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The Development of a RTD Temperature Sensor for Exhaust Applications

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ABSTRACT

A RTD (resistive temperature device) high temperature sensor was developed for exhaust gas temperature measurement. Extensive modeling and optimization was used to supplement testing in development. The sensor was developed to be capable of withstanding harsh environments (-40° to 1000°C), typical of engine applications, including poisons, while maintaining high accuracy (< 0.5% drift after 500 hrs of aging at 950°C). The following sensor characteristics are presented: resistance-temperature curve, accuracy, response time, and long-term durability. In addition, a system error analysis program was developed with representative results.

INTRODUCTION

With emissions regulations becoming more stringent, improved control on existing and new emissions devices are becoming necessary. Some new emissions devices are very sensitive to temperature, they will not work below certain temperatures, and can be damaged if the temperature goes too high. Examples of such devices are: Diesel Particulate Filters (DPF), Selective Catalytic Reduction (SCR) and Diesel Oxidation Catalysts. The need to measure temperatures on these technologies has been discussed previously. [1]

While temperature sensors have been around for hundreds of years, the ability for them to withstand harsh conditions has always been difficult to overcome. Engine exhaust environments are extremely hostile to sensors. With temperature ranges from –40°C to over 1000°C, flow velocities from 3 m/s to over 200 m/s, unburned combustion products, poisons from both oil and fuel, severe vibrations, and impact from road debris, it is challenging to attain durability requirements of up to 700,000 km. This paper discusses the development of a high temperature sensor capable of meeting these requirements.

SENSOR TYPES

Practically speaking, there are 3 sensor technologies that are viable in vehicle exhaust: thermocouples, thermistors, and resistance temperature detectors (RTD). Each have their own advantages and disadvantages, and will be discussed in brief detail.

Thermocouples

Thermocouples have been around the longest of the three sensor types. They are formed by welding two dissimilar metals together forming a bimetallic junction that produces a voltage which varies with temperature. For a vehicle application, a type K (chromel-alumel) or type R or S (platinum-rhodium) would be used for the range of temperatures previously mentioned.

Thermocouples can be relatively low cost sensors (if using type K) as compared with thermistors or RTDs. However, the electrical system is significantly more expensive since there must be compensation for voltages produced whenever there is a change in wire material (often called cold-junction compensation).

Thermocouples can be made with very little mass which allows for a fast response with changing temperature. In order for the sensor to minimize drift and be durable in a vehicle exhaust environment however, the thermocouple must be protected by a sheath, and made thicker. Thus much of the fast response advantage is eliminated.

Thermistors

Thermistors are made from various nonmetallic conductors (i.e. metal oxides). The types of thermistors found in a vehicle exhaust environment will typically produce a negative temperature coefficient (NTC), meaning the resistance will decrease with increasing temperature. Thermistors offer a high sensitivity over a smaller range in temperature than either thermocouples or RTDs. At 0°C the resistance can be over 100,000 Ω, at 200°C 200 to 500 Ω, and at 800°C 50Ω. Thus, thermistors can achieve very high sensitivities over a particular range of temperatures. However, achieving nearly the same accuracy over a large range in temperatures is not possible (unless several pull up resistors are used) due to the highly nonlinear characteristic response.

Thermistors can be made very small for quick response. However, they are not able to withstand even mild vehicle exhaust environments without being protected by a metal or ceramic insulated sheath thus causing the sensor response to be relatively slow.

Tolerance of a thermistor depends on its intended range of use. Thermistor tolerances in manifold air temperature sensors (MAT) or coolant sensors are very tight over the relatively narrow range of measurement (ex. 0.6°C from 0° to 100°C). However in a vehicle exhaust that can vary between -40°C and 1000°C, thermistors have a fairly poor tolerance depending on the temperature range (2% to > 6% of temperature).
As previously mentioned, thermistors typically have a very high resistance below 100°C. This makes it difficult to meet requirements of being able to read the sensor at -40°C, or being able to perform OBD II start up diagnostics at 20°C.

Unlike thermocouples or RTDs, each manufacturer of thermistors have their own characteristic temperature vs. resistance curve. These curves can vary significantly and thus are often not interchangeable without pull up resistor hardware changes [2].

RTD
Resistance temperature detectors or RTDs are based on the natural change in a metal's resistance with temperature. In vehicle exhaust applications the material of choice is platinum due to its capability to span the entire range of temperatures while having a near linear output. Industry standard for a RTD is 100Ω at 0°C, however the standard resistance for vehicle exhaust applications is 200Ω at 0°C. The higher resistance doubles the sensitivity and makes vehicle wiring even less significant.

Both thermistors and RTDs can be affected by self heating or Joule heating. This is caused by power loss across the sensor element caused by the measurement current. The lower the pull up resistor used to measure the sensor's resistance (to be covered later), the larger the measurement current, and thus the self heating. However, self heating is generally a concern only in still air; even at idle flow velocities, the power loss generated in the sensor element is carried away by the exhaust flow making the self heating affect insignificant.

There are two types of RTDs: wire wound and film type. Wire wound is made by winding a thin platinum wire around a mandrel until the desired resistance is reached – being careful not to stress the wire. While wire wound has the highest accuracy, they typically have a relatively large thermal mass causing them to have a slow response. The film type RTD is typically made by applying a thin film of platinum onto a ceramic forming a serpentine. The element is then passivated for high temperature environments. Thin film RTDs cost less than wire wound, have fast response times (if the element does not use a metal sheath for passivation), and are the selection of choice for vehicle exhaust environments.

COMPARISON OF SENSOR TYPES

Table 1., shows a summarized comparison of the three different sensor types. The RTD is the most accurate of the three sensor types over the entire measurement range over time. It is important to note that zero hour accuracy is only one portion of total accuracy; how the sensor performs in the application over time at temperature is vital.

Characteristic	Thermocouple	Thermistor	RTD
Linearity	Poor	Poor	Good
Accuracy	Fair	Fair to poor	Excellent
Sensitivity <600°C >600°C	 Poor Poor	 Excellent Fair	 Good Good
Signal Level <600°C >600°C	 Poor Poor	 Excellent Fair	 Good Good
Response time	Poor (3 mm dia)	Poor	Good (No sheath)
System Complexity	Poor	Good	Excellent
Standardized output signal	Excellent	Poor	Good
-40°C measurement	Excellent	Poor	Excellent
20°C OBD II measurement	Excellent	Poor	Excellent

Table 1. Comparison of three sensor technologies [2, 3, 4, 5]

Figure 1., shows two thermistors and a typical RTD designed for vehicle exhaust use (thermocouples are not shown since they generate an output voltage instead of measuring a resistance).

As can be seen from the graph, the thermistors show a very non-linear curve as compared to the RTD. Further, there is a significant difference between the two different thermistor manufacturers, with one not being practical for measuring temperatures below 100°C. The tolerances indicated on the graph show that the RTD has a much tighter tolerance than thermistors over the measurement range.

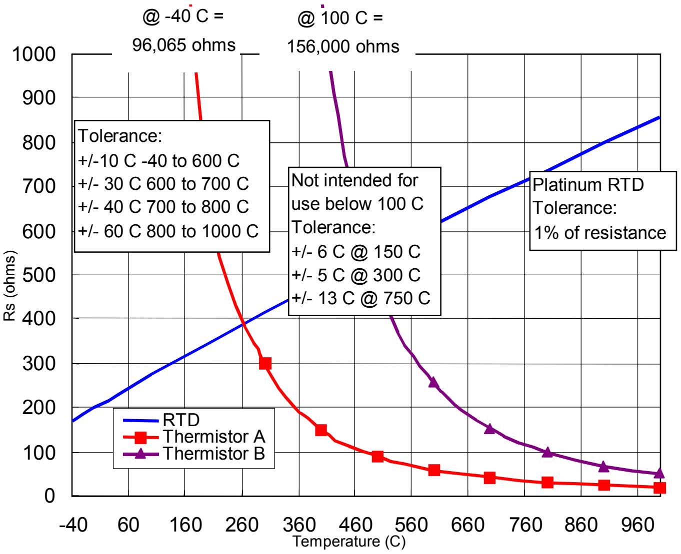


Figure 1. Comparison of sensor technologies

Thermocouples have the lowest sensitivity, followed by RTDs or thermistors depending on the temperature range. Below a range of 500 to 600°C, thermistors have very high sensitivity. Above 600°C the RTD has the highest sensitivity. Signal levels are again lowest with thermocouples followed by RTD and then thermistors up to 200°C to 600°C (depending on the type of thermistor).

Linearity of the sensor is also a desirable trait. The platinum RTD is the most linear followed by thermocouples. Being linear provides the ability for only one pull up resistor to be used over the entire measurement range without losing accuracy.

TEMPERATURE SENSOR REQUIREMENTS

Temperature

Typically the low-end temperature requirement is consistent at -40°C with a need to accurately measure temperature at 20°C for OBD II diagnostics. High-end temperature requirements depend on the application. For example, any of the following can have a significant impact on the maximum temperature requirement: Engine type (Diesel, or spark ignition), turbo charging, location of sensor in exhaust pipe, the size and load of the engine, type of emission devices and control mechanization. Typical temperature maximums for diesel engines are < 850°C and for spark ignition <1050°C.

The time spent above 800°C is critical to sensor accuracy after aging. Even short durations above 1000°C can significantly change the sensor accuracy. When specifying the maximum temperature of the sensor, a time at temperature specification should be indicated for temperatures above 800°C, 900°C and 1000°C showing both duration for a single instance as well as a percent of vehicle life.

Exposure to Exhaust Contaminants

Certain exhaust constituents, found in either the fuel or oil, can contaminate the temperature sensor and cause a resistance shift over the life of the sensor. The concentration of the constituent, air/fuel ratio of the exhaust, and temperature of the exhaust all contribute to how much the temperature sensor will be poisoned and cause a resistance shift. Typically poisoning of the exhaust sensor starts to be a concern above 600°C depending on the level of passivation.

Time Response

Time response is typically defined as the time it takes to reach one time constant (63% of final value) as temperature increases. The need for how fast the sensor responds depends on the application. In general, the faster a sensor can respond, the sooner decisions can be made which might enable emissions improvement (tighter control) or provide protection to emission devices. The time response is highly dependent on flow velocity. Some applications may not be concerned with idle conditions, thus it is important to note the time response for the flow velocity at which the sensor information will be used. Typical response times for sensors range from 3 to 16 seconds.

Sensor Durability

Heavy duty diesel engines have a requirement of 700,000 km, while light duty diesels and spark ignition engines are typically 240,000 km or less. Since temperature sensors will be exposed to the same physical conditions as other exhaust sensors, the requirements would be the same. For spark ignition engines these requirements would be equivalent to oxygen sensors which have been used for 30 years and have a very well developed durability requirement.

Dimensions

Dimensions are dependent on vehicle application. If the application temperatures are lower, the sensor package will be cooler, thus the temperature sensitive components can be moved closer towards the exhaust, and the sensor height can be reduced. Often, the exhaust system will have other exhaust sensors packaged into the same pipe. This could mean that the seat to seal height of the sensor might be the same as other exhaust sensors, depending on location. Likewise, the thread size of exhaust sensors has been standardized to M18 thread in spark ignition engines, thus it would make sense to keep this thread size consistent. Internal (female) pipe thread on the exhaust pipe has long been preferred so as to not damage the threads during vehicle assembly.

Insertion Depth

Insertion depth is again dependent on the application, with the largest variable being the size of the pipe and the flow velocity of interest. There is typically no need to locate the sensor in the center of the exhaust flow, since the temperature profile (as will be shown later) has a fairly flat shape depending on Reynolds number. At low Reynolds number the profile is less flat and can affect the exhaust temperature measurement. Oftentimes however, low flows are of little interest in temperature measurement. As will be shown later, it is fairly simple to compensate for insertion depth if the exhaust flow is known.

Accuracy

Accuracy has several components. The accuracy of the sensor itself is defined as the ability to read a uniform temperature, where the entire sensor is exposed to the same temperature. This accuracy will vary with thermal and chemical (poisons) aging.

The second component of accuracy is the difference in temperature between the location actually measured and the location desired. As previously mentioned this can be compensated for if the exhaust flow velocity is known, and the sensing element is not located in the boundary layer.

The third component of accuracy is the system level accuracy. The pull up resistor value and its tolerance as well as the analog to digital (A/D) resolution can play a large part in the overall accuracy of reading the sensor. Lastly, whether a look up table or an equation is used to convert the resistance measured to the temperature, can make some difference since an equation rarely can perfectly describe nature.

SENSOR DEVELOPMENT

Based on the previous comparisons between the different sensor types, it was decided that a RTD would best fit vehicle exhaust applications. Further, a platinum thin film planar sensor with a resistance of 200Ω at 0°C was chosen due to its stability and standardization.

Insertion Depth

Insertion depth is dependent upon the unsupported cantilever length of the element, thickness, and element cost/mm of length vs. performance. The unsupported cantilever length must be designed to withstand vibration levels (that have enough amplitude to excite the element) higher than seen in vehicles.

The longer the sensing element, the higher the cost. This is partially due to the cost of the platinum on the sensing element, and partially due to packaging. To optimize the cost, it is important to know the exhaust temperature profile under the conditions in which the temperature information will be used. The temperature profile is mainly dependent on flow velocity and pipe diameter. In most situations, the velocity profile is very uniform except in the boundary layer close to the pipe wall. Only at a very low idle condition in a large diesel exhaust pipe, will the exhaust temperature profile have a significant difference in temperature between peak and measured locations of the sensor.

Another decision to be made is whether the peak temperature, or bulk temperature is desired. Peak temperature is the maximum temperature in the pipe cross section, typically located in the center of the pipe. The bulk temperature is the average temperature of the gas over the cross section. The bulk temperature can be calculated by:

$$T_{bulk} = \frac{\int_0^R 2\pi r \rho_g \mathrm{v} T dr}{\dot{m}}$$

Where

ρ_g: density of the gas

v: velocity of the gas

$\dot{m}$: mass flow rate of the gas.

Since the area increases with the radial distance from the center of the pipe, there are larger quantities of exhaust gas the further from the pipe center. The region of the bulk flow and temperature varies with flow rate but is roughly encompasses 2/3 to 3/4 of the pipe diameter. The desired location of the temperature measurement may be dependent on what the sensor is being used for. If the sensor is used for applications such as over temperature protection, peak temperature may be desired. However, in other applications, the bulk temperature may be desired.

Performing a computational fluid dynamics (CFD) analysis, on two different pipe diameters, the difference between peak and bulk temperatures can be observed. Figure 2, shows the percentage difference in temperature between the bulk and peak temperatures, along a 24 mm location point in a 127 mm ID exhaust pipe. Table 2, describes the input and boundary conditions.

	Bulk Temperature	Ambient Temperature	Ambient velocity
127 mm pipe	500°C	0°C	22.5 m/s
57 mm pipe	250°C	0°C	22.5 m/s

Table 2. CFD model boundary conditions

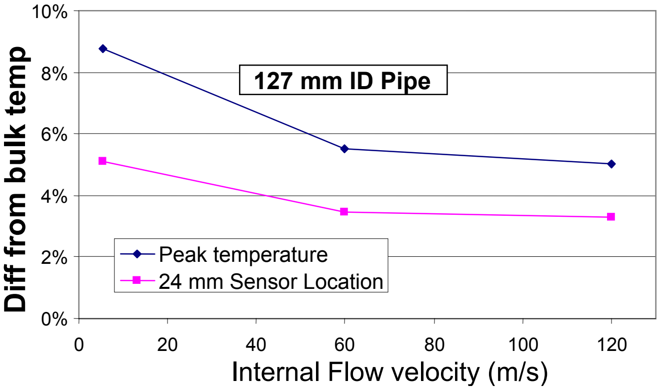


Figure 2. Comparison with bulk temperature for 127 mm ID pipe

As shown in Figure 2, there can be a significant difference between peak temperature at the center of the pipe and the bulk temperature, which is located at about 25% of the pipe diameter. The 24 mm insertion depth location follows the peak temperature shape quite well. A sensor located between the boundary layer and the pipe center can determine peak or bulk temperature by compensating for the difference in temperature since the shapes are very similar.

Figure 3, shows a CFD analysis on a 57 mm ID pipe. As shown, the peak temperature and the temperature at a 24 mm insertion depth lie almost directly on top of each other, indicating no practical difference in temperature between the two locations.

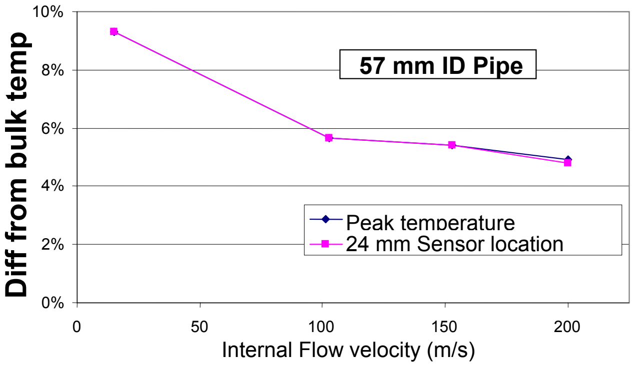


Figure 3. Comparison with bulk temperature for a 57 mm ID pipe

Element Thickness

The thickness of the element depends on the cantilever length (which was determined in the previous section) and the desired response time of the element. For a given width, the thickness will determine the mass of the element, which will in turn be directly related to the response time of the sensor.

Response Time

Several factors influence the response time of the temperature sensor; they include the exhaust gas flow conditions such as temperature, flow velocity, lower shield design and pipe geometry. In addition, the element thermal conductivity and thickness also impact the response time.

An analytical correlation was developed for the response time of the sensor in exhaust gas. The heat transfer equations can be expressed as [2]:

$$\rho_s c_s (w \bullet th)\frac{dT_s}{dt} = h[2(w+th)](T_g - T_s)$$

The solution to the above equation is:

$$T_s = T_g\left(1-e^{-\frac{T}{\tau}}\right)$$

And the convection coefficient h can be obtained from the Nusselt number Nu, which is expressed as:

$$Nu = \frac{hd}{k_g} = C\,\mathrm{Re}^n \Pr^{1/3}$$

$$\mathrm{Re} = \frac{Vd}{\nu}$$

$$\tau = \frac{\rho_s c_s w \bullet th}{2h(w+th)} = \frac{\rho_s c_s w \bullet th}{2(w+th)} C^{-1}\frac{d}{k_g}\mathrm{Re}^{-n}\Pr^{-1/3}$$

Where

ρ_S: density of the element
c_S: specific heat of the element
w: width of the element
th: thickness of the element
Re: Reynolds number
Pr: Prandtl number
V: average velocity of the gas
d: diameter of the lower shield
ν: dynamic viscosity of the gas
k_g: thermal conductivity of the gas
T_g: temperature of the gas
T_s: temperature of the element surface

The properties of the gas and the element are a function of temperature. Here the gas properties are evaluated at temperature T = $1/3*T_g+2/3*T_s$ and the element properties at temperature $T = 2/3*T_g+1/3*T_s$.
The coefficient C and exponent n are specific to the lower shield selected and can be deduced from measured data.

It is shown from above, that the response time is proportional to thickness of the sensor. Other gas properties also affect the response time. A typical trend of the response time vs. average pipe flow velocity is shown in Figure 4. It is shown that the response time is shorter for heating than for cooling. Also, heating and cooling to different temperatures also have a slightly different response time.

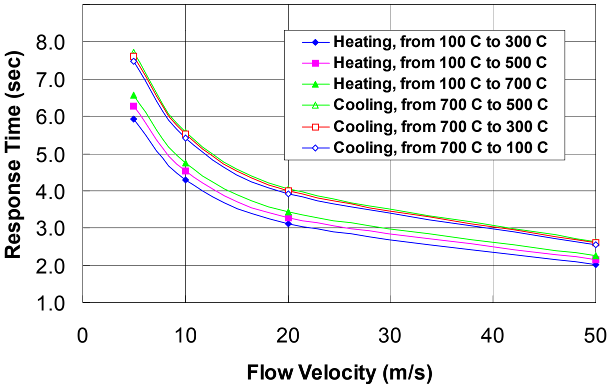


Figure 4. Response time vs. flow velocity at various flow conditions

Element Construction

The sensing element was constructed by sputtering a thin film of pure platinum onto an alumina substrate with leads that have been platinum thick filmed. Creating the serpentine pattern and trimming to a precise resistance uses a proprietary method that allows for greater stability of the platinum during thermal aging. After trimming, an alumina protective cover plate is placed on the element and sealed with a proprietary high temperature glass sealant.

Completely sealing the sensing element from the exhaust gases is critical to maintaining accuracy of the sensor. Even if the sensor is hermetically sealed, during high temperature excursions, the sealing glass can become soft – allowing poisons to pass through the glass, contaminating the sensing element. Using this special proprietary glass sealant allows the temperature sensor to be directly exposed to the exhaust stream without the need for a metal sheath, which would drastically slow the sensor's response time.

Protective Shield

The protective lower shield in a temperature sensor is only useful prior to installation. Unlike other exhaust sensors, which use the shield to limit exhaust flow past the element, in a temperature sensor, the shield must allow a maximum amount of flow past the element without first absorbing or releasing heat. Therefore, maximizing hole size and minimizing mass are important factors in minimizing the affect the lower shield will have on response time. Further, since the temperature sensor does not have a heating element, and is therefore almost always at the same temperature as the exhaust, there is no need to be concerned with water impingement on the sensor like there is with other electrically heated exhaust sensors.

Sensor Packaging

It was determined that adapting an existing high volume production planar exhaust sensor package would have several advantages. Production packaging has already demonstrated high physical durability and was designed to meet most application temperatures in the same exhaust environment that the temperature sensor will be exposed to. This packaging, along with the previous discussion determined the geometry of the sensing element.

The current production packaging does not allow the temperature sensor to make a 90° bend in the package outside the exhaust pipe. However making a 90° bend may not be advantageous. Depending on the location of the bend, oftentimes the bent sensor has the same overall height as a production straight sensor with bends in the wire. Further, installation can be more difficult since having a bend does not allow for the use of a socket wrench, which is typically used in high volume manufacturing.

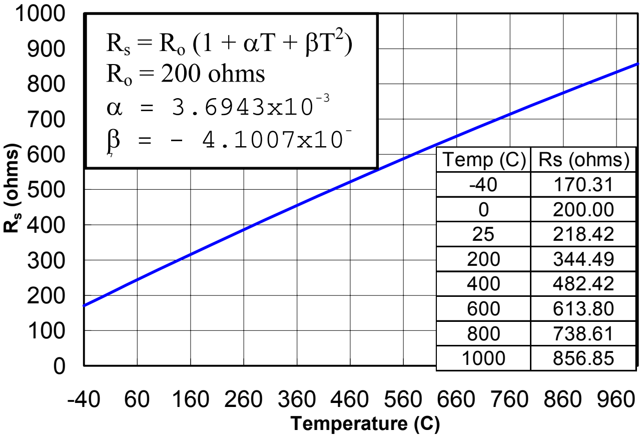
TESTING

Sensor Calibration Curve

When the sensor is in an application, it is expected that the sensor will have a temperature gradient from the sensing tip to the connector wire. This temperature gradient varies with different gas conditions inside and outside the pipe and changes the resistance of the leads. It was decided to include the resistance of the conductor lead in the overall resistance measurement. This will simplify the calibration electronics with a negligible error since the lead is a very small fraction of the total sensor resistance.

Two different calibration systems were used to calibrate the sensor resistance vs. temperature curve. From -40°C to 240°C, the sensors were set in a circulating liquid bath to measure the resistance. At elevated temperatures above 300°C, a thermocouple calibrator was used to measure the resistance.

The resistance vs. temperature curve is shown in Figure 5, which is represented by the best-fit quadratic equation of the measured data. The values in the inserted table are calculated based on this curve. As shown, the α value is slightly lower than typical (i.e. 3.825×10^{-3}) due to incorporating the lead resistance into the curve fit.



Temp (C)	Rs (ohms)
-40	170.31
0	200.00
25	218.42
200	344.49
400	482.42
600	613.80
800	738.61
1000	856.85

Figure 5. The calibration curve of the temperature sensor

Thermal durability

Thermal durability without the influence of poisons was performed in an air atmosphere oven, held at a constant temperature for a given amount of time. Figure 6, shows the effect of time vs. temperature for 750°, 850°, and 950°C. As shown, almost no shift in resistance occurs at either 750°C or 850°C up to the test time of 1,000 hours. At 950°C, the resistance shifts about 0.32% after 500 hours and 1.32% after 1,000 hrs. Thus temperatures below 850°C do not significantly affect the performance of the temperature sensor. At temperatures above 850°C, the time the sensor is exposed at these elevated temperature becomes important. Therefore it is critical to know the temperature-time histogram to determine how much the sensor will change during the vehicle life.

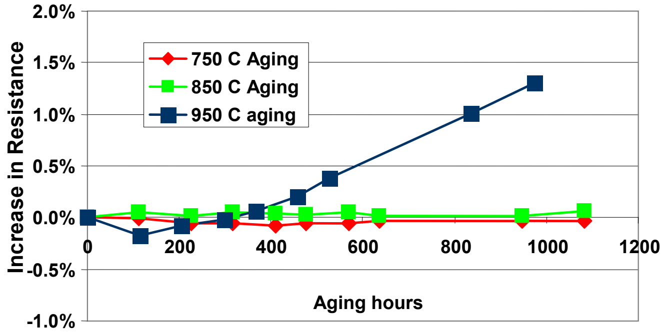


Figure 6. Oven aging at three different temperatures

Thermal Cycling – with Poisons

A test was constructed to rapidly inflict a lifetime worth of poisons on the temperature sensor in a way that might be seen on a vehicle. A diesel exhaust simulation was used for this test due to its tendency to burn larger amounts of oil and for its 700,000 km durability requirement. From previous experience with other exhaust sensors, it is known when continuously running at high temperatures, some poisons form a hard particle and tends not to attach to the sensing element. Thus the test cycle was designed so that for the majority of the time, the sensing element would collect soft deposits that would attach readily to the sensor. Then a high temperature exhaust spike would drive the poison particles on the surface into the glass seal. Figure 7, shows a graph of the cycle.

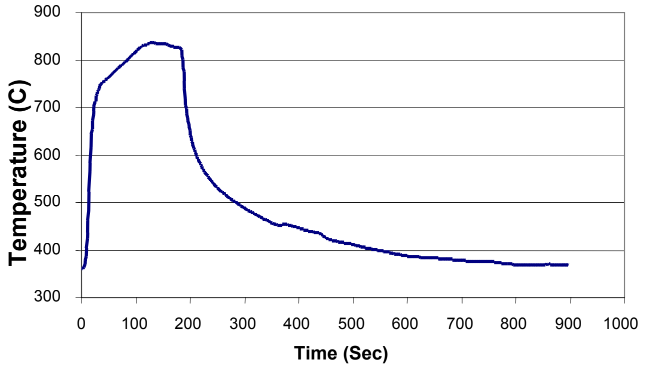


Figure 7. Thermal cycling with poisons temperature profile

This cycle was repeated so that the sensor would be exposed to an equivalent amount of oil used in a large diesel's life, with an estimated equivalent time spent at high temperature. Figure 8, shows that the sensors had an average change of only 0.38% over an equivalent 700,000 km.

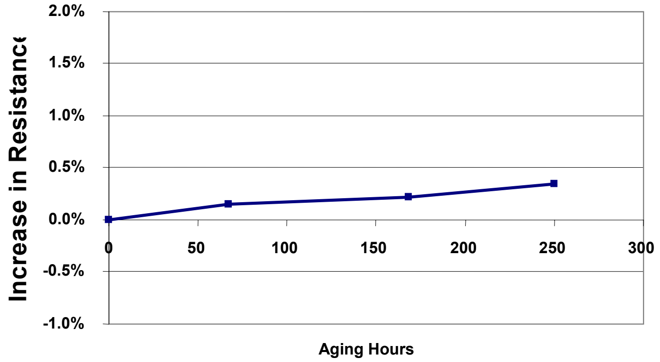


Figure 8. RTD change in resistance after a lifetime amount of exhaust poisons

Electrical System Integration

The electrical interface configuration for the temperature sensor is shown in Figure 9.

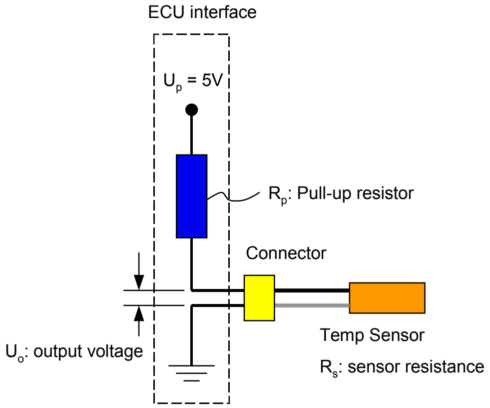


Figure 9. Electrical Interface Configuration

5 volts are applied to a pull up resistor in series with the temperature sensor. The voltage drop is measured across the temperature sensor. The corresponding voltage is the result of the following equation. Uo = Up * Rs/(Rs + Rp). After the voltage is read by the engine contol unit (ECU), the corresponding temperature can be derived by calculation or by using a look up table. The calculation method would involve a second order polynomial equation.

SYSTEM RESOLUTION

The system resolution and system errors were evaluated using an error analysis model. This model incorporates system wiring, connectors, pull up resistor effects, element accuracy, and A/D converter resolution. This model demonstrates the effects on signal output from various system configurations.

The accuracy of the temperature sensor is affected by the value of the pull up resistor labeled as Rp. This value needs to be chosen to maximize the resolution of the signal over the temperature range. Figure 10 shows sensor output with three pull up resistor values. A 2700 ohm resistor will make the sensor have an output of 0.3 volts at –40°C and 1.2 volts at 1000°C. This corresponds to a 0.9 volt output change over the whole temperature range. The 500 ohm resistor will generate a sensor output of 1.28 volts at –40C and 3.16 volts at 1000C. Total output is almost double the amount compared to a 2700 ohm resistor. The 500 ohm resistor provides the best temperature resolution for this sensor. While a 500 ohm resistor will allow higher currents – leading to more self heating, in moving exhaust flows this affect should be minimal.

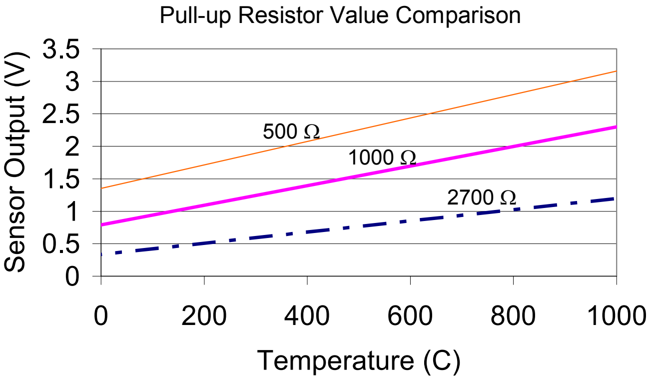


Figure 10. Various pull up resistor output voltage vs. temperature

The A/D converter also impacts system resolution. Table 3, shows the effects of A/D converter selection in conjunction with the pull up resistor. The increments represent the number of slices the sensor signal will be broken into over the temperature range.

Ohms	Sensor Voltage Range	Increments 8 - bit	Increments 10 - bit
2700	.3 - 1.2	45	184
1000	.73 - 2.3	81	327
500	1.28 - 3.16	96	388

Table 3. A/D Converter Effects

An 8-bit converter has a minimum voltage step of 19.6 mV for a 0-5 volt signal. A 10-bit has a minimum voltage step of 4.89 mV. This equates to 20°C resolution for 8 bit and 5°C for 10 bit around 800°C

System Errors

The pull up resistor tolerance has an impact on system errors. The tolerance chosen for the resistor adds to the tolerance for the sensor. It is suggested to use a resistor with a tolerance of 0.5% or less. Table 4, shows the maximum possible error of sensor temperature indicated due to resistor tolerance with a 500 ohm resistor.

Tolerance	Sensor Temp.	Signal error from Tolerance
0.5%	0°C 800°C	1.45°C 6.55°C
1%	0°C 800°C	2.86°C 13.07°C

Table 4. Pull up resistor tolerance effects

The wiring and connections for the system were also included in the error analysis model. The effects on the system are extremely small. At 0°C the wiring and connectors account for 0.02% of the system resistance, this is equivalent to 0.05°C. As the resistance of the sensor increases, the effects from system wiring further decrease.

System Suggestions

It is recommended that the pull up resistor of 500 ohms be used for best overall system resolution with a tolerance of 0.5% or less, and an A/D converter of 10 bit resolution.

CONCLUSION

This paper, presented the development of a temperature sensor suitable for vehicle exhaust applications. The sensor is based on the RTD technology. Several analytical methods were used in the development of the sensor. As the result of this study, several conclusions can be drawn:

1. The RTD type temperature sensor has the ability for the broadest range of applications for measuring vehicle exhaust temperature quickly and accurately over the life of the vehicle.

2. The result of the CFD modeling demonstrates that the temperature and velocity distributions in the exhaust pipe are similar. The temperature distributions for most applications are very flat except in the boundary layer. The thickness of this layer is about 7 mm for most applications. For these applications, the developed sensor will have sufficient insertion depth for accurate measurement. In the extreme case of the very large pipe with very low flow, such as 7 m/s in a 127 mm ID pipe, the insertion depth of the developed sensor is not sufficient to measure peak temperature; however, the peak temperature can be calculated based on the flow condition.

3. The response time can be expressed by a formula, which is dependent on the exhaust gas properties, sensor geometry, and the material properties of the sensing element. The response times are different for heating vs. cooling, with the response time for heating being faster.

4. The sensor has been exposed to high temperature aging with and without chemical contaminants. The RTD sensor developed has been demonstrated to show high accuracy throughout the life of the sensor against the effects of thermal aging and poisons.

5. A system model was developed for system error analysis. It was shown that the error from the

sensor is only part of the total error of temperature measurement. The overall measurement accuracy must include the error from other component in the system, such as the pull-up resistor and A/D converter.

REFERENCES

[1] T. V. Johnson, “Diesel Emission Control in Review – The Last 12 Months”, SAE 2003-01-0039.
[2] R. Desmarais, et al., “How to Select and Use the Right Temperature Sensor”, Sensors Magazine, Jan. 2001.
[3] J. LeGare, et al., “Temperature Sensors for On-board Diagnosis of LEV/ULEV Systems”, Automotive Engineering, April, 1995.
[4] D. Mathews, “Choosing and Using a Temperature Sensor”, Sensors Magazine, Jan. 2000.
[5] A. Volbrecht, “Temperature Measurement: Making Sense of it All”, Sensors Magazine, June 1998.
[6] Holman, J. P., Heat Transfer, McGraw-Hill. 1972.