Integrated Thermal Monitoring for Cryogenic Engine Gas Generator and Turbopump Operation

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Abstract

In cryogenic rocket propulsion systems, accurate and real-time temperature feedback is critical for closed-loop control of key subsystems like gas generators and turbopumps. These components operate under extreme conditions—high pressures, rapid transients, and oxidizer-rich environments—which pose significant challenges for sensor reliability and data acquisition. Thermocouples are widely used in industry for temperature measurement in corrosive, high temperature environment due to its low cost, ruggedness and wide operating temperature range. This paper presents the design, validation, and integration of a dual-element K-type thermocouple-based temperature sensor tailored for feedback control loops in gas generator outlets. The sensor is optimized for high-frequency response, redundancy, and robustness—critical for maintaining thermal stability, protecting hardware, and enabling real-time propulsion system control. A dual element K-Type thermocouple-based temperature sensor is designed which can be used upto 1473 K and 600 bar. INCONEL sheathed thermocouple was used to design the sensor and the sheathed junction with minimum thermal inertia was exposed to the fluid for faster response time. The packaging is done in such a way the sensor can withstand extreme environmental conditions. A series of environmental tests were carried out simulating the extreme environments faced by the sensor in gas generator outlet of cryogenic engine that produces around 20 tons of thrust in vacuum condition.

Key words: Thermocouple, Cryogenic, gas generator, turbine, Seebeck coefficients, Calibration, response time, Qualification

Nomenclature

mV/µV	Millivolt/ Microvolt
GG	Gas Generator
ms	Millisecond
MEOP	Mean Operating Pressure
MPa	Mega Pascal

1. Introduction

In industries especially aerospace sector which involves high temperatures and pressures, precise temperature measurement is crucial for ensuring efficiency, safe, and reliable performance of the system. In case of rocket engines, added extreme environmental conditions along with high temperature and pressure, makes the design of sensor crucial for reliable performance of the engine. Modern cryogenic propulsion systems rely on closed-loop control for optimizing thrust generation, mixture ratio, and turbopump efficiency. Precise thermal data from subsystems like the gas generator—which powers turbopumps—and turbine inlet/outlet lines is essential to implement effective control algorithms, fault detection, and health monitoring. The thermal sensor thus functions as a system-critical node in the engine's feedback architecture. Generally, for high pressure and high vibration environment, RTDs are preferred because of simpler design and no need for cold junction but their application is limited to 600 oC [1, 2]. Other technologies like thermistors or Semiconductor based sensors also fail to perform reliably at extreme temperatures [2,3,4]. Among the various types of temperature sensors available, thermocouples stand out as reliable and versatile instruments capable of withstanding extreme conditions specially oxidizing environment present in Gas generator outlet of cryogenic engines which operated in oxidizer rich GG cycle [5,6,7,8].

K-type thermocouples are among the most widely used thermocouple types due to their broad temperature range, low cost, high accuracy, and robustness. They belong to the family of basemetal thermocouples, consisting of two different metallic wires, Chromel (90% nickel and 10% chromium) and Alumel (95% nickel, 2% manganese, 2% aluminum, and 1% silicon). When these wires are joined at one end, a thermoelectric circuit is formed, generating a voltage proportional to the temperature difference between the junction and the reference point (usually at 0°C) [5,6].This potential difference, measured in millivolts (mV), is directly proportional to the temperature difference between the hot and cold junctions according to the thermoelectric law. The measured voltage as per thermoelectric law governing the behavior of thermocouples can be expressed by the equation [9]:

$$\Delta V = \int_{Tref}^{Tsens} (S_+(T) - S_-(T))\, dT$$

Where, S+ and S-are the Seebeck coefficients of the conductors attached to the positive and negative terminals of the voltmeter, ΔV is the generated voltage, S(T) is the Seebeck coefficient, representing the voltage generated per unit temperature difference and dT is the temperature gradient along the length of the thermocouple.

K-type thermocouples offer several advantages that make them well-suited for high-temperature and high-pressure applications. They have wide temperature range ranging from -200°C to +1,372°C, making them suitable for extreme environments encountered in industrial processes such as metallurgy, aerospace, and petrochemicals. They have high accuracy, fast response time to temperature changes and they are very cost effective and widely available sensors. With their simple construction and durable materials, K-type thermocouples are resistant to vibration, mechanical shock, and chemical corrosion, making them reliable in harsh operating conditions [5].

The robustness and versatility of K-type thermocouples make them invaluable in a wide range of industrial applications like, Furnaces and Kilns, Heat Treatment processes such as annealing, tempering, and quenching, Petrochemical Industry for monitoring and controlling temperatures in reactors, furnaces, pipelines, in Power plants for monitoring boiler temperatures, turbine exhaust gases, in Aerospace and Automotive for measuring exhaust gas temperatures, engine temperatures, and thermal management systems where high-temperature resistance and accuracy are essential, and other high-temperature components to ensure efficient and safe operation.

2. Design of K-Type Thermocouple based sensor

The design of K-type thermocouples is crucial for their performance and durability in extreme environments. The sensor must provide accurate, high-speed data to the engine controller for thermal regulation of the gas generator and turbopump inlet temperature control. From a control engineering perspective, sensor dynamics should not lag system transients, making response time (<250 ms) and low thermal inertia essential. Key design elements include:

2.1Thermoelements: K-type thermocouples consist of two thermoelements, each made of a different metal alloy. Chromel serves as the positive leg (+) and Alumel as the negative leg (-). These thermoelements are usually thin wires, typically around 0.05 to 0.5 mm in diameter, to facilitate fast response times and minimize thermal lag.For applications where sensor has to see high pressure and temperature, casing is provided over the thermocouple bead, however, in the process of transient temperature measurement, due to the large thermal inertia of the casing thermocouple, the measured temperature lags behind the actual temperature. Casing thermocouples with less thermal mass tended to have quicker response to the temperature change and apparent effect on the maximum temperature when measuring the vapor fluid [10]. Nick et. al. [11] indicates that the effect of conduction is inversely proportional to the thermocouple junction size-an effect attributed to changes in the thermal inertia of the device. So, for transient temperature change, the thermal inertia is expected to be smaller to obtain quicker response. Wang et al. [12 invented a T-type casing thermocouple with bared thermal junctions and improved its armored structure. He shortened the response time of the thermocouple to 40 ms.

2.2 Junction Types: In order to have fast response while withstanding high temperature and pressure, INCONEL sheathed junction K-Type thermocouple is selected. The junctions of K-type thermocouples can be either grounded, ungrounded, or exposed. In grounded junctions, the thermoelements are welded together and directly exposed to the measurement environment. In ungrounded junctions, the thermoelements are welded together but electrically insulated from the surrounding environment. Exposed junctions have the thermoelements exposed to the environment without any insulation or protection. To have better accuracy and high Insulation resistance (> 100 MΩ), the sensor tip is brazed with the tube for grounded connection. To enable fail-operational control in redundant avionics systems, a dual-element configuration is adopted. Both thermocouples are routed to independent signal chains, supporting diagnostics, cross-verification, and controller-level logic switching in case of single-channel failure.

2.3 Sheath Material: In high-temperature and harsh environments, K-type thermocouples are often housed within protective sheaths made of stainless steel, Inconel, or other heat-resistant alloys. The sheath material provides mechanical strength, corrosion resistance, and thermal insulation for the thermocouple wires. The sheath material used in INCONEL for high pressure and high temperature application.

2.4 Insulation: Insulation materials are used to protect the thermocouple wires from external influences such as moisture, electrical interference, and mechanical damage. Common insulation materials include ceramic beads, mineral oxides, and glass. The inside of the sheath is filled with alumina for temperature resistance (upto 1700 ^{O}C), thermal shock resistance, chemical resistance, gas tightening, electrical wire protection and soldering protection. It is also a good refractory material which reduces error due to radiation heat loss.

2.5 Heat Transfer: From heat transfer point of view, the sensor can have errors originating due to Convective heat transfer, Conduction, Radiation. The accuracy of the temperature measured by thermocouples are highly affected by the velocity and heat transfer and it plays a dominant role in the thermocouple as flow velocity increases [13]. Also, the error can be there if the sensor is not reading the stagnation temperature due to the flow conditions around the sensor because of the sensor position with respect to flow [8]. In order to minimize the errors due to convection, the tip diameter of the sensors is kept very small (1 mm) and it is kept exposed to achieve high convective heat transfer. Error due to conduction along the wire is minimized by filling the sensor sheath tube of alumina powder which is good insulator and also provides refractory properties to reduce the radiative heat lost to the cooler surfaces of the chamber wall. Sufficient probe length is provided so that the sensor tip is far away from boundary layer, avoiding any errors due to boundary layer effect and stagnation temperature can be measures accurately.

Parameter	Value
Temperature range	73 K to 1373 K
Thermocouple type	K-type (Chromel-
Construction	Exposed/ Grounded
No of thermocouple	2 nos.
Response Time	<0.25sec
Pressure Max	60 MPa

Table 1: Targeted specification of the sensor

The sensor has to perform reliably upto 1000 ^{O}C with very high accuracy and fast response time hence, a grounded design and exposed sensing element is chosen. As mentioned earlier the sensor has to work upto 600 bar pressure so based on these requirements a broad specification was worked out for the sensor as mentioned in Table 2.

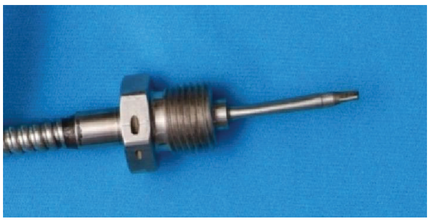

Figure 1: Sensor Assembly

The sensor was designed with 2 thermocouple beads for monitoring the gas temperature through 2 independent channels. This sensor is designed as a one-piece unit. Sensitive element is a K-type thermocouple with flexible cable and it is having a 0.7 mm jacket with 0.16 mm diameter thermo electrodes. The thermocouple junction has electric and thermal contacts with the thermometer's body. As seen in figure 1, the sensor consists of two elements which are brazed at 1100 ^{O}C. The details of theconstruction and analysis is described in next section.

Figure 2: Stem (left) &Mounting Head (right)

3. Sensor Construction

3.1 Sensor parts: The sensor used a K-type thermocouple.The K type thermocouples used for the sensor has the Seebeck coefficient to 41 µV/°C which is as per ASTM E230 standard. Thermocouple sheath material is INCONEL which is filled with Alumina powder for electrical insulation.Stemis the housing portion for the sensing elements (K type thermocouple - 2nos). The sensing elements are inserted into this part and vacuum brazed at the end. Then the mounting head as shown in figure 2 is welded with the stem by Electron beam welding. The mounting head also contains M14 threads used for mounting the sensor along with wire locking provision for reliable assembly into the system under extreme environmental condition including high vibration levels.The lead wires are then through a flexible coupling. The purpose of flexible coupling is to facilitate the mounting of sensor inside the engine which is difficult to access because of intricate plumbing of feed line to the engine. The coupling is done through coupling holders at both the ends of flexible coupling tube.Figure 3 shows different parts and various operation carried out on the sensor for the assembly.

Since the sensor has to operate upto 1000 ^{O}C, sensors were vacuum brazed with the tube at 1100 ^{O}C.

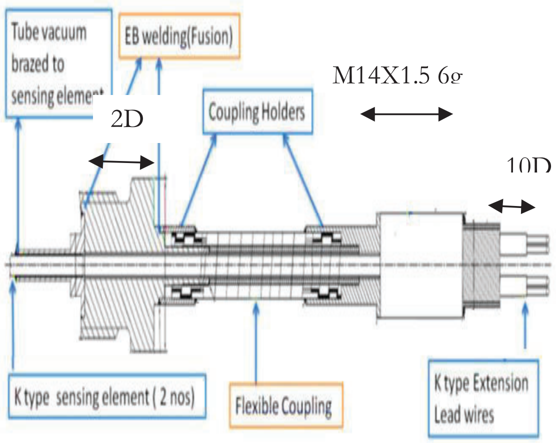

Figure 3: Sensor assembly schematic

All the parts were EB welded for high strength and hermetic sealing. EB welding will also ensure long shelf life for the sensor and prevent moisture from entering the inside of the sensor.

3.2 Material selection and structural factors

Initially the sensor was fabricated and tested with MDN 321 material as it is compatible with cryogenic fluids but the sensor failed to meet the structural integrity requirement at 600 bar. The main reason for the failure was low yield strength (~190 MPa) and low UTS (~500 MPa). During

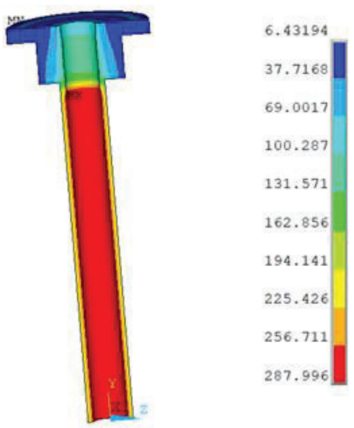

Figure 4: Stress contours (MPa) at 600 bar

the structural analysis it was found that maximum stress at MEOP of 600 bar was 288 MPa which is well below the yield strength of MDN321. This caused the sensor housing tube to buckle. However, the sensor was working even with the bucked tube but considering the critical requirement of the sensors in closed loop control of the engine, the material was then replaced with precipitation hardened steel which has yield strength of more than 900 MPa compared to 190 MPa for MDN 321. UTS is also much higher at 1050 MPa.

Structural analysis for the sensor was carried out by invoking geometric and material non-linearity forprecipitation hardened steel. Maximum stress at mean operating pressure of 600 bar was 288 MPa which shows enough positive margin at MEOP. Stress plots are shown in figure 4. Similar analysis was done to establish proof pressure (1.5-times MEOP) and Design Ultimate Pressure (2 times MEOP) and positive margins were available at this pressure as well. Maximum stress at 900 bar was 431.72 MPa and maximum stress at 1200 bar was 575.26 MPa.

4. Thermo-Mechanical Validation

From the systems perspective, the sensor is part of the engine's sensory feedback matrix.

Its performance affects the thermal control loop bandwidth, Kalman filter estimations, and real-time failure detection systems. The developed sensor has to operate under sever environmental condition as described in previous section. It is thus validated through tests exceeding mission profiles. In order to ascertain the consistent performance, the sensor was subjected to a series of test as list below which was harsher than the actual condition faced by the sensor in the engine. After each test electrical checks were performed on the sensor to ensure sensor integrity.

4.1 Electrical checks and reference static calibration: Initially reference electrical checks were performed and the sensor resistance was around 22 Ω and insulation resistance was more than 100 MΩ. Calibration was carried out at 0^0C, 100^0C, 200^0C, 300^0C, 400^0C, 500^0C & 800^0C on 2 sensors. Errors of the two elements of the two no. of sensor taken up for reference calibration are shown in Figure 5.

During the calibration, sensor was meeting ASTM E230 specifications for error (± 2.2 ^{O}C or 0.75% of reading).

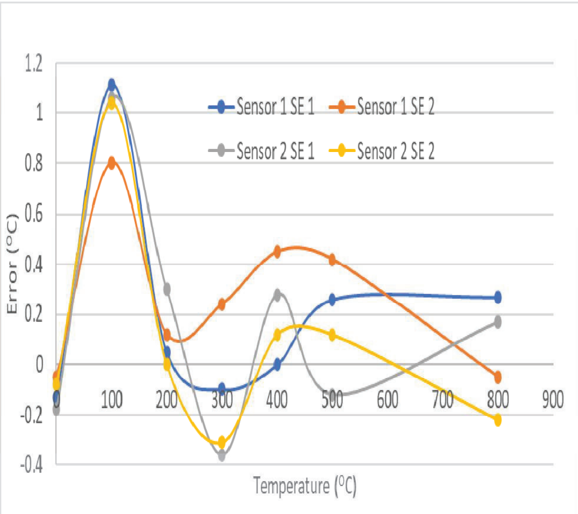

Figure 5: Error evaluation during Reference calibration before the testing

4.2 Proof Pressure Test and Thermal Cycle test (SRC to LN2): Subsequent to the calibration, sensors were subjected to 3 cycles of proof pressure test upto900 bar with a hold time of 3 minutes which is twice the operating pressure and duration of actual application. The senor as subjected to 10 cycles of thermal cycling between room temperature and Liquid nitrogen.

4.3 Vibration and Shock test: Since the targeted application for the sensor is a gas generator of Cryogenic engine, the influence of environmental variables such as vibration and shock on calibration retention is important. The impact of vibration on the static calibration of the sensor has been determined by using an electro-dynamic shaker to generate known levels of vibration and shock as per launch vehicle requirements.

An initial static calibration of the sensor under test was obtained (shown in figure 5) before subjecting it to vibrations of particular magnitude, frequency and duration. The sensor was mounted on the shaker face-plate and subjected to sinusoidal and random vibration then shock test was done at the levels 1.5 time the level experience by the senor in actual operating condition. The static calibration of the sensor was then repeated at the end and the two data were compared. The sensor appears to show no evidence of being affected by the vibration, with the difference in repeat calibrations being similar to the variability seen in initial static calibrations shown in figure 7. Finally, the sensor was subjected to vibration and shock test. Sensor was subjected for 19 grms Random vibration from 20 to 2000 Hz & sine vibration tests from 10 to 100 Hz at 10g levels in lateral and longitudinal axis. The sensor was also subjected to half sine 50g shock per axis in lateral and longitudinal axis.

4.4 Response time measurement: Response time test was conducted by dipping the sensor in boiling water from room temperature. The sensors have a time constant of 20 to 28 milliseconds which is at par with typical thermocouple behavior [9]. In real life condition, the response time will be faster as the sensor will be facing flowing gas which will have higher heat transfer coefficient.

4.5Final Static Calibration: One sensor was calibrated from 100 to 1000°C and the other sensor was calibrated from 100 to 1200°C using R Type thermocouple as standard. The calibration results are shown in figure 6. Sensor showed linear behavior and the error was well within acceptable limits as per ASTM E230 (±2.2 ^{O}C or 0.75% of reading) standard as shown in figure 7.

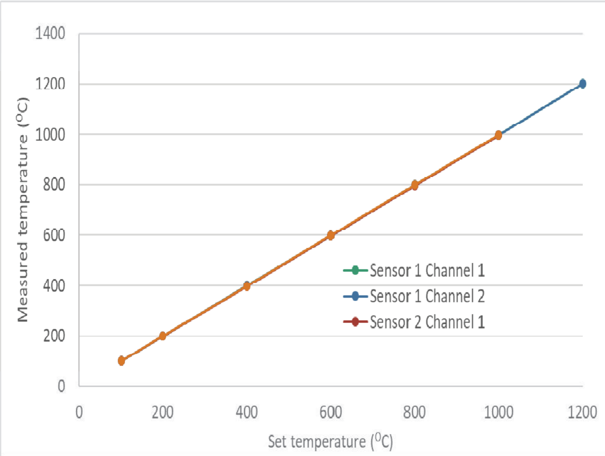

Figure6: Sensor output with temperature (Calibratio)

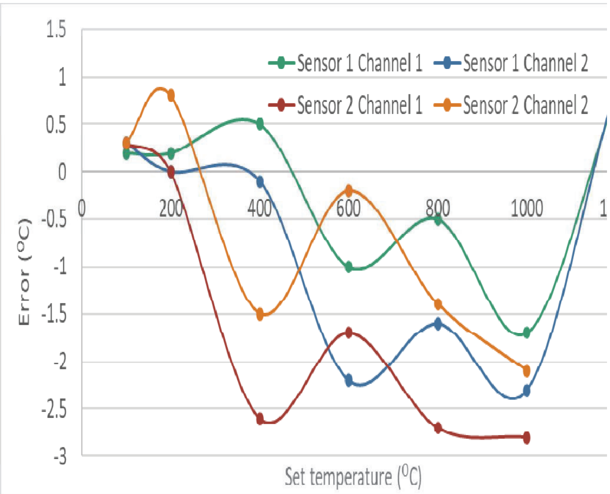

Figure 7: Sensor Error during calibration w.r.t. standard (S-type Thermocouple)

4.6System integration &Engine testing: During the qualification of the cryogenic engine, one sensor was mounted in the gas generator of the engine. The sensor was installed in the gas generator outlet, where transient temperature data supports combustion stability diagnostics, GG ignition sequencing, and turbopump pre-conditioning. The sensor experienced a pressure of 200 bar and temperature of upto 450 ^{O}C. The output of both the elements of the sensor is shown in figure 8 and the dispersion between the two elements is shown in figure 9. It can be seen from the plots; the performance of the sensor was as expected and the two elements showed minimum dispersion. Average dispersion between the elements was 0.6 ^{O}C. Data from this sensor feeds into Turbopump inlet temperature regulation, Gas generator mixture ratio tuning & Health monitoring and abort logic for GG anomalies.

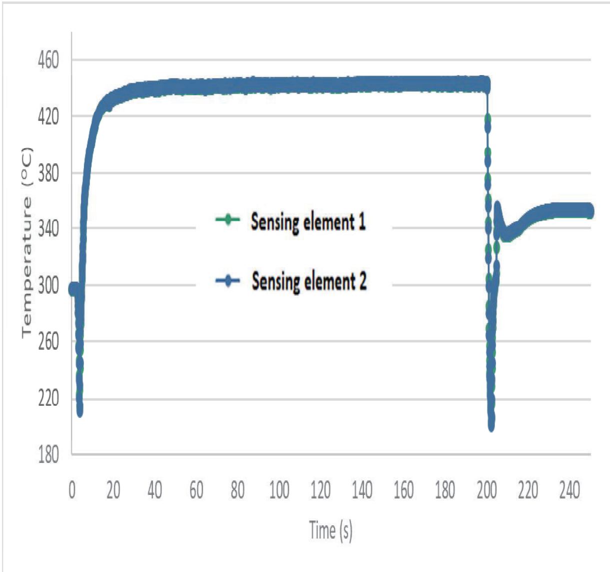

Figure 8: Readings from both the elements of the sensor during GG test

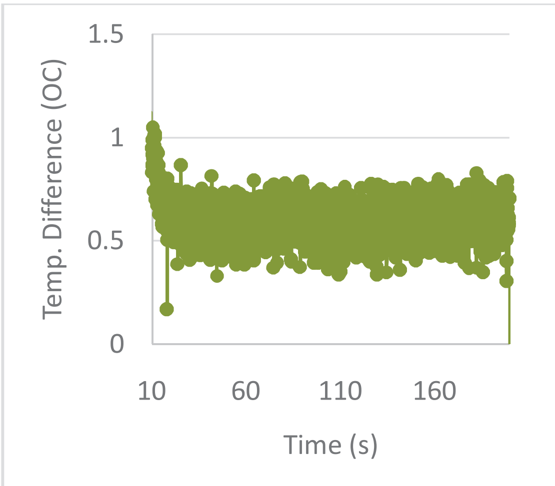

Figure 9: Dispersion among the elements of the sensor

5. Conclusion

K-type thermocouple-based temperature sensors offer a reliable and cost-effective solution for high-temperature and high-pressure applications across various industries. Their wide temperature range, high accuracy, fast response time, and robustness make them indispensable tools for monitoring and controlling critical processes, ensuring safety, efficiency, and product quality.

Dual element K-type thermocouple-based sensors are successfully realized and the tested. The results are found to be satisfactory under the extreme environment condition. The sensor has successfully demonstrated good performance under vibration levels of 19.5g RMS random, 10g sine and 50 g shock. It has also been tested upto 1473 K without fail. The sensor is proof pressure tested upto 900 bar static pressure. The sensor was integrated with the cryogenic engine during a 200s qualification test it performed satisfactorily. The developed sensor is made with 2 channels for dual mode redundancy for use in gas generator outlet and turbine inlet and outlet of cryogenic engines.

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