°C)	125.25	99.83
$T_l(t)$ (°C)	120.08	98.74
L (in)	0.875	0.875
d (in)	0.125	0.125
T_∞ (°C)	22	22

Table 2: Data used to Calculate Uncertainty [1]

The error values obtained upon using the original sensor design for the low heat flux condition was 143% and for the high heat flux condition, it was 32%.

On implementing the new thermocouple circuit and by using the differential temperature, rather than the individual temperatures, the error in the low heat flux condition should reduce to 101% while that in the high heat flux condition should reduce to 22%. A comparison of the results are shown in Table 3.

Thermocouple Circuit	Percentage Error (%)	
	High Heat Flux (64.2 kW-m^{-2})	Low Heat Flux (12.7 kW-m^{-2})
Original	143	32
Differential Circuit (New)	101	22

Table 3: Percentage Errors of both the Original and the Proposed Thermocouple Circuits

4.0 RESULTS AND RECOMMENDATIONS

- By implementing the new thermocouple circuit, the error in the heat flux estimates should be reduced significantly in both the low and high heat flux scenarios.
- To further reduce the error, the J-type thermocouples could be replaced by T-type thermocouples. The T-type thermocouples have a manufacturer-rated error of 0.5°C, which can significantly reduce the error values in the estimated heat fluxes. In the low heat flux condition for the measured data from Sullivan [1], the error can be reduced to 65% while the error in the high heat flux condition can be reduced to 16%. These new

error values are less than half of the initial error values that were obtained with the J-type thermocouples. An issue that arises with the T-type thermocouple, however, is that it can withstand only a maximum of 350°C which, at times, could be lower than the temperatures to which the heat flux sensor would be exposed.

- A change to R/S-type thermocouple would be a more suitable, but more expensive option. The R/S-type thermocouples have a manufacturer-rated error of 0.6°C and using the aforementioned data in this report would yield an error of 78% in the low heat flux condition and 18% in the high heat flux condition which is a significant reduction in the errors obtained from the J-type thermocouple. In additicn, the R/S-type thermocouple can withstand temperatures of up to 1450°C, which is an improvement over the T-type thermocouple.
- Another option to further reduce the error would be to change the material of the cube from aluminium to another material that has lower thermal conductivity. This would provide a larger difference in temperatures between the front face and back face and hence, reduce the error significantly. Material options could be cast iron or mild steel.

5.0 FUTURE WORK

Based on the findings and recommendations from this preliminary study, the next logical step is to perform controlled experiments using the mass loss cone calorimeter and the radiant panel. The proposed differential temperature thermocouple circuit could be designed with R/S- or T-type thermocouples in order to verify the calculated error reduction in the sensor. The heat flux data from the experiments could be compared with that from the original circuit and also the commercially available Schmidt-Boelter Gauge.

Based on the results from the experiments, further consideration can be given to the use of other sensor material that has lower thermal conductivity to reduce the error further to acceptable standards, that is, below 20%.

6.0 REFERENCES

[1] E. Sullivan, Measuring Energy Transfer from Wildland Forest Fires, University of Alberta, MSc. Thesis, 2014, pp. 1-2, 15-26, 62-65.