A Numerical Investigation of Automotive Lambda Sensor to Improve the Life Span of the Sensor using CFD

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Abstract. The modern technology has tremendously improved the controlling technologies for fuel injection system and the emission of various harmful greenhouse gases. For detecting oxygen level in the combustion chamber and exhaust gases, a sensor named lambda sensor is used in most of the automobiles. In this paper, a numerical simulation of this lambda sensor was carried out to improve the life span of the sensors protection wall by changing its design with the help of computational fluid dynamics techniques. The simulation results showed that exhaust gas entering the sensor with a pressure range reduced by about 1.41% in comparison to its prevailing design. At the central zone of the sensor, the pressure value reduced by 9.81% with the design modification performed in the protection layer of the lambda sensor. Similarly, the exhaust gas leaving the sensor showed a 6.45% pressure drop in par with the prevailing model. The velocity and temperature of the exhaust gas were the other parameters studied. The simulation results of improved protection layer design when compared to the prevailing model indicated that, the exhaust gas velocity at the inlet and central zone of the sensor was reduced by 19.37% and 17.1% respectively. The exhaust gas temperature showed a drop of 15% in the central zone of the sensor for the new improved model. Thus, from the simulation results it can be stated that, the design modification done in the protection layer of the lambda sensor will positively improve the life span of the sensor from present life time of 2.5 Lakh kilometres or 15 years.

1. Introduction

In the modern world, automotive revolution is going on in a fast pace. The automotive sectors are trying their best to put forward innovations in automobiles. In order to automate the processes in the automobiles, it needs the help of engineering technology. It uses many types of sensors for controlling the processes in the automobiles. It controls processes like engine performance, parking automatically and cruise control are some of the applications where it needs the help of sensors [1,2,4-6]. One such sensor is the oxygen sensor, which measures the amount of oxygen in the fluid that is under investigation. The lambda sensor with zirconia ceramic layered sensing element with a tinny layer of platinum were mutually found in exhaust and reference region was used in this investigation [6]. It is available in both heated and unheated forms. The sensor measures the change between the amount of oxygen in the exhaust gas and air. Excess oxygen request was seen for rich mixtures. This request develops a voltage in the sensor, because of transference of oxygen particles over the sensor. Mixtures of lean nature resulted in voltage reduction due to overabundance of oxygen [4-5]. Data on oxygen fixation is directed to the engine administration system or engine control unit (ECU), this alters the measure of proper specific air–fuel proportion by translating the data it picked up from the oxygen sensor. Such a valuable sensor helps in expanding the utilization of
fuel proficiently [1-6]. Many research works have been carried out in studying and analyzing such lambda sensors [4-15]. Tiffee et al. [4] described various types of oxygen sensors for emission control and reduce the fuel consumption by controlling the air fuel ratio. They elucidated about the lambda sensors with for DI engines with $\lambda = 1$ and other sensors with $\lambda > 1$. Shuk et al. [7] tested oxygen sensors with different electrode materials and found that oxide electrodes showed fast response and long-term stability for varying oxygen (O2) concentration. Antonio et al. [10] studied the application of automotive lambda sensor for measuring the concentration of O2 in the exhaust flue gases in industrial combustion system. They suggested two different methods for use of lambda sensors in the industry. Lima et al. [8] reported the application of titanium dioxide thin film gas sensor for measurement of lambda and analyzed to check its response for different O2 concentration in the exhaust gases. Izu et al. [9] investigated the resistive O2 sensor using ceria-zirconia as the sensing element and it acted as the temperature recompensing material. They noticed that sensor elements made of such material was independent of the temperature for wide range of 773 to 1073 K. Klett et al. [13] in their work numerically and experimentally tested the lambda sensor with double protection tube for its heat transfer, flow pattern and temperature field. They found that the projected outcomes of numerical model were in phase with the experimental outcomes. This helped to find the aging and heating power of the lambda sensor. The performance of such lambda sensors can also be studied effectively by creating numerical models using some of the commercially available numerical tools. Since it reduces the experimentation cost and time. Some of the researchers put in their interest in modeling the lambda sensor using CFD tools. Bruck et al. [15] conducted numerical and experimental investigation on lambda sensors to find the mass transfer of the exhaust gases flowing through them. Experimental setup based on similarity theory was modelled and the same was numerically modelled in CFD software. This model projected the flow outline and species transference inside the shield of the lambda sensor. Zhang et al. [11] performed a numerical investigation using CFD tool in an exhaust system. This work provided the guidelines for the application of CFD tools in various zones of the exhaust system. This helps in building up of new concepts and modifying the existing design for optimum performance. Chen et al. [12] performed CFD analysis to model the flow field in an oxygen sensor to envisage the convection coefficient, poisoning and swapping time. The CFD investigation results were found to be in par with the tested outcomes.

Many works have been done in lambda sensors but the thought of improvising the life time of the sensor was not done. So, in this present numerical investigation, design of the protection barrier of the lambda sensor is modified and analyzed under the real-time observations to extend the life time. The existing and new design of the protection wall was modeled and analyzed using CFD package.

### 2. Numerical analysis

#### 2.1. Working of Lambda sensors

The ALS is introduced in the engines exhaust gas framework at a location where the engines exhaust temperature range is quite good, which is important for proficient sensor working. The sensor projects into the exhaust gas, outlining being with the end goal that one cathode surface is encompassed by the exhaust gas and the other is associated with the environment. Indeed, even under abundance fuel conditions, there is constantly residual oxygen in the spark ignition engine's exhaust gas (at $\lambda = 0.94$, approx. 0.101 to 0.301% by volume). Amid progress from a lean mixture (high lingering oxygen level) to a rich mixture (low leftover oxygen level), the remaining oxygen level diminishes suddenly by a power of ten in the stoichiometric location ($\lambda = 1$) of air-fuel mixture. This outcomes in the abrupt rise in voltage of the sensor which yields at $\lambda = 1$. The voltage range of the sensor and its inward resistance rely on temperature. Dependable closed loop control happens at temperatures over 360°C (unheated sensor) or more 140°C (warmed sensor) [6]. The characteristics of the Lambda sensor working at 600°C for Rich mixture is explained in figure 1 (air insufficiency) and Lean mixture (air excess). The engine (controlled framework), the Lambda sensor (measuring component), the controller in the engine control unit, and the injectors (actuators) are in closed loop control. The variable under control in the exhaust gas is the leftover oxygen [5]. The objective is to produce an ideal air-fuel mixture by modifying the fuel quantity (controlled variable) infused by the injectors is done by the control loop system. The closed loop control naturally considers uncommon modes, for example, commence, increasing speed, and full load. In the Lambda Sensors, the outer wall is protecting core part or heart of
lambda sensors from the high temperature and high velocity exhaust gas. Two wall protections and three wall protection systems are available in the lambda sensors. These walls are reducing the temperature, pressure, velocity and other parameters in the exhaust gas flow. The figure 2 shows the SI engine with exhaust system with catalytic converter and position of the lambda sensor [5].

![Figure 1 Voltage characteristics of the Lambda sensor at working temperature of 600°C for a. Rich mixture (insufficient air) b. Lean mixture (excess air)](image)

![Figure 2 a) Engine with exhaust-gas system b) Lambda sensor](image)

2.2. Computational fluid dynamics (CFD)
CFD confines over area of interest, with stated (known) circumstances on the bounded area. It is a numerical tool for simulating the behaviour of systems involving fluid stream, heat transfer and other associated physical processes with the help of computers. It works by resolving the fluid flow equations starting with equations of conservation of mass, momentum and energy [16-18]. These are given below from eq. 1, 2a-2c and 3. The CFD became a vital tool in practically every branch of fluid dynamics, from aerospace applications to weather forecast. Different stages in Fluent Analysis are,
1. Pre-processing: problem formulation, governing equations and constraints in the boundary; Discretization.
2. Solving: Numerical solution of the given equation.
3. Post-processing: Plot and analyze the results.
2.2.1 Governing equations.
The equations governing the flow are obtained by the application of physical principle [16-18]. The most important equations governing the fluid dynamics are namely:

a. Mass is Conserved (Continuity equation)
The integral form of the continuity equation:

\[ \frac{\partial}{\partial t} \iiint \rho \, dv + \iint \rho \, V \, ds = 0 \]  

b. Newton’s second law, \( F=ma \) (Momentum equation)

- \( \text{X-component} \)
\[ \rho \frac{Du}{Dt} = - \frac{\partial P}{\partial x} + \frac{\partial \tau_{xx}}{\partial x} + \frac{\partial \tau_{xy}}{\partial y} + \frac{\partial \tau_{xz}}{\partial z} + \rho f_x \]  

- \( \text{Y-component} \)
\[ \rho \frac{Dv}{Dt} = - \frac{\partial P}{\partial y} + \frac{\partial \tau_{yx}}{\partial x} + \frac{\partial \tau_{yy}}{\partial y} + \frac{\partial \tau_{yz}}{\partial z} + \rho f_y \]  

- \( \text{Z-component} \)
\[ \rho \frac{Dw}{Dt} = - \frac{\partial P}{\partial z} + \frac{\partial \tau_{zx}}{\partial x} + \frac{\partial \tau_{zy}}{\partial y} + \frac{\partial \tau_{zz}}{\partial z} + \rho f_z \]  

c. Energy is conserved (First law of thermodynamics equation)

\[ \frac{\partial}{\partial t} \left( \rho (e + \frac{V^2}{2}) \right) + \rho \left( \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} \right) \left( k \frac{\partial T}{\partial x} + \frac{\partial w}{\partial y} + \frac{\partial v}{\partial z} \right) \left( k \frac{\partial T}{\partial y} + \frac{\partial w}{\partial x} + \frac{\partial u}{\partial z} \right) \left( k \frac{\partial T}{\partial z} + \frac{\partial w}{\partial x} + \frac{\partial u}{\partial y} \right) 
+ \frac{\partial (\rho u T)}{\partial x} + \frac{\partial (\rho v T)}{\partial y} + \frac{\partial (\rho w T)}{\partial z} \right) + \rho f_v \]  

2.3 Methodology
Life time of the Lambda (Oxygen) sensors depends on the Exhaust gas flow parameters (Temperature, Pressure, Velocity) Starting conditions, Usage of gears, Exhaust gas containment and others. It is known that by reducing the temperature at the sensing element area we can reduce the pressure by Gas eqn. \( PV=RT \) which leads to the extended life time of Lambda sensors. By changing the protection layer design, exhaust gas temperature can be reduced by making an obstacle in the flow passage. To perform that break, there is a need to change the design in existing protection wall [11]. The exhaust gas flow inside the sensor need to be determined for the impact of new design on temperature loss. The figure 3 shows the prevailing design of the double wall and triple wall protection lambda sensors.

![Figure 3. prevailing design of double wall and triple wall protection lambda sensor](image)

3. Results and discussions
The CFD analysis of the existing double wall protection lambda sensor was performed and the figures 4-6 shows the pressure, velocity and temperature distribution respectively.

3.1. Double wall protection lambda sensor
The exhaust gas at high temperature enters the sensor through the protection wall and passes over the sensing element. The pressure inside the sensing chamber and the velocity distribution is shown in the figure 4 and 5. The Figure 6 shows the distribution of temperature inside the sensor when the hot exhaust gas enters.

The exhaust gas maximum pressure is 2.05 kPa at the entry of exhaust gas. The pressure at the core sensing part is around 2.0 kPa and the minimum pressure is 1.98 kPa at exit of exhaust gas from the lambda sensors. The maximum velocity in the exhaust gas is 89 m/s at the entry of exhaust gas. The velocity at the core sensing part is around 49 m/s.

The exhaust gas maximum temperature is 800°C at the entry of exhaust gas. The temperature at the core sensing part is around 675°C.

3.2. Triple wall protection lambda sensor

The exhaust gas at high temperature enters the sensor through the protection wall and passes over the sensing element. The pressure inside the sensing chamber and the velocity distribution is shown in the figure 7 and 8. The figure 9 shows the distribution of temperature inside the sensor when the hot exhaust gas enters. The exhaust gas maximum pressure is 2.23 kPa at the entry of exhaust gas. The pressure at the core sensing part is around 2.2 kPa and the minimum pressure is 1.97 kPa at exit of exhaust gas from the lambda sensors. The maximum velocity in the exhaust gas is 90 m/s at the entry of exhaust gas. The velocity at the core sensing part is around 35 m/s.
The exhaust gas maximum temperature is 800°C at the entry of exhaust gas. The temperature at the core sensing part is around 700°C.

Figure 9. Temperature distribution of double wall protection lambda sensor

3.3. Modified double wall protection lambda sensor

The exhaust gas at high temperature enters the sensor through the protection wall and passes over the sensing element. The pressure inside the sensing chamber and the velocity distribution is shown in the figure 10 and 11. The figure 12 shows the distribution of temperature inside the sensor when the hot exhaust gas enters. The exhaust gas maximum pressure is 2.20 kPa at the entry of exhaust gas. The pressure at the core sensing part is around 2 kPa and the minimum pressure is 1.85 kPa at exit of exhaust gas from the lambda sensors. The maximum velocity of the exhaust gas is 75 m/s at the entry of exhaust gas. The velocity at the core sensing part is around 30 m/s.

Figure 10. and Figure 11. Pressure and Velocity distribution of modified double wall protection lambda sensor

The maximum temperature exhaust gas is 800°C at the entry of exhaust gas. The temperature at the core sensing part is around 610°C.

Figure 12. Temperature distribution of modified double wall protection lambda sensor
The comparison of the pressure, velocity and temperature distribution of existing protection wall and modified protection wall is shown in the chart form in figure. 13. The analysis result shows that, the modified double wall protection lambda sensor is better than the existing ones. The pressure distribution of modified double wall protection at the core of the sensor reduced by about 10% when compared to triple wall protection. This is due to the positioning of the exhaust gas entry to the core somewhere at the middle of the sensor wall module [11, 12, 15]. The exhaust gas velocity entering the center of the modified double wall protection sensor reduced by 63.3% and 16.6% when compared to the triple and double wall protection sensor. This reduction in the velocity distribution in the modified design is due to the presence of the inlet for the entry of exhaust gas at somewhere middle. This acts as a block for the streamlined flow of the exhaust gas [5, 8,11]. The temperature distribution at the core of the modified double wall protection sensor decreased by about 14.75% and 10.65% when compared to the double and triple wall protection sensor. This reduction in temperature distribution of the modified design is due to the delayed contact between the wall and the core area of the sensor [10, 13, 14].

4. Conclusion
The outcomes of the investigation show that the design modification made in the protection layer of the lambda sensor performs more effectively when compared to the prevailing design. The simulation results show the exhaust gas pressure at the entry level has reduced by about 1.35% in par with the prevailing design. There is a reduction of about 10.1% in the pressure at the central zone of the lambda sensor by the design modification made in the protection layer. The exhaust gas pressure at the exit of the sensor also show a reduction by 6.4% due to the design alteration made. The design of protection layer of the lambda sensor was modified in this investigation because of this, the exhaust gas velocity at the inlet region and central region reduced by 20.5% and 16.5% respectively. The third parameter under study was the exhaust gas temperature which got reduced by 15% at the central zone of the sensor. Thus, the simulation results of prevailing protection layer design and the modified design were compared and found that the modified design showed appreciable reduction in the all the three parameters like exhaust gas pressure, velocity and temperature. This would certainly increase the life of the oxygen sensor which is around 15 plus years for existing model to around 17 plus years or even more.

Figure. 13 comparison charts of pressure, velocity and temperature of the existing and modified protection wall.
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