Thin Film Heat Flux Sensor for Measuring Film Coefficient of Rubber Components of a Rolling Tire

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ABSTRACT: Heat flux is one of a number of parameters, together with pressure, temperature, flow, etc., of interest to engine designers and fluid dynamicists. The ability to measure heat flux magnitude and direction was incorporated into a resistance bridge design fabricated using the thin film techniques to allow fast response. The result is a sensor that does not need the large area and stiff packaging required for the thermopile design nor have its low output, but has nearly as fast response. The development of this sensor offers a new laboratory procedure to establish heat transfer coefficients for different regions of a tire. Testing generated heat transfer coefficients that were within the range reported in the literature, and the numerically predicted temperatures from this data agree well with the experimentally generated values.

KEY WORDS: Tires; Heat flux; Thin films; Heat transfer coefficients; Measuring instruments

Introduction

Accurate heat transfer analysis requires proper measurement of material constants such as heat transfer coefficient (also called film coefficient). The Sensors and Electronics Branch at NASA Glenn Research Center (GRC) in Cleveland, Ohio designed a small flexible sensor that can bend with the tire as it rolls. The sensor measures the temperature and the transient heat flux at the inner and outer surfaces of a tire under dynamometer testing. This new sensor design measures a change in electric resistance instead of temperature difference used in classical thermocouple sensors. This unique feature allows for a smaller size sensor while permitting to raise the level of the signal output.

The new sensor design consists of a resistor bridge fabricated onto a 0.25 millimeter (0.010 inch) thick *Mylar*® polyester film*. The temperature sensitive element is sputter-deposited platinum, patterned and applied using a newly developed photolithography technique at NASA GRC, with line width and line spacing approximately sixty (60)

* *Mylar*® is a DuPont Teijin Films registered trademark for its polyester film. This usage is for identification only, and does not constitute an official endorsement, expressed or implied, by Goodyear or NASA.

micrometers. The variation of platinum's electrical resistance with temperature is well characterized. The ability to measure heat flux magnitude and direction of the thermopile designs was incorporated into a resistance bridge design fabricated using the thin film techniques that allow fast response. The result is a sensor that does not need the large area and stiff packaging required for the thermopile design nor has its low output, but has much faster response.

The development of this sensor offers Goodyear a new laboratory procedure to measure temperature and to establish heat transfer coefficients for different regions of a tire. For NASA, the new sensor can be used in components for process control, modeling validation, determination of cooling requirements, and general calorimetry in rocketry, aerospace, and automotive environments. One specific application is to enable thermal control in advanced multi-use Extravehicular Activity (EVA) pressure suits for future lunar missions. The heat flux sensor is small enough to allow measurement of heat flux of the thermal cooling system as well as the heat flux from various parts of the suit. The correlation of these parameters will give a more accurate estimate of the astronaut's metabolism and any external thermal loading and permit a more rapid adjustment of the suit's cooling system.

Goodyear, with the guidance of NASA GRC, established a procedure to attach flexible copper lead wires to the heat flux sensor. The sensor was glued to a passenger tire (P225/55R16) Eagle RSA. The new mounting procedure allows for multiple use of the sensor. The tire was inflated up to 207 kPa (30 psi), loaded against a drum wheel at 3.34 kN and 5.34 kN (750 lbs, 1200 lbs), and spun to produce a tire speed of 22.35 m/s (50 mph). The whole assembly survived the test procedure. The heat transfer (film) coefficient values were derived from the collected data and compared to the values reported in the literature with a very good agreement.

Discussion

All heat flux sensors operate by measuring the temperature difference across a thermal resistance. There are various designs of heat flux sensors, such as Gardon gauges, plug gauges, and thin film thermocouple arrays. The thin film designs have the advantage of high frequency response and minimal flow disturbance.

The proper measurement of material constants such as heat transfer coefficient (also called film coefficient) requires measurements on curved surfaces over an area that is smaller than the area of sensors currently available commercially. Thus, a design was developed that retains the advantages of the fast response of the thin film sensors, has a larger output and can be made smaller in a flexible package (ref. 1).

A schematic illustration of the double-sided thin film Wheatstone bridge heat flux sensor is shown in Figure 1. A 2-D idealized view of the sensor glued to the tire surface is also provided to serve as a free body diagram for the mathematical modeling of the heat flow.

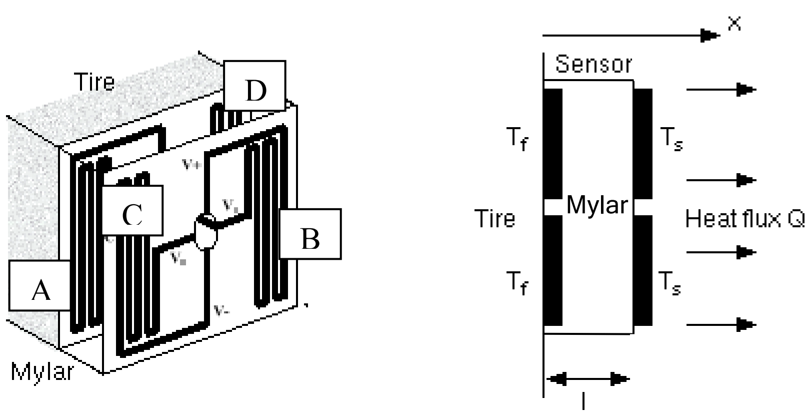

Figure 1. Double sided heat flux sensor schematic

In the absence of heat flux, the temperature at the surface is T_0 and all of the bridge elements (A, B, C, and D in Figure 1) have a resistance R_0. There are four lead wires for the sensor. Two wires provide the excitation voltage ($\leq$100 mV) to the bridge, and the other two wires supply the read out V_1 and V_2 as shown in Figure 2.

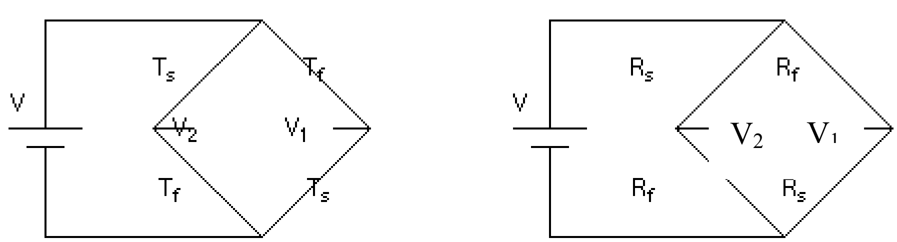

Figure 2. Voltage reading V_1, V_2 due to excitation voltage V

The heat flux Q causes a temperature gradient (T_s-T_f) through the *Mylar*® of thickness l and thermal conductivity k is expressed as follows:

$$Q = -k \cdot \frac{dT}{dx} \cong -k \cdot \frac{(T_s - T_f)}{l} \tag{1}$$

Where T_f is the tire surface temperature, T_s is the sink or ambient temperature, R_s is the resistance of the outside *s* elements and R_f is the resistance of the tire-side *f* elements of the sensor. As the elements of the sensor heat up due to the flux Q, their resistance will change linearly with the temperature as follows where β is the linear temperature coefficient of resistance:

$$R(T) = R_0 \cdot [1 + \beta(T - T_0)] \tag{2}$$

Thus, for the elements under temperature T_s and T_f, the corresponding resistances R_s and R_f can be expressed as follows:

$$R_s = R_0 \cdot [1 + \beta(T_s - T_0)] \tag{3}$$

$$R_f = R_0 \cdot [1 + \beta(T_f - T_0)] \tag{4}$$

The output voltage from each arm is expressed in terms of the excitation voltage V, and the resistances R_s and R_f:

$$V_1 = V \cdot \frac{R_s}{R_f + R_s} \tag{5}$$

$$V_2 = V \cdot \frac{R_f}{R_f + R_s} \tag{6}$$

The instantaneous output from the sensor called V_{SIG}:

$$V_{SIG} = V_2 - V_1 = V \cdot \frac{\beta(T_f - T_s)}{2 + \beta(T_f + T_s - 2T_0)} \tag{7}$$

This expression (eq. 7) can be further simplified by introducing the term R_m defined as the average resistance of R_s and R_f:

$$R_m = \frac{R_s + R_f}{2} \tag{8}$$

$$2\frac{R_m}{R_0} = 2 + \beta\left(T_f + T_s - 2T_0\right) \tag{9}$$

The expression for the heat flux Q can be used to express the difference between T_f and T_s:

$$T_f - T_s = \frac{l}{k}Q \tag{10}$$

The output signal V_{SIG} is then expressed in terms of the heat flux, applied voltage and measured resistance of the sensor:

$$V_{SIG} = V \cdot \frac{\beta\left(\frac{l}{k}Q\right)}{2\frac{R_m}{R_0}} \tag{11}$$

Or, the heat flux as a function of applied voltage and measured resistance and output signal:

$$Q = \frac{V_{SIG}}{V} \cdot \frac{k}{\beta \cdot l} \cdot 2\frac{R_m}{R_0} \tag{12}$$

Ultimately, the film coefficient that gives rise to the convective heat can be expressed as function of the heat flux (Q) being dissipated due to convection and radiation:

$$Q = h \cdot \left(T_f - T_0\right) + \sigma \cdot \varepsilon \cdot \left(T_f^4 - T_0^4\right) \tag{13}$$

Where h is the heat transfer (film) coefficient which varies based on the tire geometry, speed and load and includes any conductive losses through the tire structure, σ is the Stefan-Boltzman constant (σ = 5.67x10^{-8}Wm^{-2}K^{-4}), and ε is the emissivity of the tire (ε = 0.94). By further expanding eq. 13 in light of eq. 12, h can be solved using measured quantities:

$$h=\frac{\frac{V_{SIG}}{V}\cdot\frac{k}{\beta\cdot l}\cdot\frac{2R_m}{R_0}-\sigma\cdot\varepsilon\cdot\left(T_f^4-T_0^4\right)}{\left(T_f-T_0\right)} \tag{14}$$

Further simplifications can be made to eq. 14 recognizing that the difference between T_f and T_s is very small due to the minimal thickness of the sensor (approximately 1.7mK per 1 W/m² of heat flux from eq. 10):

$$h\doteq\frac{\frac{V_{SIG}}{V}\cdot\frac{k}{l}\cdot\frac{2R_m}{R_0}-\beta\cdot\sigma\cdot\varepsilon\cdot\left(T_f^4-T_0^4\right)}{\left(\frac{R_m}{R_0}-1\right)} \tag{15}$$

If the temperature rise in the tire is assumed small compared to the absolute temperature of the environment, a further simplification can be applied to eq. 15:

$$h\cong\frac{\frac{V_{SIG}}{V}\cdot\frac{k}{l}}{\frac{1}{2}\left(1-\frac{R_0}{R_m}\right)}-\sigma\cdot\varepsilon\cdot 4T_0^3 \quad \left[for\left(\frac{T_f-T_0}{T_0}\right)<<1\right] \tag{16}$$

In eqs. 14-16, l is the thickness of the *Mylar*® substrate (l = 0.010 inch), β is the linear temperature coefficient of resistance for the sensor elements (determined in the calibration), k is the thermal conductivity of *Mylar*® ($k = 0.15\text{Wm}^{-1}\text{K}^{-1}$), V and I are the excitation voltage and current applied to the sensor, V_{SIG} is the sensor reading voltage, and T_0 is the room temperature. The bridge resistance R_m is measured by dividing the excitation voltage over the current. The bridge resistance R_0 is measured at the initial temperature T_0.

Calibration

The Sensors and Electronics Branch at NASA GRC fabricated 24 sensors based on the previous discussion of thin film platinum on polyester film. The output of the sensors can be monitored with either one or two meters. If two meters are available at the same time, the following schematic illustration (see Figure 3) of the connecting wires provides both

V_{SIG} and I. However, if only one meter is available, the wiring shown in Figure 4 is recommended.

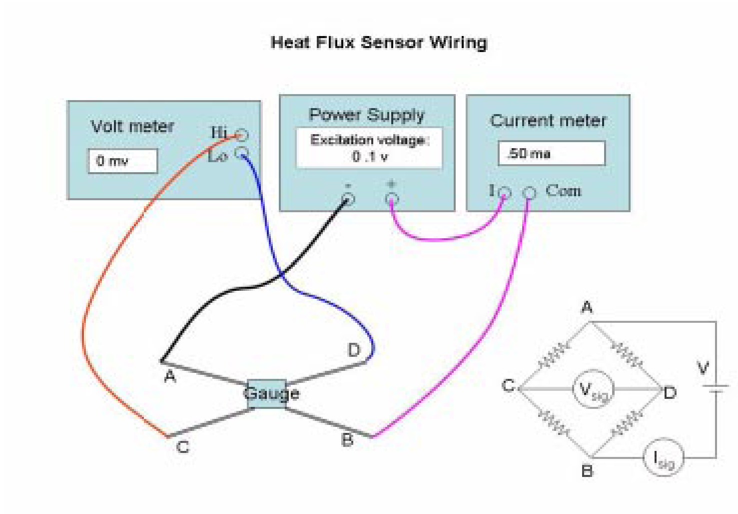

Figure 3. Wire connection with 2 meters

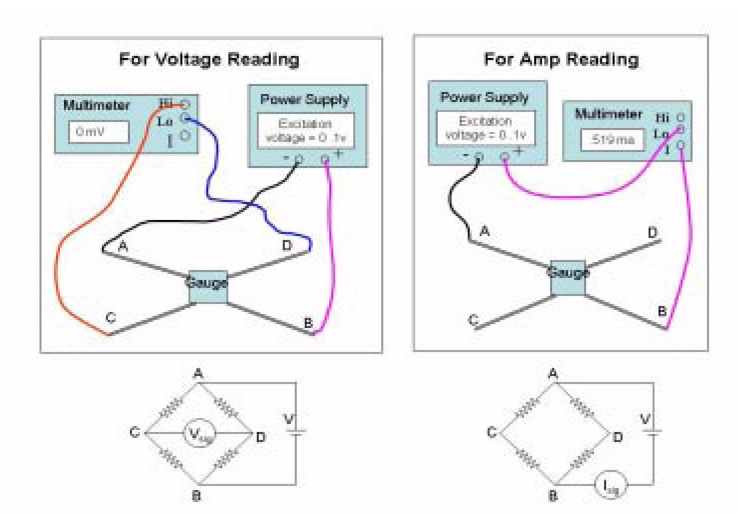

Figure 4. Wire connection with 1 meter

Since the temperatures T_f and T_s are very nearly equal, either quantity can be deduced by establishing a relationship that correlates the bridge resistance to its temperature. NASA GRC fabricated an ANSI Type T (copper vs. copper-nickel alloy) thin film thermocouple on a piece of alumina and attached the heat flux gauge to the alumina using a cement supplied by Goodyear and placed the whole assembly on a hot plate. An illustration of the combined thermocouple and heat flux sensor is shown in Figure 5. The voltage, current and thin film thermocouple temperature were recorded as the temperature of the assembly was changed by the hot plate. With this procedure, a surface temperature calibration was determined from the voltage and the current. For the range of temperatures that is expected from a tire under service condition, a calibration curve was generated as shown in Figure 6.

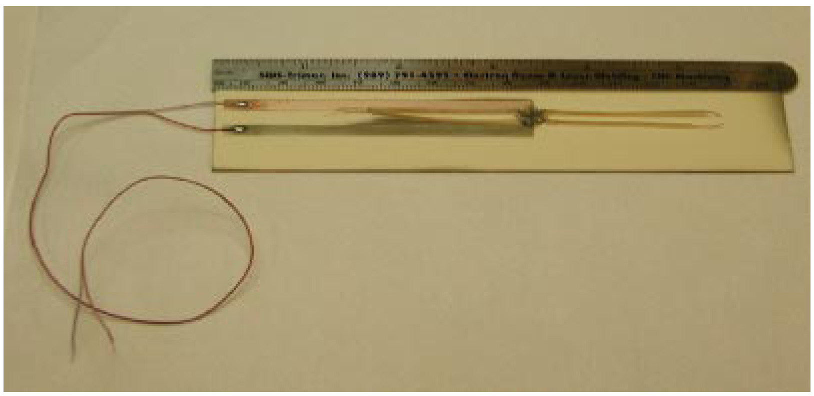

Figure 5. Combined thermocouple and heat flux sensor used for calibrating the bridge resistance vs. its temperature

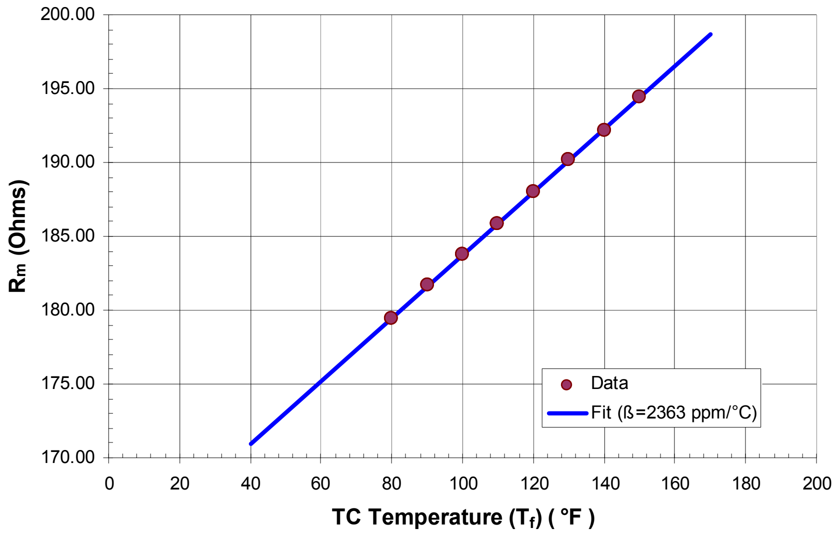

Figure 6. Calibration curve relating bridge resistance to its temperature

Dynamic deformation of a 2-ply composite laminate

As an intermediate step, a sensor was applied to a 2-ply composite laminate undergoing a dynamic deformation (ref. 2). The sensor, which measures 6mm x 6mm (0.25in x 0.25in), was mounted by gluing it to the flat free surface of a 2-ply composite laminate as demonstrated in Figure 7. Goodyear has developed a soldering technique that enables the use of flexible lead wires attached to the four elements of the sensor.

Figure 7. Heat flux sensor mounted on a 2-ply composite laminate

A sinusoidal deformation (1 to 4 mm) was applied at 10 Hz frequency. The hysteretic property of the rubber raised the surface temperature which was monitored by an IR camera. The procedure calls for a power source to supply an excitation voltage V of 100 mV, another voltmeter to measure V_{SIG}, and an ammeter to measure the current I of the excitation source. The set up used in this laboratory test is delineated in Figure 8.

Figure 8. Connection of lead wires from the sensor to the power and reading meters

The primary objective is to calculate the coefficient of heat convection. An intermediate step where the temperature is derived and compared to the IR measurement was considered as a confidence measure. Therefore, the calibration curve was used also to derive the value of the temperature associated with the corresponding resistance. The table shown in Table 1a is a typical collection of the readings collected from the multimeters.

Table 1a. Reading of the voltage V and current I and the change in resistance R=V/I

Cycles	Stroke Control		T_f (IR Camera) (°C)	V (mV)	V_{SIG} (mV)	I (mA)	R_m (Ohms)
	min (mm)	max (mm)					
0	-	-	26.92	97.22	6.032	0.500	194.44
65,400	1	4	32.82	97.32	6.042	0.490	198.61
67,450	1	4	36.75	97.33	6.047	0.470	207.09
71,830	1	4	38.69	97.33	6.065	0.470	207.09
74,725	1	4	39.68	97.42	6.063	0.470	207.28
85,740	1	4	39.72	97.42	6.072	0.470	207.28
83,250	1	4	39.68	97.51	6.075	0.470	207.47

Based on the resistance values, the temperatures at different number of cycles was calculated and compared to the reading registered by the IR camera. In addition, the heat transfer coefficient was calculated as previously demonstrated. The comparison is shown in Table 1b along with the relative difference.

Table 1b: Predicted values of temperature and film coefficients

T(IR)	T (Sensor)	%diff	h (W/m²·K)
103.42	103.20	0.22	4.57
103.50	103.20	0.29	5.81
103.42	103.63	-0.20	6.24

The values of the heat transfer coefficient are very close to what has been reported in the literature (ref. 3) by A. Browne and L. Wickliffe.

Tire inflated & deflected against a rolling drum

The heat transfer coefficient is generally believed to be dependent on rotational velocity (ref. 3). The heat flux generated in a tire is usually considered to be an artifact of the change in strain energy in deforming through a rotation and the tire rotational velocity (ref. 4). Changes to the tire load will induce changes to the strain energy, and the extent of change depends on the region of the tire in question, but in general is a function of the deformation from the pressure load on the tire. As the strain energy is the trace of the strain and stress tensors, changes in strain energy, and thus generated heat flux, is expected to change as a quadratic function of the pressure on the tire. The tire temperature will therefore increase with the higher tire load, allowing investigation of heat transfer at different tire temperatures (T_f). The increase in surface contact of the tread due to the increased load is expected to not influence the heat transfer coefficient measured at the sidewalls.

The sensor was mounted by gluing it to the flat free surface of the upper sidewall of a passenger tire (EAGLE RSA P225/55R16) as demonstrated in Figure 9. The lead wires are attached to a slip ring mounted on the axle of rotation of the tire as shown in Figure 10.

The tire was inflated to 207 kPa (30 psi) and pressed against a rolling drum at a speed of 22.35 m/s (50 mph) to produce a vertical load of 3.34 kN (750 lbs). The same procedure was repeated with a higher vertical load of 5.34 kN (1200 lbs) after the tire was allowed to cool down to room temperature (29 °C).

Figure 9. Sensor glued to rolling tire

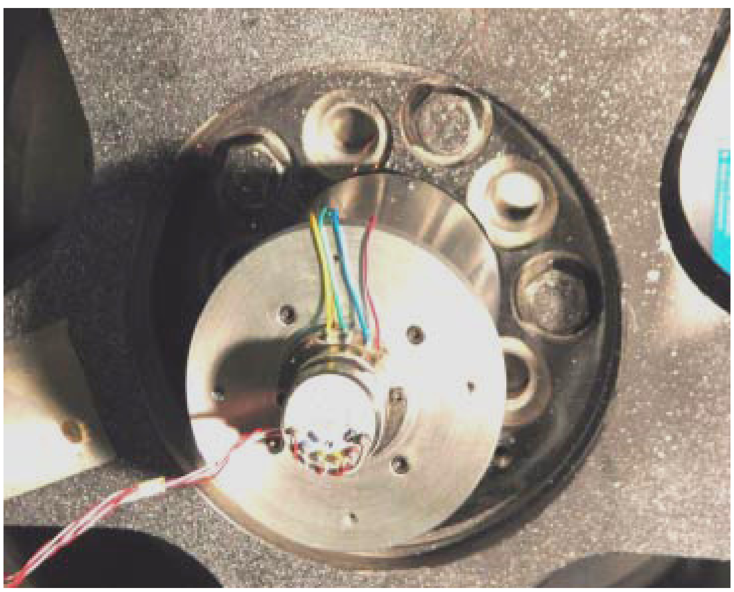

Figure 10. Lead wires attached to a slip ring

Results

The measurements were collected using data acquisition meters comprised of a voltmeter and an ammeter as illustrated in Figure 11.

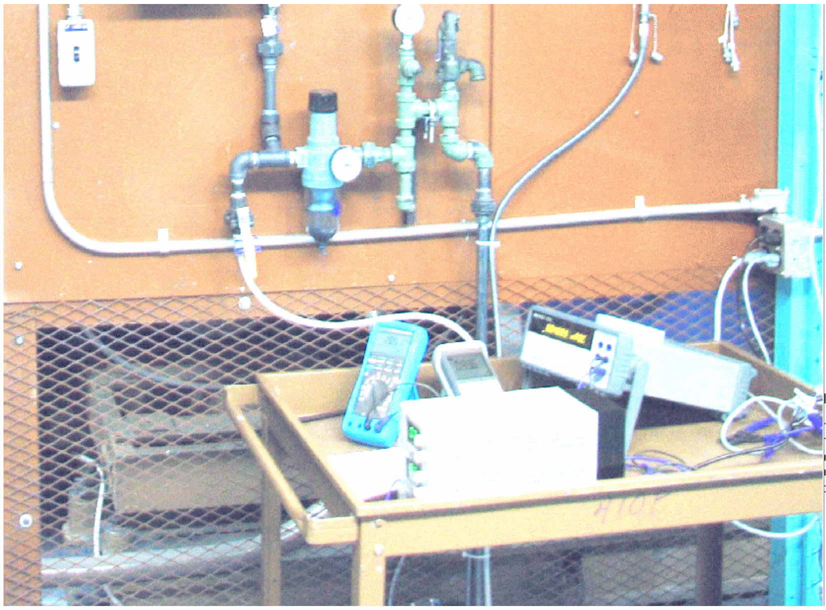

Figure 11. Data acquisition system

The calibration curve was used to derive the value of the temperature associated with the corresponding resistance. Under a light vertical load of 3.34 kN (750 lbs), the voltage V_{SIG} and the current I reached a steady state in a short period of time (20 min) as shown in Table 2. The uncertainty in reading V_{SIG} was ±1 μV, by far the largest uncertainty in calculating h. The speed of the air around the tire near the location of the sensor was not determined. The air flow is assumed to be turbulent and close to tire's speed of 22.35 m/s (50 mph). The values of the heat transfer coefficient shown in Table 2 for data taken after 10 minutes of rolling are on average 76.9 ± 1.8 W/m²K, very close to the 77±5 W/m²K for 22 m/s tire speed that has been reported in the literature (ref. 3) by A. Browne and L. Wickliffe.

To investigate the dependency of the film coefficient on the temperature, the load was increased to 5.34 kN (1200 lbs) while the inflation was kept at 207 kPa (30 psi) and the drum rotation to an equivalent tire speed of 22.35 m/s (50 mph). The duration of the test was not long enough to reach steady-state as evident from the data shown in Table 3. This behavior clearly indicates that the film coefficient is temperature dependent, as shown in Figure 12 with a least squares fit to an Arrhenius function ($h \sim e^{-1/kT}$). However, repeating the test is recommended until the tire reaches a steady-state.

Table 2: Measured data and calculated film coefficients under 3.34 kN (750 lbs) loading

time (min)	V_{SIG} (mV)	I (ma)	V (mV)	R_m (Ohms)	T_f (K)	Q (W/m^2)	h ($W/m^2 \cdot K$)
0	6.006	0.4757	99.7	209.6	302.0	0	-
5	6.027	0.4743	99.7	210.2	303.2	105.6	78.6
7.5	6.033	0.4737	99.7	210.5	303.8	135.9	70.2
10	6.042	0.4731	99.7	210.7	304.3	181.4	72.1
12.5	6.051	0.4726	99.7	211.0	304.8	227.0	75.9
15	6.054	0.4725	99.7	211.0	304.9	242.2	78.6
17.5	6.057	0.4723	99.7	211.1	305.0	257.5	78.6
20	6.057	0.4722	99.7	211.1	305.1	257.5	76.2
22.5	6.057	0.4722	99.7	211.1	305.1	257.5	76.2
25	6.057	0.4722	99.7	211.1	305.1	257.5	76.2

Table 3: Measured data and calculated film coefficients under 5.34 kN (1200 lbs) loading

time (min)	V_{SIG} (mV)	I (ma)	V (mV)	R_m (Ohms)	T_f (K)	Q (W/m^2)	h ($W/m^2 \cdot K$)
0	6.006	0.4757	99.7	209.6	302.0	0	-
5	6.075	0.4713	99.7	211.5	306.0	349	82.4
7.5	6.138	0.4699	99.7	212.2	307.2	670	122.2
10	6.159	0.4688	99.7	212.7	308.2	778	118.9
12.5	6.168	0.4685	99.7	212.8	308.5	825	120.7
15	6.177	0.4681	99.7	213.0	308.9	871	120.7
17.5	6.195	0.4675	99.7	213.3	309.4	964	123.8

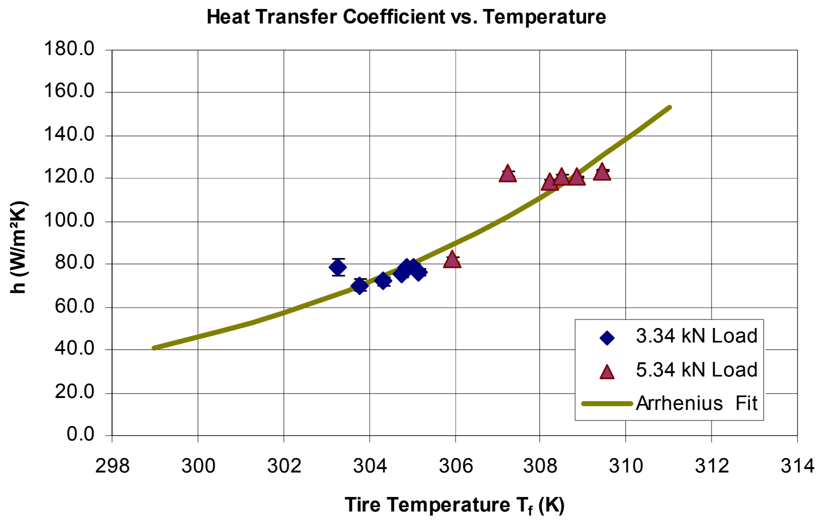

Figure 12: Heat Transfer (Film) Coefficient vs. Tire Temperature T_f.

Summary

The Sensors and Electronics Branch at NASA GRC designed and manufactured thin film heat flux sensors for the purpose of determining the coefficient of convection of the convective part of the heat transfer analysis of a tire. The sensors, which measure 6mm x 6mm (0.25in x 0.25in), are small enough to be mounted within the tread of a passenger tire as demonstrated in Figure 13.

• Goodyear established a procedure to attach flexible copper lead wires to the heat flux sensor.

• A sensor with four lead wires was glued to a passenger tire (P225/55R16) Eagle RSA. The new mounting procedure allows for multiple use of the sensor.

• The tire was inflated up to 207 kPa (30 psi), loaded against a drum wheel at 3.34 and 5.34 kN (750 lbs, 1200 lbs), and spun to produce a tire speed of 22.35 m/s (50 mph). The whole assembly survived the test procedure.

• Heat transfer (film) coefficient values were derived from the collected data and compared to the values reported in the literature with very good agreement.

Figure 14. Heat flux sensor mounted on a passenger tire

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