Experimental Analysis of Errors Induced in Surface Temperature Measurement on Aerospace Vehicle

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Abstract—**Temperature is inherently a transient phenomenon in which heat is constantly flowing from a hotter medium to a colder medium by conduction, radiation and convection. Insulation barriers such as walls, shields, etc., simply slowdown the rate of heat flow, but do not stop it. Accurate measurement of surface temperature is extremely difficult to accomplish because, regardless of type of temperature sensor used for measurement, the temperature sensed is the temperature of the sensor- not the temperature of the surface. This paper presents the possible sources of error in surface temperature measurement using thermocouples and experimental analysis of error due to the cables and connectors used for interfacing thermocouples to signal conditioner.**

Keywords-Aerospace enginest; surface temperature measurement; cement- on thermocouples; sources of error; experimental analysis

I. INTRODUCTION

The continuous development and evaluation of Aerospace components, systems and engines require accurate measurement of surface temperature during testing to aid design. Thermocouples are preferred for this purpose due to its wide ranges, availability of different types, ease handling and simple in construction [1]. As thermal conduction error of probe type thermocouple is dominant, it is less preferred for surface temperature measurement. Thin film thermocouples are mostly used in Aerospace applications due to its fast response time and less perturbation of surface on which temperature to be measured[2].Thin film thermocouples provide a more accurate measurement of the actual surface temperature due to its negligible thermal mass[3]. Exact surface temperature can be measured only when the surface of interest, the surrounding and the instrumentation are in thermal equilibrium. Any thermal gradient will induce measurement errors as a result of flow of heat. In the Aerospace application, achieving thermal equilibrium is difficult due to design limitation and transient temperature measurement. Hence, the sensor output represents a balance of the following conditions.

- Heat transferred to the sensing element
- Heat stored by the element
- amount of heat lost to the surrounding environment.

For transient surface temperature measurement the information from the sensor need to be corrected using dynamic calibration data [4].However, location of the temperature sensor, attachment method and test methodologies affect the validity of the data [5].Miniaturized thermocouples are preferred in thermoplastic process to measure temperature in the depth and at the surface of the injected thermoplastic parts due to its less conduction error [6].

II. SURFACE TEMPERATURE MEASUREMENT

A. *Temperature Measurement Chain*

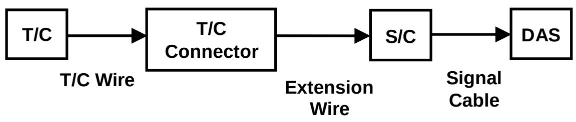

Figure 1. Temperature measurement chain

Measurement chain contains thermocouple, thermocouple connector, interface cable, signal conditioner and data acquisition system [7]. Cement on thermocouple is preferred in surface temperature measurement due to its flexibility to bond even on curved surface and less perturbation of surface on which temperature to be measured. Proper selection of thermocouple connector and extension wire suitable to the thermocouple is required to minimize the error [8]. Extension wire is a cable used to interface and carry thermocouple output to the signal conditioner. Thermoelectric characteristics of the selected extension wire must be as close as to that of the thermocouple being planned for measurement [9]. Signal conditioner is an interface between thermocouple and Data Acquisition System (DAS). It provides reference junction, compensation, linearization, amplification and band limitation to record correct data. Data Acquisition system is used to monitor/ record thermocouple output.

B. *Construction of Cement-on Thermocouple*

Cement-On thermocouple is a foil sensor. It is embedded between two papers thin; glass reinforced high temperature polymer laminates. Thermocouple leads are electrically insulated from each other as well as being mechanically supported. Lamination also provides a flat surface for cementing. Glass braid insulated 30 gage thermocouple wire is bonded to the foil and strain relieved by laminate to minimize the error due to thermocouple junction interface. It is suitable for bonding on curved and plain surfaces. The polymer/glass laminate limits the maximum temperature of the thermocouple up to 260°C continuous and 370°C for short time about 10 Hours. The response time of the thermocouple varies from 5 to 300 milli seconds depending on the style of construction [10].

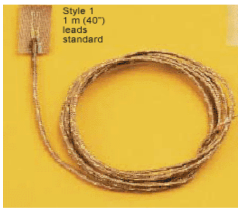

Figure 2. Foil sensor

C. *Principle of Thermocouple*

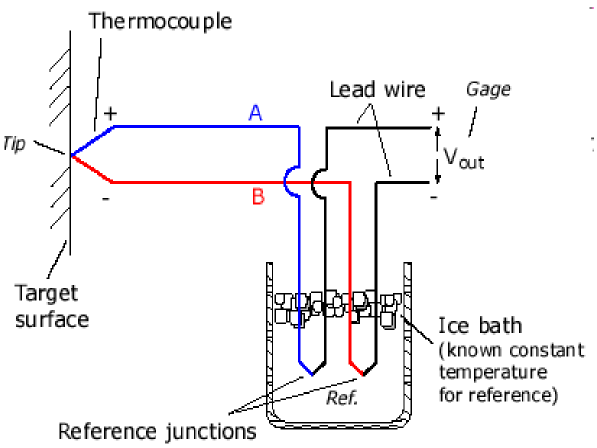

Figure 3. Principle of thermocouple

Thermocouple works on the principle of Seebeck effect. When two dissimilar metals are joined together to form two junctions and if temperature gradient occurs between those two junctions then an emf is generated proportional to the temperature gradient provided the circuit is open [11]. In Fig.3, one of the junction is kept in ice bath (Cold/Reference Junction) and another junction is fixed to the target surface for measuring temperature (Hot/Measuring Junction).Thermocouple produces output voltage proportional to the difference of temperature between measuring and reference junctions [9].

D. *Calibration of Thermocouple*

Figure 4. Surface temperature calibrator

Surface Temperature Calibrator is preferred to calibrate cement on thermocouple due to its uniformity of temperature on calibrator surface and multisensor calibration feature [12]. Calibration range varies from ambient temperature to 300^0 C with an accuracy of ± 1^0C. It has a built in reference sensor to display the calibration surface temperature. Calibration procedure as per ASTM E220 standard is preferred to maintain traceability [13].

III. Sources of Errors

Various attributing elements/ factors introduce errors in the surface temperature measurement of the Aerospace components during testing of Aerospace vehicle for its performance evaluation [14].

- Thermocouple
- Extension wire
- Connector Temperature
- Temperature gradient of T/C connectors
- Measuring instrument's error
- Bonding/Installation error
- Polarity reversal

IV. *Extension Wire*

Extension wires/compensation wires are used between measuring junction and the reference junction to avoid multi junction formations which act as additional EMF generators. It is necessary to select extension wire and connectors having same thermo electric characteristic as the thermocouple for the entire temperature range. Generally, copper cable and compensating cable are used to interface thermocouple to signal conditioner if the reference junction is a long distance away from the measuring junction. In some cases, thermocouple wire is used as interface cable where the ambient temperature is adverse in nature.

V. *Thermocouple Connector Temperature*

Thermocouple Connector needs to be selected according to the measuring thermocouple to interface thermocouple wire to extension cable without introducing additional EMF generators. The temperature of the connector may affect the measurement if proper extension wire is not selected.

VI. *Temperature Gradient of Connector Terminals*

It is generally assumed that a negligible temperature difference exists across the connector terminals but, in aerospace applications, if proper care in not taken to thermally Isolate thermo connectors from the test article, possibility of temperature gradient between connector terminals occurs and affects the measurement. There are two possibilities on which temperature gradient across connector terminals exist. Connector either body of the connector near to negative terminal touches the body of the test article and positive terminal at ambient temperature or body of the connector near to positive terminal is in contact with the body of the test article and negative terminal at ambient.

VII. *Polarity Reversal of Connector Terminals*

When the polarity of the wires is reversed, it causes an error related to the ambient temperature. Although it would be detectable, a double reversal could likewise a cause an error which may not be so easily noticed.

VIII. Test Results and Discussions

Surface Temperature Calibrator is used to explore the possible errors due to compensation cable and copper cable when the interface junction is subjected to be different temperature. Three temperature measurement chains with different extension wires between thermocouple and signal conditioner were configured and calibrated to study the effect of interface cable on temperature measurement due to interface junction temperature. Thermocouple interface connections (thermocouple connectors) were kept in thermal chamber to vary the ambient of thermocouple connectors from -30°C to 100°C.

TABLE 1. Calibration data with connector at 25°C

T°C	**T1°C**	**T2°C**	**T3°C**
25	26.2	25.6	4.8
50	51.6	51.4	30.4
100	101.0	101.6	81.6
150	151.5	150.3	133
200	201.8	201.4	180

T- Calibrator Temperature
T1- Configuration with thermocouple wire
T2- Configuration with compensating cable
T3- Configuration with copper cable

From Table.1, it is clear that the calibration results of three configurations are within the specified error limit when the thermocouple connectors are kept in ambient temperature around 25°C.

TABLE 2. Calibration data with connector at 50°C

T°C	**T1°C**	**T2°C**	**T3°C**
25	25.4	25.8	85.2
50	50.8	50.5	110.3
100	100.4	99.6	159.2
150	150.2	149.8	210.1
200	201.2	199.5	258.2

TABLE 3. Calibration data with connector at 70°C

T°C	T1°C	T2°C	T3°C
25	25.8	25.4	26
50	51.2	51.6	51.8
100	99.8	101.7	101.4
150	150.4	150.8	150.2
200	201	201.4	202.2

TABLE 4. Calibration data with connector at 100°C

T°C	**T1°C**	**T2°C**	**T3°C**
25	25.8	26.1	-16.6
50	51.3	51.7	+8.2
100	101.6	101.2	56.8
150	150.8	150.6	105.8
200	201.4	201.7	158.8

From the tables 2-4, copper cable is not suitable for temperature measurement if the connector temperature exceeds 40°C. In case of T3 configuration, measurement error increases as the thermocouple connector temperature increases. But the calibration data pertaining to other two configurations (T1&T2) are within the tolerance limit irrespective of thermocouple connector temperature.

TABLE 5. Calibration data with connector at-30°C

T°C	**T1°C**	**T2°C**	**T3°C**
25	25.6	25.4	-34.8
50	50.6	49.4	-6.2
100	98.8	99.4	+42.4
150	150.7	151.2	88.7
200	201.2	199.7	141

From table 5, it is evident that T3 configuration read more than the calibrator temperature when thermocouple connector temperature is -30°C.But other two configurations read close to the calibrator temperature.

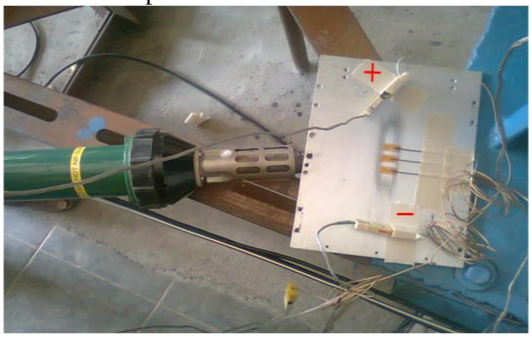

Figure 5. Experimental set up

An experiment was carried out on three temperature measurement chains of configurations as shown in Fig.5 to analyze the error due to the temperature gradient across thermocouple connector terminals. Fig.6-8 displays the deviation of temperature data among the three configurations.

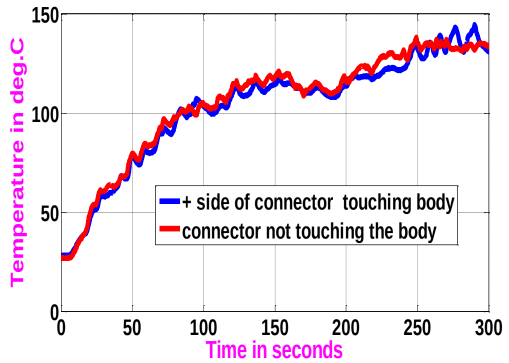

Figure 6. Deviation due to connector side (+) touches body

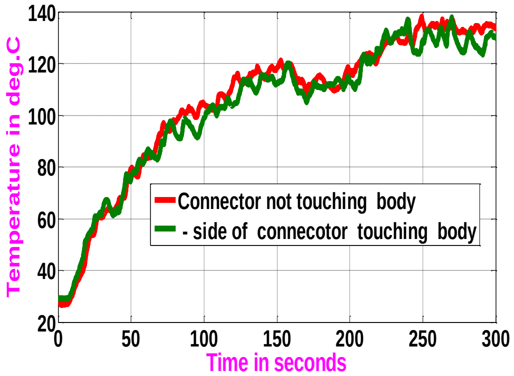

Figure 7. Deviation due to connector side (-) touches body

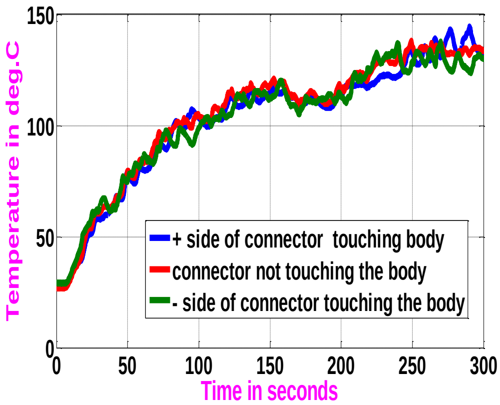

Figure 8. Deviation due to connector side (+/-) touches body

Calibration of thermocouple with reverse polarity was carried out using surface temperature calibrator to determine the formula for correcting the error due to polarity reversal. From the calibration results shown in table 6, correct data can be achieved from polarity reversal thermocouple data using the Eqn. (1)

$$T_c = 2 * T_a - T_p \qquad (1)$$

T_c - *Corrected data (°C)*
T_a - *Ambient temperature (°C)*
T_p - *Polarity reversed thermocouple data (°C)*

TABLE 6. POLARITY REVERSED THERMOCOUPLE DATA

Calibrator Temperature °C	**T1°C (without Polarity Reversal)**	**T2°C (with Polarity Reversal)**	**T2°C (corrected Data)**
30	30	30	30
60	60	0	60
90	90	- 30	90
120	120	- 60	120

As a case study, an additional temperature channel (thermocouple) with polarity reversal of wire was recorded along with other temperature channels during static testing of aerospace vehicle. Fig. 9 shows the deviation between the polarity reversed thermocouple test data and near location test data.

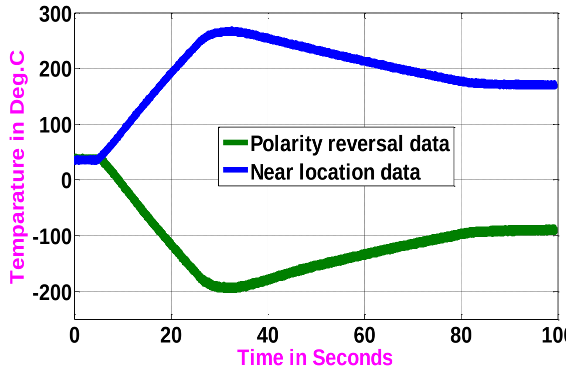

Figure 9. Polarity reversed thermocouple data profile

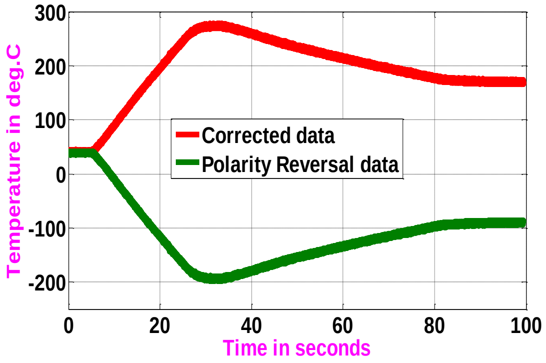

Figure 10. Corrected data profile

Fig.10 shows the profile of corrected data using Eqn.1. Corrected data profile is a mirror image of polarity reversed data about the ambient temperature. Fig.11 highlights the closeness of corrected data with respect to near location data.

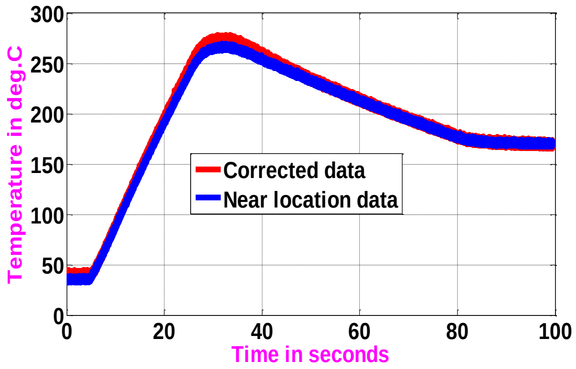

Figure 11. Comparison of corrected and near location data profile

CONCLUSION

Temperature measurement errors due to interface elements with different possible configurations and environments have been analyzed with experimental results. Extension wire and thermocouple connector suitable to thermocouple need to be selected to minimize the error due to additional EMF generators. Copper cable can be used as an extension wire provided the thermocouple connector temperature is below 30°C .Incase, compensating cable/thermocouple wire is used as extension wire, connector temperature up to 100°C, may not affect the measurement accuracy as long as temperature gradient across connector terminals is zero. As any temperature gradient leads to inaccuracy of measurement, it is necessary to thermally isolate junction of thermocouple connector and extension wire from adverse temperature in testing of aerospace engines. Though, correct data can be derived from polarity reversal data, it is recommended to avoid polarity reversal by heating/cooling the thermocouple junction before test. However, double polarity reversal cannot be identified easily; care must be taken while interfacing thermocouple to signal conditioner.

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