SENSORS IN AUTOMOBILES

INTERNAL COMBUSTION ENGINES SENSORS

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Dedication

In the name of Allah, the merciful, the compassionate

All praise is due to Allah and blessings and peace is upon his messenger and servant, Mohammed, and upon his family and companions and whoever follows his guidance until the day of resurrection.

To the memory of Professor Sabir Mohammed Salih, Professor Elfadil Adam Abdallah, Associate Professor Mohi-Eldin Idris Harba, Associate Professor Hashim Ahmed Ali, Associate Professor Abdel-Jaleel Yousef, Lecturer Ishraga Salih, Lecturer Intisar Abdu and Associate Professor Salah Ahmed Ali who they taught me the greatest value of hard work and encouraged me in all our endeavors.

This textbook is dedicated mainly to undergraduate engineering students, especially mechanical, and production engineering students where most of the applications presented are focused on the necessity and importance of using sensors in automobiles, which includes how fuel injection system works, crankshaft position sensor, cylinder head temperature gauge, internal combustion engine cooling, exhaust gas temperature gauge, idle air control actuator, engine knocking, manifold absolute pressure sensor (MAP), mass flow sensor, nitrogen oxide sensor, oxygen sensor, and throttle position sensor.

The present textbook presents a brief outline of the usage and functions of automobile sensors. Engine sensors in a vehicle are incorporated to provide the correct amount of fuel for all operating conditions. A large number of input sensors are monitored by the engine control unit. Today, sensor technology has become common in modern vehicles. Sensors enhance safety of the people - both on board and on road, control vehicle emissions and make vehicles more efficient. In this article, we will discuss different types of engine sensors used in modern vehicles.

Last but not least, may Allah accepts this humble work and i hope that it will be beneficial to its readers.

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I am also indebted to many people. Published texts in the necessity and importance of using sensors in automobiles have been contributed to the author’s thinking. The present study has been taken from the point of view of how fuel injection system works, crankshaft position sensor, cylinder head temperature gauge, internal combustion engine cooling, exhaust gas temperature gauge, idle air control actuator, engine knocking, manifold absolute pressure sensor (MAP), mass flow sensor, nitrogen oxide sensor, oxygen sensor, and throttle position sensor.

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Contents

Preface

Sensors are essential components of automotive electronic control systems. Sensors are defined as “devices that transform (or transduce) physical quantities such as pressure or acceleration (called measurands) into output signals (usually electrical) that serve as inputs for control systems". It wasn’t that long ago that the primary automotive sensors were discrete devices used to measure oil pressure, fuel level, coolant temperature, etc.

Starting in the late1970s, microprocessor-based automotive engine control modules were phased into satisfy federal emissions regulations .These systems required new sensors such as MAP (manifold absolute pressure), air temperature, and exhaust-gas stoichiometric air-fuel-ratio operating point sensors. The need for sensors is evolving and is progressively growing. For example, in engine control applications, the number of sensors used will increase from approximately ten in1995, to more than thirty in 2010. Automotive engineers are challenged by a multitude of stringent requirements. For example, automotive sensors typically must have combined/total error less than 3% over their entire range of operating temperature and measurands change, including all measurement errors due to nonlinearity.

Engine sensors in a vehicle are incorporated to provide the correct amount of fuel for all operating conditions. A large number of input sensors are monitored by the engine control unit. Today, sensor technology has become common in modern vehicles. Sensors enhance safety of the people - both on board and on road, control vehicle emissions and make vehicles more efficient. In this article, we will discuss different types of engine sensors used in modern vehicles.

The aim of the present textbook was to review the importance of using sensors in automobiles from different points of view which include how fuel injection system works, crankshaft position sensor, cylinder head temperature gauge, internal combustion engine cooling, exhaust gas temperature gauge, idle air control actuator, engine knocking, manifold absolute pressure sensor (MAP), mass flow sensor, nitrogen oxide sensor, oxygen sensor, and throttle position sensor.

Chapter one which is entitled as how fuel injection system works constitutes introduction to sensors used in automobiles, mass airflow sensor, oxygen sensor, throttle position sensor, coolant temperature sensor, voltage sensor, manifold absolute pressure sensor and engine speed sensor. Engine sensors in a vehicle are incorporated to provide the correct amount of fuel for all operating conditions. A large number of input sensors are monitored by the engine control unit. Today, sensor technology has become common in modern vehicles. Sensors enhance safety of the people - both on board and on road, control vehicle emissions and make vehicles more efficient. In this article, we will discuss different types of engine sensors used in modern vehicles.

Chapter two which is entitled crankshaft position sensor includes introduction, types of sensors, and function of sensor. A crank sensor is an electronic device used in an internal combustion engine, both petrol and diesel, to monitor the position or rotational speed of the crankshaft. This information is used by engine management systems to control the fuel injection or the ignition system timing and other engine parameters. Before electronic crank sensors were available, the distributor would have to be manually adjusted to a timing mark on petrol engines. The crank sensor can be used in combination with a similar camshaft position sensor to monitor the relationship between the pistons and valves in the engine, which is particularly important in engines with variable valve timing. This method is also used to "synchronize" a four stroke engine upon starting, allowing the management system to know when to inject the fuel. It is also commonly used as the primary source for the measurement of engine speed in revolutions per minute. Common mounting locations include the main crank pulley, the flywheel, the camshaft or on the crankshaft itself. This sensor is one of the two most important sensors in modern-day engines, together with the camshaft position sensor. As the fuel injection (diesel engines) or spark ignition (petrol engines) is usually timed from the crank sensor position signal, failing sensor will cause an engine not to start, or will cut out while running. Engine speed indicator takes speed indication also from this sensor.

Chapter three discusses the cylinder head temperature gauge handled in the present study. A cylinder head temperature gauge (CHT) measures the cylinder head temperature of an engine. Commonly used on air-cooled engines, the head temperature gauge displays the work that the engine is performing more quickly than an oil or water temperature gauge. As the engine works at high speed or uphill, head temperature will increase quickly. The meter can be digital or analog.

Chapter four discusses internal combustion engine cooling from the point of view of introduction, overview, basic principles, generalization difficulties, further information on air-cooled engine, and liquid cooling (radiator engine cooling). Internal combustion engine cooling uses either air or liquid to remove the waste heat from an internal combustion engine. For small or special purpose engines, cooling using air from the atmosphere makes for a lightweight and relatively simple system. Watercraft can use water directly from the surrounding environment to cool their engines. For water-cooled engines on aircraft and surface vehicles, waste heat is transferred from a closed loop of water pumped through the engine to the surrounding atmosphere by a radiator.

Chapter five discusses exhaust gas temperature gauge from the points of view of introduction, applications, oxygen sensor, and advanced tuning. An exhaust gas temperature gauge (EGT gauge) is a meter used to monitor the exhaust gas temperature of an internal combustion engine in conjunction with a thermocouple-type pyrometer. EGT gauges are found in certain cars and aero planes. By monitoring EGT, the driver or pilot can get an idea of the vehicle's air-fuel ratio (AFR). At a stoichiometric air-fuel ratio, the exhaust gas temperature is different from that in a lean or rich air-fuel ratio. At rich air-fuel ratio, the exhaust gas temperature either increases or decreases depending on the fuel. High temperatures (typically above 1,600 °F or 900 °C) can be an indicator of dangerous conditions that can lead to catastrophic engine failure.

Chapter six deliberates idle air control actuator from the viewpoint of introduction, description, and problems with IAC. An idle air control actuator or idle air control valve (IAC actuator/valve) is a device commonly used in fuel-injected vehicles to control the engine's idling rotational speed (RPM). In carbureted vehicles a similar device known as an idle speed control actuator is used.

Chapter seven studies Engine knocking from the following considerations: introduction, normal combustion, and abnormal combustion, knock detection, knock prediction, and knock control. Knocking also could be called knock, detonation, spark knock, pinging or pinking in spark ignition internal combustion engines occurs when combustion of some of the air/fuel mixture in the cylinder does not result from propagation of the flame front ignited by the spark plug, but one or more pockets of air/fuel mixture explode outside the envelope of the normal combustion front. The fuel-air charge is meant to be ignited by the spark plug only, and at a precise point in the piston's stroke. Knock occurs when the peak of the combustion process no longer occurs at the optimum moment for the four-stroke cycle. The shock wave creates the characteristic metallic "pinging" sound, and cylinder pressure increases dramatically. Effects of engine knocking range from inconsequential to completely destructive. Knocking should not be confused with pre-ignition, they are two separate events. However, pre-ignition can be followed by knocking. The phenomenon of detonation was first observed and described by Harry Ricardo during experiments carried out between 1916 and 1919 to discover the reason for failures in aircraft engines.

Chapter eight focusses on MAP sensor and includes introduction, a typical example, varying RPM and engine loads, vacuum comparison, EGR testing, and common confusion with boost sensors and gauges. The manifold absolute pressure sensor (MAP sensor) is one of the sensors used in an internal combustion engine's electronic control system. Engines that use a MAP sensor are typically fuel injected. The manifold absolute pressure sensor provides instantaneous manifold pressure information to the engine's electronic control unit (ECU). The data is used to calculate air density and determine the engine's air mass flow rate, which in turn determines the required fuel metering for optimum combustion (see stoichiometry) and influence the advance or retard of ignition timing. A fuel-injected engine may alternatively use a mass airflow sensor (MAF sensor) to detect the intake airflow. A typical naturally aspirated engine configuration employs one or the other, whereas forced induction engines typically use both; a MAF sensor on the charge pipe leading to the throttle body and a MAP sensor on the intake tract pre-turbo. MAP sensor data can be converted to air mass data by using a second variable coming from an IAT Sensor (intake air temperature sensor). This is called the speed-density method. Engine speed (RPM) is also used to determine where on a look up table to determine fueling, hence speed-density (engine speed / air density). The MAP sensor can also be used in OBD II (on-board diagnostics) applications to test the EGR (exhaust gas recirculation) valve for functionality, an application typical in OBD II equipped General Motors engines.

Chapter nine discusses mass flow sensor from the following consideration: introduction, moving vane meter, hot wire sensor (MAF), cold wire sensor, Kármán vortex sensor, membrane sensor, and laminar flow elements. A mass (air) flow sensor (MAF) is a sensor used to determine the mass flow rate of air entering a fuel-injected internal combustion engine. The air mass information is necessary for the engine control unit (ECU) to balance and deliver the correct fuel mass to the engine. Air changes its density with temperature and pressure. In automotive applications, air density varies with the ambient temperature, altitude and the use of forced induction, which means that mass flow sensors are more appropriate than volumetric flow sensors for determining the quantity of intake air in each cylinder. There are two common types of mass airflow sensors in use on automotive engines. These are the vane meter and the hot wire. Neither design employs technology that measures air mass directly. However, with additional sensors and inputs, an engine's ECU can determine the mass flow rate of intake air. Both approaches are used almost exclusively on electronic fuel injection (EFI) engines. Both sensor designs output a 0.0–5.0 volt or a pulse-width modulation (PWM) signal that is proportional to the air mass flow rate, and both sensors have an intake air temperature (IAT) sensor incorporated into their housings for most post on-board diagnostics (OBDII) vehicles. Vehicles prior to 1996 could have MAF without an IAT. An example is 1994 Infiniti Q 45. When a MAF sensor is used in conjunction with an oxygen sensor, the engine's air/fuel ratio can be controlled very accurately. The MAF sensor provides the open-loop controller predicted air flow information (the measured air flow) to the ECU, and the oxygen sensor provides closed-loop feedback in order to make minor corrections to the predicted air mass. Also see manifold absolute pressure sensor (MAP sensor).

Chapter ten handles nitrogen oxide sensor from the view point of introduction, overview, and challenges. A nitrogen oxide sensor or NOx sensor is typically a high-temperature device built to detect nitrogen oxides in combustion environments such as an automobile, automotive truck tailpipe or smokestack.

Chapter eleven discusses oxygen sensor from the point of view of introduction, automotive applications, and function of a lambda probe, the probe, and operation of the probe, location of the probe in a system, sensor surveillance, sensor failures, diving applications, and scientific applications. An oxygen sensor (or lambda sensor, where lambda refers to air–fuel equivalence ratio, usually denoted by λ) is an electronic device that measures the proportion of oxygen (O_2) in the gas or liquid being analyzed. It was developed by Robert Bosch GmbH during the late 1960s under the supervision of Dr. Günter Bauman. The original sensing element is made with a thimble-shaped zirconia ceramic coated on both the exhaust and reference sides with a thin layer of platinum and comes in both heated and unheated forms. The planar-style sensor entered the market in 1990 and significantly reduced the mass of the ceramic sensing element, as well as incorporating the heater within the ceramic structure. This resulted in a sensor that started sooner and responded faster. The most common application is to measure the exhaust-gas concentration of oxygen for internal combustion engines in automobiles and other vehicles in order to calculate and, if required, dynamically adjust the air-fuel ratio so that catalytic converters can work optimally, and also determine whether the converter is performing properly or not. Divers also use a similar device to measure the partial pressure of oxygen in their breathing gas. Scientists use oxygen sensors to measure respiration or production of oxygen and use a different approach. Oxygen sensors are used in oxygen analyzers, which find extensive use in medical applications such as anesthesia monitors, respirators and oxygen concentrator so. Oxygen sensors are also used in hypoxic air fire prevention systems to continuously monitor the oxygen concentration inside the protected volumes. There are many different ways of measuring oxygen. These include technologies such as zirconia, electrochemical (also known as galvanic), infrared, ultrasonic, paramagnetic, and very recently, laser methods.

Chapter twelve discusses throttle position sensor. A throttle position sensor (TPS) is a sensor used to monitor the air intake of an engine. The sensor is usually located on the butterfly spindle/shaft so that it can directly monitor the position of the throttle. More advanced forms of the sensor are also used, for example an extra closed throttle position sensor (CTPS) may be employed to indicate that the throttle is completely closed. Some engine control units (ECUs) also control the throttle position electronic throttle control (ETC) or "drive by wire" systems and if that is done the position sensor is used in a feedback loop to enable that control.

Keywords: Fuel Injection System; Crankshaft Position Sensor; Cylinder Head Temperature Gauge; Internal Combustion Engine Cooling; Exhaust

Gas Temperature Gauge; Idle Air Control Actuator; Engine knocking and Detonation; MAP Sensor; Mass Flow Sensor; Nitrogen Oxide Sensor; Oxygen Sensor; Throttle Position Sensor.

Chapter One

How Fuel Injection System Works

1.1 Introduction

Sensors are essential components of automotive electronic control systems. Sensors are defined as “devices that transform (or transduce) physical quantities such as pressure or acceleration (called measurands) into output signals (usually electrical) that serve as inputs for control systems". It wasn’t that long ago that the primary automotive sensors were discrete devices used to measure oil pressure, fuel level, coolant temperature, etc. [1].

Starting in the late1970s, microprocessor-based automotive engine control modules were phased into satisfy federal emissions regulations .These systems required new sensors such as MAP (manifold absolute pressure), air temperature, and exhaust-gas stoichiometric air-fuel-ratio operating point sensors. The need for sensors is evolving and is progressively growing. For example, in engine control applications, the number of sensors used will increase from approximately ten in1995, to more than thirty in 2010, as predicted in [2]. Automotive engineers are challenged by a multitude of stringent requirements. For example, automotive sensors typically must have combined/total error less than 3% over their entire range of operating temperature and measurands change, including all measurement errors due to nonlinearity.

Engine sensors in a vehicle are incorporated to provide the correct amount of fuel for all operating conditions. A large number of input sensors are monitored by the engine control unit. Today, sensor technology has become common in modern vehicles. Sensors enhance safety of the people - both on board and on road, control vehicle emissions and make vehicles more efficient. In this article, we will discuss different types of engine sensors used in modern vehicles.

In order to provide the correct amount of fuel for every operating condition, the engine control unit (ECU) has to monitor a huge number of input sensors. Here are just a few:

1.2 Mass Airflow Sensor

The mass airflow sensor tells the engine control unit (ECU) the mass of air entering the engine. The mass airflow sensor (MAF) sensor (electric sensor) is an integral part of the engine system. It is controlled by a computer . It is located in a plastic covering between the engine and the air filter. The purpose of MAF is to calculate the amount of air intake by the engine, in terms of volume and density. For measuring the volume and density of air, the sensor uses either a hot wire or a heated filament. After the measurement, it sends a voltage signal to the computer. With this, the computer can calculate the right amount of fuel needed to maintain the correct fuel mixture for every operating condition. If there is any fault in the MAF sensor, it may result in rough idle, stalling and poor fuel economy.

1.3 Oxygen Sensor

Oxygen sensor monitors the amount of oxygen in the exhaust so the e-ngine control unit (ECU) can determine how rich or lean the fuel mixture is and makes adjustments accordingly.

The oxygen sensor is located on the exhaust manifold. This sensor monitors the amount of unburned oxygen present in the exhaust. When the fuel mixture is rich, most of the oxygen is exhausted during the combustion. So, only a little unburned oxygen will be left out in the exhaust. Difference in the oxygen levels creates an electrical potential, which causes the sensor to generate a voltage signal. This helps the ECU to check the quality of fuel mixture to make the changes accordingly. The sensor output will be high if the fuel mixture is rich, and the sensor output will be low if the fuel mixture is lean.

1.4 Throttle Position Sensor

Throttle position sensor monitors the throttle valve position (which determines how much air goes into the engine) so the engine control unit (ECU) can respond quickly to changes, increasing or decreasing the fuel rate as necessary.

The Throttle Position Sensor (TPS) is a variable resistor attached or mounted on the throttle body and is operated by moving along with the throttle shaft or spindle. The TPS changes the resistances as the throttle opens and closes, and sends a voltage signal to the computer showing the angle or position of the throttle. Thus, the TPS causes the Electronic Control Unit (ECU) to use the data to measure the engine load, fuel delivery adjust timing, acceleration, deceleration when the engine is idle or in wide open throttle, and then makes the changes according to the operating conditions. Fuel rate is either increased or decreased to achieve this.

1.5 Coolant Temperature Sensor

Coolant temperature sensor allows the engine control unit (ECU) to determine when the engine has reached its proper operating temperature.

The Coolant Temperature Sensor (CTS) is a temperature dependent variable resistor located on the cylinder head or intake manifold. The CTS is an important sensor and the operating strategy of the engine depends on the signal it sends. So, it is called the “master” sensor .

The CTS measures the internal temperature of the engine coolant. It also senses the changes in temperature and sends a voltage signal to the Power train Control Module (PCM) for determining whether the engine is cold or warming up, is at normal operating temperature or is overheating.

1.6 Voltage Sensor

Voltage sensor monitors the system voltage in the car so the engine control unit (ECU) can raise the idle speed if voltage is dropping (which would indicate a high electrical load).

The voltage sensor monitors the system voltage of the vehicle and reports it to PCM so that it can rise the idle speed of the vehicle, if the voltage is dropping .

Engine sensors are an important technological innovation. They lead to better performance, better quality and more years of driving experience.

1.7 Manifold Absolute Pressure Sensor

Manifold absolute pressure sensor monitors the pressure of the air in the intake manifold.

The amount of air being drawn into the engine is a good indication of how much power it is producing; and the more air that goes into the engine, the lower the manifold pressure, so this reading is used to gauge how much power is being produced.

The MAP is a key sensor as it senses the engine load. It is mounted on the intake manifold. It monitors the difference between the air pressure in the intake manifold and outside. This sensor responds to the vacuum in the intake manifold and generates a voltage signal accordingly. It then sends the signal to the PCM. The input of the sensor is used for adjusting the fuel mixture and ignition timing, according to the changes.

1.8 Engine Speed Sensor

Engine speed sensor monitors engine speed, which is one of the factors used to calculate the pulse width.

There are two main types of control for multi-port systems: The fuel injectors can all open at the same time, or each one can open just before the intake valve for its cylinder opens (this is called sequential multi-port fuel injection).

The advantage of sequential fuel injection is that if the driver makes a sudden change, the system can respond more quickly because from the time the change is made, it only has to wait only until the next intake valve opens, instead of for the next complete revolution of the engine.

The Engine Speed Sensor (ESS) is a sensor attached to the crankshaft of the car's engine. It is different from vehicle speed sensor. The ESS is used for monitoring the engine speed. In other words, it is meant for assessing the speed at which the crankshaft spins.

Chapter Two

Crankshaft Position Sensor

2.1 Introduction

A crank sensor is an electronic device used in an internal combustion engine, both petrol and diesel, to monitor the position or rotational speed of the crankshaft. This information is used by engine management systems to control the fuel injection or the ignition system timing and other engine parameters. Before electronic crank sensors were available, the distributor would have to be manually adjusted to a timing mark on petrol engines.

The crank sensor can be used in combination with a similar camshaft position sensor to monitor the relationship between the pistons and valves in the engine, which is particularly important in engines with variable valve timing. This method is also used to "synchronize" a four stroke engine upon starting, allowing the management system to know when to inject the fuel. It is also commonly used as the primary source for the measurement of engine speed in revolutions per minute.

Common mounting locations include the main crank pulley, the flywheel, the camshaft or on the crankshaft itself. This sensor is one of the two most important sensors in modern-day engines, together with the camshaft position sensor. As the fuel injection (diesel engines) or spark ignition (petrol engines) is usually timed from the crank sensor position signal, failing sensor will cause an engine not to start, or will cut out while running. Engine speed indicator takes speed indication also from this sensor.

2.2 Types of Sensor

There are several types of sensor in use. The inductive sensor, Hall Effect sensor, magneto resistive sensor, optical sensor. Inductive sensors have the simplest construction and are usually purely passive devices. Hall Effect and magneto resistive sensors have the advantage over inductive sensors in that they can detect static (non-changing) magnetic fields. Optical sensors do not have great resistance against fouling, but are able to provide the most precise edge detection.

Some engines, such as GM's Premium V family, use crank position sensors which read a reluctor ring integral to the harmonic balancer. This is a much more accurate method of determining the position of the crankshaft, and allows the computer to determine within a few degrees the exact position of the crankshaft (and thereby all connected components) at any given time.

2.3 Function of Sensor

The functional objective for the crankshaft position sensor is to determine the position and/or rotational speed (RPM) of the crank. Engine Control Units use the information transmitted by the sensor to control parameters such as ignition timing and fuel injection timing. In a diesel the sensor will control the fuel injection. The sensor output may also be related to other sensor data including the cam position to derive the current combustion cycle, this is very important for the starting of a four stroke engine.

Sometimes, the sensor may become burnt or worn out - or just die of old age at high mileage. One likely cause of crankshaft position sensor failure is exposure to extreme heat. Others are vibration causing a wire to fracture or corrosion on the pins of harness connectors. Many modern crankshaft sensors are sealed units and therefore will not be damaged by water or other fluids. When it goes wrong, it stops transmitting the signal which contains the vital data for the ignition and other parts in the system.

A bad crank position sensor can worsen the way the engine idles, or the acceleration behavior. If the engine is revved up with a bad or faulty sensor, it may cause misfiring, motor vibration or backfires. Acceleration might be hesitant, and abnormal shaking during engine idle might occur. In the worst case the car may not start.

The first sign of crankshaft sensor failure, usually, is the refusal of the engine to start when hot but will start again once the engine has cooled.

One detail of some designs is the "three wire" inductive crank sensor whereby the third wire is actually just a co-axial shield around the two main sensor wires to prevent them from picking up stray electrical pulses from elsewhere in the vehicle engine bay.

Chapter Three

Cylinder Head Temperature Gauge

A cylinder head temperature gauge (CHT) measures the cylinder head temperature of an engine. Commonly used on air-cooled engines, the head temperature gauge displays the work that the engine is performing more quickly than an oil or water temperature gauge. As the engine works at high speed or uphill, head temperature will increase quickly. The meter can be digital or analog.

An air-cooled engine requires a steady flow of air for cooling. Unlike water cooled engine, air cooled engines have no thermostat. Over temperature can cause engine failure. Air-cooled engine are used in aircraft engine control and other air-cooled engines as in cars and air-cooled motorcycles [3], [4], [5], [6] and [7]. Figure 3.1 shows a cylinder from an air-cooled aviation engine, a continental C85. Notice the rows of fins on both the steel cylinder barrel and the aluminum cylinder head. The fins provide additional surface area for air to pass over the cylinder and absorb heat.

The CHT senders usually has a K-type thermocouple that is mounted under the spark plug. The K-type thermocouple is pair of two dissimilar metals that produce a small voltage signal when heated. The metal closest to the spark plug is called the hot junction and the other close to the head cold junction. The ring under the spark plug is used to transfer the heat from the plug to the thermocouple. The gauge and cold junction are usually calibrated at room temperature 72 °F (22 °C). Because the thermocouple is calibrated for room temperature, the gauge readings will only be 100% accurate at that engine compartment temperature. If the engine compartment temperature is colder the CHT temperature will display higher. If the engine compartment temperature is higher the reading will be lower. The error can be fixed with a cold-junction compensating thermistor, which measures the temperature at the cold junction so the gauge can adjust the reading. Low budget gauges do not have this compensating thermistor. Figure 3.2 shows a flat-four aircraft engine

Figure 3.1 a Cylinder from an Air-Cooled Aviation Engine, a Continental C85

Figure 3.2 Flat-Four Aircraft Engine

Chapter Four

Internal Combustion Engine Cooling

4.1 Introduction

Internal combustion engine cooling uses either air or liquid to remove the waste heat from an internal combustion engine. For small or special purpose engines, cooling using air from the atmosphere makes for a lightweight and relatively simple system. Watercraft can use water directly from the surrounding environment to cool their engines. For water-cooled engines on aircraft and surface vehicles, waste heat is transferred from a closed loop of water pumped through the engine to the surrounding atmosphere by a radiator.

Water has a higher heat capacity than air, and can thus move heat more quickly away from the engine, but a radiator and pumping system add weight, complexity, and cost. Higher-power engines generate more waste heat, but can move more weight, meaning they are generally water-cooled. Radial engines allow air to flow around each cylinder directly, giving them an advantage for air cooling over straight engines, flat engines, and V engines. Rotary engines have a similar configuration, but the cylinders also continually rotate, creating an air flow even when the vehicle is stationary.

Aircraft design more strongly favors lower weight and air-cooled designs. Rotary engines were popular on aircraft until the end of World War I, but had serious stability and efficiency problems. Radial engines were popular until the end of World War II, until gas turbine engines largely replaced them. Modern propeller-driven aircraft with internal-combustion engines are still largely air-cooled. Modern cars generally favor power over weight, and typically have water-cooled engines. Modern motorcycles are lighter than cars, and both cooling fluids are common [8]. Some sport motorcycles were cooled with both air and oil (sprayed underneath the piston heads).

4.2 Overview

Heat engines generate mechanical power by extracting energy from heat flows, much as a water wheel extracts mechanical power from a flow of mass falling through a distance. Engines are inefficient, so more heat energy enters the engine than comes out as mechanical power; the difference is waste heat which must be removed. Internal combustion engines remove waste heat through cool intake air, hot exhaust gases, and explicit engine cooling.

Engines with higher efficiency have more energy leave as mechanical motion and less as waste heat. Some waste heat is essential: it guides heat through the engine, much as a water wheel works only if there is some exit velocity (energy) in the waste water to carry it away and make room for more water. Thus, all heat engines need cooling to operate.

Cooling is also needed because high temperatures damage engine materials and lubricants and becomes even more important in hot climates [9]. Internal-combustion engines burn fuel hotter than the melting temperature of engine materials, and hot enough to set fire to lubricants. Engine cooling removes energy fast enough to keep temperatures low so the engine can survive [10].

Some high-efficiency engines run without explicit cooling and with only incidental heat loss, a design called adiabatic. Such engines can achieve high efficiency but compromise power output, duty cycle, engine weight, durability, and emissions.

4.3 Basic Principles

Most internal combustion engines are fluid cooled using either air (a gaseous fluid) or a liquid coolant run through a heat exchanger (radiator) cooled by air. Marine engines and some stationary engines have ready access to a large volume of water at a suitable temperature. The water may be used directly to cool the engine, but often has sediment, which can clog coolant passages, or chemicals, such as salt, that can chemically damage the engine. Thus, engine coolant may be run through a heat exchanger that is cooled by the body of water.

Most liquid-cooled engines use a mixture of water and chemicals such as antifreeze and rust inhibitors. The industry term for the antifreeze mixture is engine coolant. Some antifreezes use no water at all, instead using a liquid with different properties, such as propylene glycol or a combination of propylene glycol and ethylene glycol. Most "air-cooled" engines use some liquid oil cooling, to maintain acceptable temperatures for both critical engine parts and the oil itself. Most "liquid-cooled" engines use some air cooling, with the intake stroke of air cooling the combustion chamber. An exception is Wankel engines, where some parts of the combustion chamber are never cooled by intake, requiring extra effort for successful operation.

There are many demands on a cooling system. One key requirement is to adequately serve the entire engine, as the whole engine fails if just one part overheats. Therefore, it is vital that the cooling system keep all parts at suitably low temperatures. Liquid-cooled engines are able to vary the size of their passageways through the engine block so that coolant flow may be tailored to the needs of each area. Locations with either high peak temperatures (narrow islands around the combustion chamber) or high heat flow (around exhaust ports) may require generous cooling. This reduces the occurrence of hot spots, which are more difficult to avoid with air cooling. Air-cooled engines may also vary their cooling capacity by using more closely spaced cooling fins in that area, but this can make their manufacture difficult and expensive.

Only the fixed parts of the engine, such as the block and head, are cooled directly by the main coolant system. Moving parts such as the pistons, and to a lesser extent the crank and rods, must rely on the lubrication oil as a coolant, or to a very limited amount of conduction into the block and thence the main coolant. High performance engines frequently have additional oil, beyond the amount needed for lubrication, sprayed upwards onto the bottom of the piston just for extra cooling. Air-cooled motorcycles often rely heavily on oil-cooling in addition to air-cooling of the cylinder barrels.

Liquid-cooled engines usually have a circulation pump. The first engines relied on thermo-syphon cooling alone, where hot coolant left the top of the engine block and passed to the radiator, where it was cooled before returning to the bottom of the engine. Circulation was powered by convection alone.

Other demands include cost, weight, reliability, and durability of the cooling system itself.

Conductive heat transfer is proportional to the temperature difference between materials. If engine metal is at 250 °C and the air is at 20 °C, then there is a 230 °C temperature difference for cooling. An air-cooled engine uses all of this difference. In contrast, a liquid-cooled engine might dump heat from the engine to a liquid, heating the liquid to 135 °C (Water's standard boiling point of 100 °C can be exceeded as the cooling system is both pressurized, and uses a mixture with antifreeze) which is then cooled with 20 °C air. In each step, the liquid-cooled engine has half the temperature difference and so at first appears to need twice the cooling area.

However, properties of the coolant (water, oil, or air) also affect cooling. As example, comparing water and oil as coolants, one gram of oil can absorb about 55% of the heat for the same rise in temperature (called the specific heat capacity). Oil has about 90% the density of water, so a given volume of oil can absorb only about 50% of the energy of the same volume of water. The thermal conductivity of water is about four times that of oil, which can aid heat transfer. The viscosity of oil can be ten times greater than water, increasing the energy required to pump oil for cooling, and reducing the net power output of the engine.

Comparing air and water, air has vastly lower heat capacity per gram and per volume (4000) and less than a tenth the conductivity, but also much lower viscosity (about 200 times lower: 17.4 × 10−6 Pa.s for air vs 8.94 × 10−4 Pa.s for water). Continuing the calculation from two paragraphs above, air cooling needs ten times of the surface area, therefore the fins, and air needs 2000 times the flow velocity and thus a recirculating air fan needs ten times the power of a recirculating water pump. Moving heat from the cylinder to a large surface area for air cooling can present problems such as difficulties manufacturing the shapes needed for good heat transfer and the space needed for free flow of a large volume of air. Water boils at about the same temperature desired for engine cooling. This has the advantage that it absorbs a great deal of energy with very little rise in temperature (called heat of vaporization), which is good for keeping things cool, especially for passing one stream of coolant over several hot objects and achieving uniform temperature. In contrast, passing air over several hot objects in series warms the air at each step, so the first may be over-cooled and the last under-cooled. However, once water boils, it is an insulator, leading to a sudden loss of cooling where steam bubbles form (for more, see heat transfer). Steam may return to water as it mixes with other coolant, so an engine temperature gauge can indicate an acceptable temperature even though local temperatures are high enough that damage is being done.

An engine needs different temperatures. The inlet including the compressor of a turbo and in the inlet trumpets and the inlet valves need to be as cold as possible. A countercurrent heat exchange with forced cooling air does the job. The cylinder-walls should not heat up the air before compression, but also not cool down the gas at the combustion. A compromise is a wall temperature of 90 °C. The viscosity of the oil is optimized for just this temperature. Any cooling of the exhaust and the turbine of the turbocharger reduces the amount of power available to the turbine, so the exhaust system is often insulated between engine and turbocharger to keep the exhaust gases as hot as possible.

The temperature of the cooling air may range from well below freezing to 50 °C. Further, while engines in long-haul boat or rail service may operate at a steady load, road vehicles often see widely varying and quickly varying load. Thus, the cooling system is designed to vary cooling so the engine is neither too hot nor too cold. Cooling system regulation includes adjustable baffles in the air flow (sometimes called 'shutters' and commonly run by a pneumatic 'shutter stat); a fan which operates either independently of the engine, such as an electric fan, or which has an adjustable clutch; a thermostatic valve or just 'thermostat' that can block the coolant flow when too cool. In addition, the motor, coolant, and heat exchanger have some heat capacity which smooths out temperature increase in short sprints. Some engine controls shut down an engine or limit it to half throttle if it overheats. Modern electronic engine controls adjust cooling based on throttle to anticipate a temperature rise, and limit engine power output to compensate for finite cooling.

Finally, other concerns may dominate cooling system design. As example, air is a relatively poor coolant, but air cooling systems are simple, and failure rates typically rise as the square of the number of failure points. Also, cooling capacity is reduced only slightly by small air coolant leaks. Where reliability is of utmost importance, as in aircraft, it may be a good trade-off to give up efficiency, longevity (interval between engine rebuilds), and quietness in order to achieve slightly higher reliability; the consequences of a broken airplane engine are so severe, even a slight increase in reliability is worth giving up other good properties to achieve it.

Air-cooled and liquid-cooled engines are both used commonly. Each principle has advantages and disadvantages, and particular applications may favor one over the other. For example, most cars and trucks use liquid-cooled engines, while many small airplane and low-cost engines are air-cooled.

4.4 Generalization Difficulties

It is difficult to make generalizations about air-cooled and liquid-cooled engines. Air-cooled diesel engines are chosen for reliability even in extreme heat, because air-cooling would be simpler and more effective at coping with the extremes of temperatures during the depths of winter and height of summer, than water cooling systems, and are often used in situations where the engine runs unattended for months at a time [11].

Similarly, it is usually desirable to minimize the number of heat transfer stages in order to maximize the temperature difference at each stage. However, Detroit Diesel two-stroke cycle engines commonly used oil cooled by water, with the water in turn cooled by air [12].

The coolant used in many liquid-cooled engines must be renewed periodically, and can freeze at ordinary temperatures thus causing permanent engine damage when it expands. Air-cooled engines do not require coolant service, and do not suffer damage from freezing, two commonly cited advantages for air-cooled engines. However, coolant based on propylene glycol is liquid to −55 °C, colder than is encountered by many engines; shrinks slightly when it crystallizes, thus avoiding damage; and has a service life over 10,000 hours, essentially the lifetime of many engines.

It is usually more difficult to achieve either low emissions or low noise from an air-cooled engine, two more reasons most road vehicles use liquid-cooled engines. It is also often difficult to build large air-cooled engines, so nearly all air-cooled engines are under 500 kW (670 hp), whereas large liquid-cooled engines exceed 80 MW (107000 hp) (Wärtsilä-Sulzer RTA96-C 14-cylinder diesel).

4.5 Further Information on Air-Cooled Engine

Cars and trucks using direct air cooling (without an intermediate liquid) were built over a long period from the very beginning and ending with a small and generally unrecognized technical change. Before World War II, water-cooled cars and trucks routinely overheated while climbing mountain roads, creating geysers of boiling cooling water. This was considered normal, and at the time, most noted mountain roads had auto repair shops to minister to overheating engines.

ACS (Auto Club Suisse) maintains historical monuments to that era on the Susten Pass where two radiator refill stations remain. These have instructions on a cast metal plaque and a spherical bottom watering can hanging next to a water spigot. The spherical bottom was intended to keep it from being set down and, therefore, be useless around the house, in spite of which it was stolen, as the picture shows.

During that period, European firms such as Magirus-Deutz built air-cooled diesel trucks, Porsche built air-cooled farm tractors [13], and Volkswagen became famous with air-cooled passenger cars. In the United States, Franklin built air-cooled engines.

For many years air cooling was favored for military applications as liquid cooling systems are more vulnerable to damage by shrapnel.

The Czech Republic–based company Tatra is known for their large displacement air-cooled V8 car engines; Tatra engineer Julius Mackerle published a book on it. Air-cooled engines are better adapted to extremely cold and hot environmental weather temperatures: you can see air-cooled engines starting and running in freezing conditions that seized water-cooled engines and continue working when water-cooled ones start producing steam jets. Air-cooled engines have may be an advantage from a thermodynamic point of view due to higher operating temperature. The worst problem met in air-cooled aircraft engines was the so-called "Shock cooling", when the airplane entered in a dive after climbing or level flight with throttle open, with the engine under no load while the airplane dives generating less heat, and the flow of air that cools the engine is increased, a catastrophic engine failure may result as different parts of engine have different temperatures, and thus different thermal expansions. In such conditions, the engine may seize, and any sudden change or imbalance in the relation between heat produced by the engine and heat dissipated by cooling may result in an increased wear of engine, as a consequence also of thermal expansion differences between parts of engine, liquid-cooled engines having more stable and uniform working temperatures.

4.6 Liquid Cooling (Radiator Engine Cooling)

Today, most automotive and larger IC engines are liquid-cooled [14], [15] and [16].

Liquid cooling is also employed in maritime vehicles (vessels, etc.). For vessels, the seawater itself is mostly used for cooling. In some cases, chemical coolants are also employed (in closed systems) or they are mixed with seawater cooling [17] and [18].

The change of air cooling to liquid cooling occurred at the start of World War II when the US military needed reliable vehicles. The subject of boiling engines was addressed, researched, and a solution found. Previous radiators and engine blocks were properly designed and survived durability tests, but used water pumps with a leaky graphite-lubricated "rope" seal (gland) on the pump shaft. The seal was inherited from steam engines, where water loss is accepted, since steam engines already expend large volumes of water. Because the pump seal leaked mainly when the pump was running and the engine was hot, the water loss evaporated inconspicuously, leaving at best a small rusty trace when the engine stopped and cooled, thereby not revealing significant water loss. Automobile radiators (or heat exchangers) have an outlet that feeds cooled water to the engine and the engine has an outlet that feeds heated water to the top of the radiator. Water circulation is aided by a rotary pump that has only a slight effect, having to work over such a wide range of speeds that its impeller has only a minimal effect as a pump. While running, the leaking pump seal drained cooling water to a level where the pump could no longer return water to the top of the radiator, so water circulation ceased and water in the engine boiled. However, since water loss led to overheat and further water loss from boil-over, the original water loss was hidden.

A special class of experimental prototype internal combustion piston engines have been developed over several decades with the goal of improving efficiency by reducing heat loss [19]. These engines are variously called adiabatic engines, due to better approximation of adiabatic expansion, low heat rejection engines, or high-temperature engines [20]. They are generally diesel engines with combustion chamber parts lined with ceramic thermal barrier coatings [21]. Some make use of titanium pistons and other titanium parts due to its low thermal conductivity [22] and mass. Some designs are able to eliminate the use of a cooling system and associated parasitic losses altogether [23]. Developing lubricants able to withstand the higher temperatures involved has been a major barrier to commercialization [24]. Figure 4.1 shows a typical engine coolant radiator used in an automobile and Figure 4.2 below shows coolant being poured into the radiator of an automobile.

Figure 4.1 A Typical Engine Coolant Radiator used in an Automobile

Figure 4.2 Coolant being poured into the Radiator of an Automobile

Figure 4.3 below shows a fully closed IC engine cooling system and Figures 4.4 and 4.5 below shows respectively an open IC engine cooling system and a semi-closed IC engine cooling system.

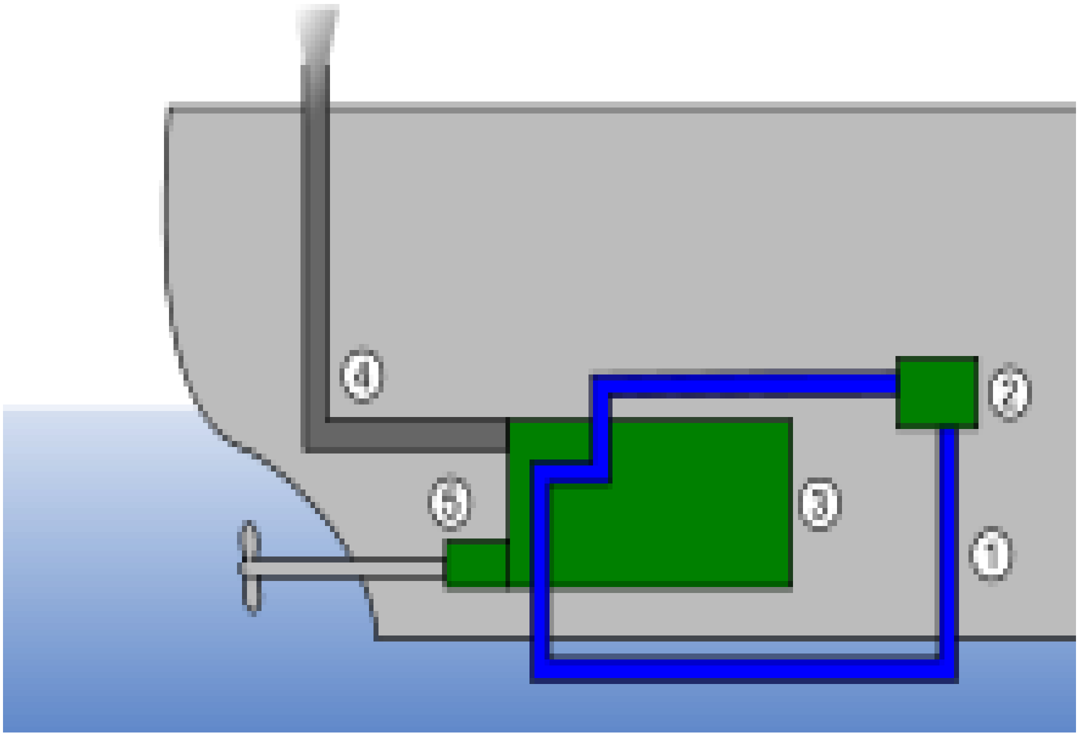

Figure 4.3 a Fully Closed IC Engine Cooling System

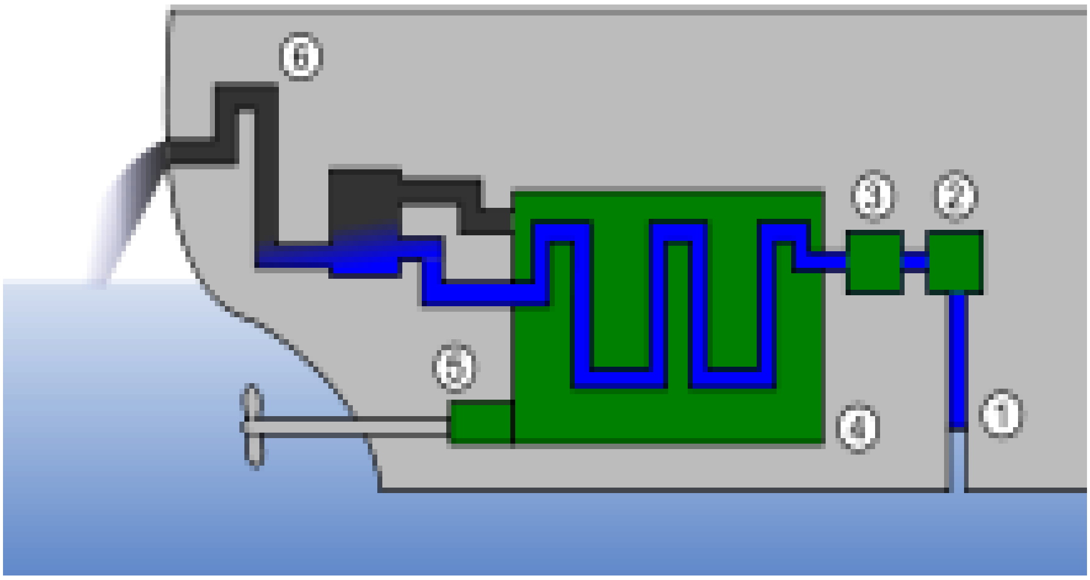

Figure 4.4 Open IC Engine Cooling System

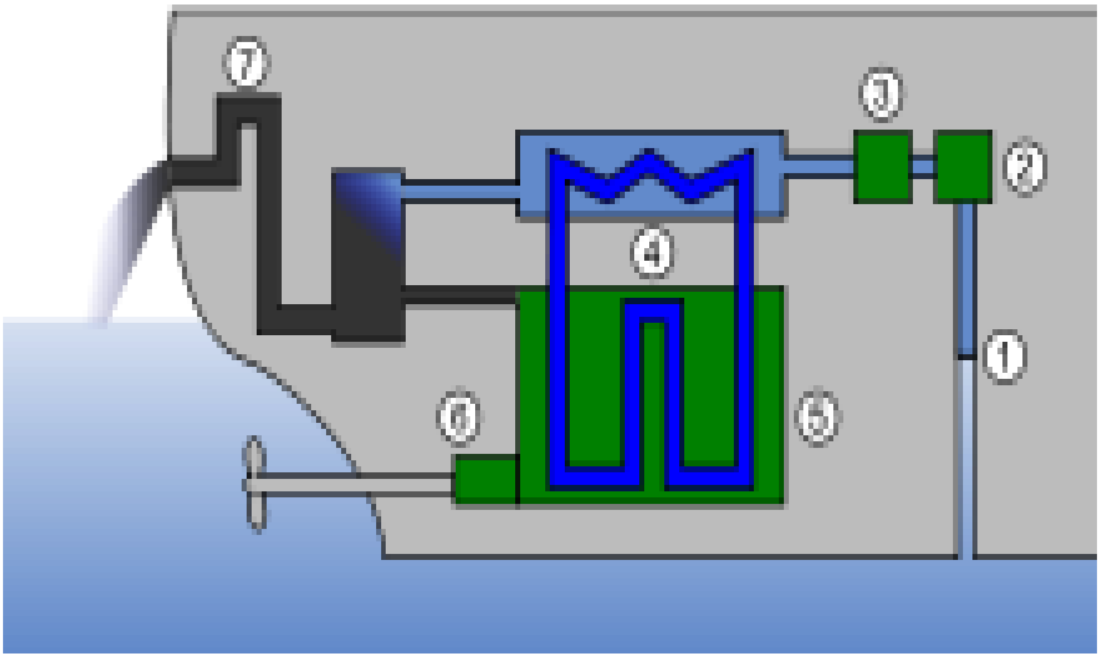

Figure 4.5 Semi-Closed IC Engine Cooling System

Chapter Five

Exhaust Gas Temperature Gauge

5.1 Introduction

An exhaust gas temperature gauge (EGT gauge) is a meter used to monitor the exhaust gas temperature of an internal combustion engine in conjunction with a thermocouple-type pyrometer. EGT gauges are found in certain cars and aero planes. By monitoring EGT, the driver or pilot can get an idea of the vehicle's air-fuel ratio (AFR).

At a stoichiometric air-fuel ratio, the exhaust gas temperature is different from that in a lean or rich air-fuel ratio. At rich air-fuel ratio, the exhaust gas temperature either increases or decreases depending on the fuel. High temperatures (typically above 1,600 °F or 900 °C) can be an indicator of dangerous conditions that can lead to catastrophic engine failure.

5.2 Applications

Most light piston aircraft still have manual mixture controls, and pilots use an EGT gauge to set the optimal fuel-air mixture for their current density altitude and power. The hottest cylinder-head temperatures (CHT) and highest internal cylinder pressures occur around 50 °F rich of peak EGT, and risk pre-detonation, so it's essential to avoid that area, and fly either lean of peak EGT or richer than 100° rich of peak EGT. Leaner mixtures result in significant fuel savings, but may result in rough operation of some carbureted or badly-tuned fuel-injected engines [25].

EGT meters are used for tuning turbo-equipped cars. If the sensor is installed at the manifold collector before the turbo, the turbine inlet temperature can be monitored. If the sensor is installed after the turbo, the exhaust temperature can be monitored. Because EGT typically drops 200–300 °F (110–170 °C) across the turbine, installers try to put the thermocouple as close to the cylinder head as possible to give a true reading, and a reading that will react faster to the engine's condition compared to an installation after the turbo.

Air-cooled engines, like used in Volkswagen, Porsche and other cars can be damaged by overheating. An exhaust gas temperature gauge can be used to prevent damage [26]. Air-cooled motorcycle engines also can be damaged by overheating.

5.3 Oxygen Sensor

Using an EGT meter alone is considered an older technique for getting the most out of petrol and diesel engines, as a gauge-type wideband digital oxygen sensor can be purchased for about the same price, or for a little more. However, some advanced racers will use EGT gauges in combination with a wideband oxygen sensor to 'lean' the fuel ratio a bit to safely raise the temperature for more power.

5.4 Advanced Tuning

Though by tuning primarily by EGT and air fuel ratio values, EGT is still to this day a used data output for engine tuning. When fine tuning an engine, if possible with the ECU manipulation with the cylinder's timing can be made. By adjusting the timing, the resultant cylinder temperature can be used to improve cylinder efficiency. Though this is still widely done, EGT values should be used as a safe guard sensor measure and as a tuning guide [25].

Chapter Six

Idle Air Control Actuator

6.1 Introduction

An idle air control actuator or idle air control valve (IAC actuator/valve) is a device commonly used in fuel-injected vehicles to control the engine's idling rotational speed (RPM) [27]. In carbureted vehicles a similar device known as an idle speed control actuator is used.

6.2 Description

The IAC actuator is an electrically controlled device, which gets its input from the vehicle's engine control unit (ECU). The actuator is fitted such that it either bypasses the throttle or operates the throttle butterfly valve directly. The actuator consists of a linear servo actuator servomotor that controls a plunger which varies air flow through the throttle body. The position of the servomotor and hence the amount of air bypass is controlled digitally by the engine ECU. This allows the engine's idle speed to be maintained constant. The linear servo is most commonly a combination of a DC motor, lead screw and a digital optical encoder.

There is essentially no difference in efficiency between the technique of bypassing the throttle butterfly and operating the butterfly itself. The IAC allows the ECU to maintain minimum RPM irrespective of changes in engine load, sometimes referred to as anti-stall feature. Thus the driver can more easily move the car from stand-still by merely releasing the clutch (manual transmission) or the brake (automatic transmission) without having to simultaneously press the accelerator.

6.3 Problems with IAC

Although the IAC is supposed to last the vehicle's lifetime, various reasons may cause it to fail/malfunction prematurely. The most common failure mode is partial/complete jamming of the actuator (due to dirt/dust or even oil) where it cannot be smoothly controlled. The result is an engine that fails to maintain idle RPM and frequently stalls. A jammed actuator may be freed simply by cleaning it. However an actuator that has stopped working due to a fault in its servomotor will need replacement.

Air leaks in either the stepper housing or pipes will cause elevated idle RPM.

Chapter Seven

Engine Knocking

7.1 Introduction

Knocking also could be called knock, detonation, spark knock, pinging or pinking in spark ignition internal combustion engines occurs when combustion of some of the air/fuel mixture in the cylinder does not result from propagation of the flame front ignited by the spark plug, but one or more pockets of air/fuel mixture explode outside the envelope of the normal combustion front. The fuel-air charge is meant to be ignited by the spark plug only, and at a precise point in the piston's stroke. Knock occurs when the peak of the combustion process no longer occurs at the optimum moment for the four-stroke cycle. The shock wave creates the characteristic metallic "pinging" sound, and cylinder pressure increases dramatically. Effects of engine knocking range from inconsequential to completely destructive.

Knocking should not be confused with pre-ignition, they are two separate events. However, pre-ignition can be followed by knocking.

The phenomenon of detonation was first observed and described by Harry Ricardo during experiments carried out between 1916 and 1919 to discover the reason for failures in aircraft engines [28].

7.2 Normal Combustion

Under ideal conditions the common internal combustion engine burns the fuel/air mixture in the cylinder in an orderly and controlled fashion.

The combustion is started by the spark plug some 10 to 40 crankshaft degrees prior to top dead center (TDC), depending on many factors including engine speed and load. This ignition advance allows time for the combustion process to develop peak pressure at the ideal time for maximum recovery of work from the expanding gases [29].

The spark across the spark plug's electrodes forms a small kernel of flame approximately the size of the spark plug gap. As it grows in size, its heat output increases, which allows it to grow at an accelerating rate, expanding rapidly through the combustion chamber. This growth is due to the travel of the flame front through the combustible fuel air mix itself, and due to turbulence which rapidly stretches the burning zone into a complex of fingers of burning gas that have a much greater surface area than a simple spherical ball of flame would have. In normal combustion, this flame front moves throughout the fuel/air mixture at a rate characteristic for the particular mixture. Pressure rises smoothly to a peak, as nearly all the available fuel is consumed, then pressure falls as the piston descends. Maximum cylinder pressure is achieved a few crankshaft degrees after the piston passes TDC, so that the force applied on the piston (from the increasing pressure applied to the top surface of the piston) can give its hardest push precisely when the piston's speed and mechanical advantage on the crank shaft gives the best recovery of force from the expanding gases, thus maximizing torque transferred to the crankshaft [29] and [30].

7.3 Abnormal Combustion

When unburned fuel/air mixture beyond the boundary of the flame front is subjected to a combination of heat and pressure for a certain duration (beyond the delay period of the fuel used), detonation may occur. Detonation is characterized by an almost instantaneous, explosive ignition of at least one pocket of fuel/air mixture outside of the flame front. A local shockwave is created around each pocket, and the cylinder pressure will rise sharply – and possibly beyond its design limits – causing damage.

If detonation is allowed to persist under extreme conditions or over many engine cycles, engine parts can be damaged or destroyed. The simplest deleterious effects are typically particle wear caused by moderate knocking, which may further ensue through the engine's oil system and cause wear on other parts before being trapped by the oil filter. Such wear gives the appearance of erosion, abrasion, or a "sandblasted" look, similar to the damage caused by hydraulic cavitation. Severe knocking can lead to catastrophic failure in the form of physical holes melted and pushed through the piston or cylinder head (i.e., rupture of the combustion chamber), either of which depressurizes the affected cylinder and introduces large metal fragments, fuel, and combustion products into the oil system. Hypereutectic pistons are known to break easily from such shock waves [30].

Detonation can be prevented by any or all of the following techniques:

1. The use of a fuel with high octane rating, which increases the combustion temperature of the fuel and reduces the proclivity to detonate.

2. Enriching the air–fuel ratio which alters the chemical reactions during combustion, reduces the combustion temperature and increases the margin to detonation.

3. Reducing peak cylinder pressure

4. Decreasing the manifold pressure by reducing the throttle opening or boost pressure.

5. Reducing the load on the engine

6. Retarding ignition timing.

Because pressure and temperature are strongly linked, knock can also be attenuated by controlling peak combustion chamber temperatures by compression ratio reduction, exhaust gas recirculation, appropriate calibration of the engine's ignition timing schedule, and careful design of the engine's combustion chambers and cooling system as well as controlling the initial air intake temperature.

The addition of certain materials such as lead and thallium will suppress detonation extremely well when certain fuels are used. The addition of tetraethyl lead (TEL), a soluble organolead compound added to gasoline, was common until it was discontinued for reasons of toxic pollution. Lead dust added to the intake charge will also reduce knock with various hydrocarbon fuels. Manganese compounds are also used to reduce knock with petrol fuel.

Knock is less common in cold climates. As an aftermarket solution, a water injection system can be employed to reduce combustion chamber peak temperatures and thus suppress detonation. Steam (water vapor) will suppress knock even though no added cooling is supplied.

Certain chemical changes must first occur for knock to happen, hence fuels with certain structures tend to knock more easily than others. Branched chain paraffin tends to resist knock while straight chain paraffin knocks easily. It has been theorized that lead, steam, and the like interfere with some of the various oxidative changes that occur during combustion and hence reduce knock.

Turbulence, as stated, has a very important effect on knock. Engines with good turbulence tend to knock less than engines with poor turbulence. Turbulence occurs not only while the engine is inhaling but also when the mixture is compressed and burned. Many pistons are designed to use "squish" turbulence to violently mix the air and fuel together as they are ignited and burned, which reduces knock greatly by speeding up burning and cooling the unburnt mixture. One example of this is all modern side valve or flathead engines. A considerable portion of the head space is made to come in close proximity to the piston crown, making for much turbulence near TDC. In the early days of side valve heads this was not done and a much lower compression ratio had to be used for any given fuel. Also such engines were sensitive to ignition advance and had less power [30].

Knocking is more or less unavoidable in diesel engines, where fuel is injected into highly compressed air towards the end of the compression stroke. There is a short lag between the fuel being injected and combustion starting. By this time there is already a quantity of fuel in the combustion chamber which will ignite first in areas of greater oxygen density prior to the combustion of the complete charge. This sudden increase in pressure and temperature causes the distinctive diesel 'knock' or 'clatter', some of which must be allowed for in the engine design.

Careful design of the injector pump, fuel injector, combustion chamber, piston crown and cylinder head can reduce knocking greatly, and modern engines using electronic common rail injection have very low levels of knock. Engines using indirect injection generally have lower levels of knock than direct injection engines, due to the greater dispersal of oxygen in the combustion chamber and lower injection pressures providing a more complete mixing of fuel and air. Diesels actually do not suffer exactly the same "knock" as gasoline engines since the cause is known to be only the very fast rate of pressure rise, not unstable combustion. Diesel fuels are actually very prone to knock in gasoline engines but in the diesel engine there is no time for knock to occur because the fuel is only oxidized during the expansion cycle. In the gasoline engine the fuel is slowly oxidizing all the time while it is being compressed before the spark. This allows for changes to occur in the structure/makeup of the molecules before the very critical period of high temperature/pressure [30].

7.4 Knock Detection

Due to the large variation in fuel quality, a large number of engines now contain mechanisms to detect knocking and adjust timing or boost pressure accordingly in order to offer improved performance on high octane fuels while reducing the risk of engine damage caused by knock while running on low octane fuels.

An early example of this is in turbocharged Saab H engines, where a system called Automatic Performance Control was used to reduce boost pressure if it caused the engine to knock [31].

Various monitoring devices are commonly utilized by tuners as a method of seeing and listening to the engine in order to ascertain if a tuned vehicle is safe under load or used to re-tune a vehicle safely. A commonly used type of knock sensor consists of a piezoelectric sensor attached to the engine block, tuned to detect the sound of knocking.

7.5 Knock Prediction

Since the avoidance of knocking combustion is so important to development engineers, a variety of simulation technologies have been developed which can identify engine design or operating conditions in which knock might be expected to occur. This then enables engineers to design ways to mitigate knocking combustion whilst maintaining a high thermal efficiency.

Since the onset of knock is sensitive to the in-cylinder pressure, temperature and auto ignition chemistry associated with the local mixture compositions within the combustion chamber, simulations which account for all of these aspects have thus proven most effective in determining knock operating limits and enabling engineers to determine the most appropriate operating strategy [32].

7.6 Knock Control

The objective of knock control strategies is to attempt to optimize the trade-off between protecting the engine from damaging knock events and maximizing the engine's output torque. Knock events are an independent random process [33]. It is impossible to design knock controllers in a deterministic platform. A single time history simulation or experiment of knock control methods are not able to provide a repeatable measurement of controller's performance because of the random nature of arriving knock events. Therefore, the desired trade-off must be done in a stochastic framework which could provide a suitable environment for designing and evaluating different knock control strategies performances with rigorous statistical properties.

Chapter Eight

MAP Sensor

8.1 Introduction

The manifold absolute pressure sensor (MAP sensor) is one of the sensors used in an internal combustion engine's electronic control system.

Engines that use a MAP sensor are typically fuel injected. The manifold absolute pressure sensor provides instantaneous manifold pressure information to the engine's electronic control unit (ECU). The data is used to calculate air density and determine the engine's air mass flow rate, which in turn determines the required fuel metering for optimum combustion (see stoichiometry) and influence the advance or retard of ignition timing. A fuel-injected engine may alternatively use a mass airflow sensor (MAF sensor) to detect the intake airflow. A typical naturally aspirated engine configuration employs one or the other, whereas forced induction engines typically use both; a MAF sensor on the charge pipe leading to the throttle body and a MAP sensor on the intake tract pre-turbo.

MAP sensor data can be converted to air mass data by using a second variable coming from an IAT Sensor (intake air temperature sensor). This is called the speed-density method. Engine speed (RPM) is also used to determine where on a look up table to determine fueling, hence speed-density (engine speed / air density). The MAP sensor can also be used in OBD II (on-board diagnostics) applications to test the EGR (exhaust gas recirculation) valve for functionality, an application typical in OBD II equipped General Motors engines.

8.2 Example

The following example assumes the same engine speed and air temperature in a naturally aspirated engine.

Condition 1:

An engine operating at wide open throttle (WOT) on top of a very high mountain has a manifold pressure of about 50 KPa (essentially equal to the barometer at that high altitude).

Condition 2:

The same engine at sea level will achieve that same 50 KPa (7.25 psi, 14.7 in Hg) of manifold pressure at less than (before reaching) WOT due to the higher barometric pressure.

The engine requires the same mass of fuel in both conditions because the mass of air entering the cylinders is the same.

If the throttle is opened all the way in condition 2, the manifold absolute pressure will increase from 50 KPa to nearly 100 KPa (14.5 psi, 29.53 in Hg), about equal to the local barometer, which in condition 2 is sea level. The higher absolute pressure in the intake manifold increases the air's density, and in turn more fuel can be burned resulting in higher output.

8.3 Varying RPM and Engine Loads

Another example is varying rpm and engine loads. Where an engine may have 60 KPa of manifold pressure at 1800 rpm in an unloaded condition, introducing load with a further throttle opening will change the final manifold pressure to 100kPa, engine will still be at 1800 rpm but its loading will require a different spark and fueling delivery.

8.4 Vacuum Comparison

Engine vacuum is the difference between the pressures in the intake manifold and ambient atmospheric pressure. Engine vacuum is a "gauge" pressure, since gauges by nature measure a pressure difference, not an absolute pressure. The engine fundamentally responds to air mass, not vacuum, and absolute pressure is necessary to calculate mass. The mass of air entering the engine is directly proportional to the air density, which is proportional to the absolute pressure, and inversely proportional to the absolute temperature.

Carburetors are largely dependent on air volume flow and vacuum, and neither directly infers mass. Consequently, carburetors are precise, but not accurate fuel metering devices. Carburetors were replaced by more accurate fuel metering methods, such as fuel injection in combination with an air mass flow sensor (MAF).

8.5 EGR Testing

With OBD II standards, vehicle manufacturers were required to test the exhaust gas recirculation (EGR) valve for functionality during driving. Some manufacturers use the MAP sensor to accomplish this. In these vehicles, they have a MAF sensor for their primary load sensor. The MAP sensor is then used for rationality checks and to test the EGR valve. The way they do this is during a deceleration of the vehicle when there is low absolute pressure in the intake manifold (i.e., a high vacuum present in the intake manifold relative to the outside air) the powertrain control module (PCM) will open the EGR valve and then monitor the MAP sensor's values. If the EGR is functioning properly, the manifold absolute pressure will increase as exhaust gases enter.

8.6 Common Confusion with Boost Sensors and Gauges

MAP sensors measure absolute pressure. Boost sensors or gauges measure the amount of pressure above a set absolute pressure. That set absolute pressure is usually 100 KPa. This is commonly referred to as gauge pressure. Boost pressure is relative to absolute pressure - as one increases or decreases, so does the other. It is a one-to-one relationship with an offset of -100 KPa for boost pressure. Thus a MAP sensor will always read 100 KPa more than a boost sensor measuring the same conditions. A MAP sensor will never display a negative reading because it is measuring absolute pressure, where zero is the total absence of pressure. Vacuum is measured as a negative pressure relative to normal atmospheric pressure. Vacuum-Boost sensors can display negative readings, indicating vacuum or suction (a condition of lower pressure than the surrounding atmosphere). In forced induction engines (supercharged or turbocharged), a negative boost reading indicates that the engine is drawing air faster than it is being supplied, creating suction. The suction is caused by throttling in spark ignition engines and is not present in diesel engines. This is often called vacuum pressure when referring to internal combustion engines.

In short, in a standard atmosphere most boost sensors will read one atmosphere less than a MAP sensor reads. At sea level one can convert boost to MAP by adding approximately 100 KPa. One can convert from MAP to boost by subtracting 100 KPa.

Chapter Nine

Mass Flow Sensor

9.1 Introduction

A mass (air) flow sensor (MAF) is a sensor used to determine the mass flow rate of air entering a fuel-injected internal combustion engine.

The air mass information is necessary for the engine control unit (ECU) to balance and deliver the correct fuel mass to the engine. Air changes its density with temperature and pressure. In automotive applications, air density varies with the ambient temperature, altitude and the use of forced induction, which means that mass flow sensors are more appropriate than volumetric flow sensors for determining the quantity of intake air in each cylinder.

There are two common types of mass airflow sensors in use on automotive engines. These are the vane meter and the hot wire. Neither design employs technology that measures air mass directly. However, with additional sensors and inputs, an engine's ECU can determine the mass flow rate of intake air.

Both approaches are used almost exclusively on electronic fuel injection (EFI) engines. Both sensor designs output a 0.0–5.0 volt or a pulse-width modulation (PWM) signal that is proportional to the air mass flow rate, and both sensors have an intake air temperature (IAT) sensor incorporated into their housings for most post on-board diagnostics (OBDII) vehicles. Vehicles prior to 1996 could have MAF without an IAT. An example is 1994 Infiniti Q 45.

When a MAF sensor is used in conjunction with an oxygen sensor, the engine's air/fuel ratio can be controlled very accurately. The MAF sensor provides the open-loop controller predicted air flow information (the measured air flow) to the ECU, and the oxygen sensor provides closed-loop feedback in order to make minor corrections to the predicted air mass. Also see manifold absolute pressure sensor (MAP sensor).

9.2 Moving Vane Meter

The VAF (volume air flow) sensor measures the air flow into the engine with a spring-loaded air vane (flap/door) attached to a variable resistor (potentiometer). The vane moves in proportion to the airflow. A voltage is applied to the potentiometer and a voltage appears on the output terminal of the potentiometer proportional to the angle the vane rotates, or the movement of the vane may directly regulate the amount of fuel injected, as in the K-Jetronic system.

Many VAF sensors have an air-fuel adjustment screw, which opens or closes a small air passage on the side of the VAF sensor. This screw controls the air-fuel mixture by letting a metered amount of air flow past the air flap, thereby leaning or richening the mixture. By turning the screw clockwise the mixture is enriched and counterclockwise the mixture is leaned. Figure 9.1 shows an intake-air flap type flowmeter.

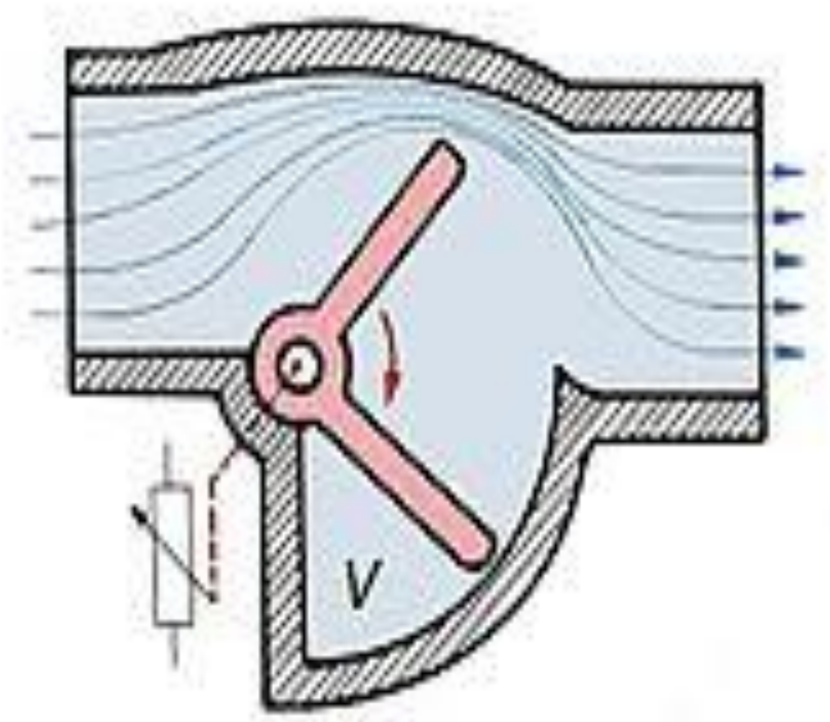

Figure 9.1 Intake-Air Flap Type Flowmeter

The vane moves because of the drag force of the air flow against it; it does not measure volume or mass directly. The drag force depends on air density (air density in turn depends on air temperature), air velocity and the shape of the vane, see drag equation. Some VAF sensors include an additional intake air temperature sensor (IAT sensor) to allow the engines ECU to calculate the density of the air, and the fuel delivery accordingly.

The vane meter approach has some drawbacks:

It restricts airflow which limits engine output.

Its moving electrical or mechanical contacts can wear.

Finding a suitable mounting location within a confined engine compartment is problematic.

The vane has to be oriented with respect to gravity.

In some manufacturers fuel pump control was also part on the VAF internal wiring.

9.3 Hot Wire Sensor (MAF)

A hot wire mass airflow sensor determines the mass of air flowing into the engine’s air intake system. The theory of operation of the hot wire mass airflow sensor is similar to that of the hot wire anemometer (which determines air velocity). This is achieved by heating a wire suspended in the engine’s air stream, like a toaster wire, by applying a constant voltage over the wire. The wire's electrical resistance increases as the wire’s temperature increases, which varies the electrical current flowing through the circuit, according to Ohm's law. When air flows past the wire, the wire cools, decreasing its resistance, which in turn allows more current to flow through the circuit, since the supply voltage is a constant. As more current flows, the wire’s temperature increases until the resistance reaches equilibrium again. The current increase or decrease is proportional to the mass of air flowing past the wire. The integrated electronic circuit converts the proportional measurement into a calibrated signal which is sent to the ECU.

If air density increases due to pressure increase or temperature drop, but the air volume remains constant, the denser air will remove more heat from the wire indicating a higher mass airflow. Unlike the vane meter's paddle sensing element, the hot wire responds directly to air density. This sensor's capabilities are well suited to support the gasoline combustion process which fundamentally responds to air mass, not air volume. This sensor sometimes employs a mixture screw, but this screw is fully electronic and uses a variable resistor (potentiometer) instead of an air bypass screw. The screw needs more turns to achieve the desired results. A hot wire burn-off cleaning circuit is employed on some of these sensors. A burn-off relay applies a high current through the platinum hot wire after the vehicle is turned off for a second or so, thereby burning or vaporizing any contaminants that have stuck to the platinum hot wire element.

The hot film MAF sensor works somewhat similar to the hot wire MAF sensor, but instead it usually outputs a frequency signal. This sensor uses a hot film-grid instead of a hot wire. It is commonly found in late 1980s and early 1990s fuel-injected vehicles. The output frequency is directly proportional to the air mass entering the engine. So as mass flow increases so does frequency. These sensors tend to cause intermittent problems due to internal electrical failures. The use of an oscilloscope is strongly recommended to check the output frequency of these sensors. Frequency distortion is also common when the sensor starts to fail. Many technicians in the field use a tap test with very conclusive results. Not all HFM systems output a frequency. In some cases, this sensor works by outputting a regular varying voltage signal.

Some of the benefits of a hot-wire MAF compared to the older style vane meter are:

Responds very quickly to changes in air flow.

Low airflow restriction.

Smaller overall package.

Less sensitive to mounting location and orientation.

No moving parts improve its durability.

Less expensive.

Separate temperature and pressure sensors are not required to determine air mass, even though the intake air temperature sensor is still sometimes included inside the MAF assembly.

There are some drawbacks:

Dirt and oil can contaminate the hot-wire deteriorating its accuracy.

Installation requires a laminar flow across the hot-wire.

The sensor contains a thin platinum wire, which can break if handled incorrectly.

9.4 Cold Wire Sensor

The GM LS engine series (as well as others) use a cold wire MAF system (produced by AC Delco) that works similarly to the hot-wire MAF system; however, it uses an additional "cold" resistor to measure the ambient air and provide a reference for the "hot" resistor element used to measure the air flow [34]. Figure 9.2 below shows a Holden Commodore's MAF sensor.

Figure 9.2 A Holden Commodore's MAF Sensor

The mesh on the MAF is used to smooth out airflow to ensure the sensors have the best chance of a steady reading. It is not used for measuring the air flow per se. In situations where owners use oiled-gauze air filters, it is possible for excess oil to coat the MAF sensor and skew its readings. Indeed, General Motors has issued a Technical Service Bulletin, indicating problems from rough idle all the way to possible transmission damage resulting from the contaminated sensors. To clean the delicate MAF sensor components, a specific MAF sensor cleaner or electronics cleaner should be used, not carburetor or brake cleaners, which can be too aggressive chemically. Instead, the liquid phase of MAF sensor cleaners and electronics cleaners is typically based on hexanes or heptane with little to no alcohol content and use either carbon dioxide or HFC-152a as aerosol propellants. The sensors should be gently sprayed from a careful distance to avoid physically damaging them and then allowed to thoroughly dry before reinstalling. Manufacturers claim that a simple but extremely reliable test to ensure correct functionality is to tap the unit with the back of a screwdriver while the car is running, and if this causes any changes in the output frequency then the unit should be discarded and an OEM replacement installed.

9.5 Kármán Vortex Sensor

A Kármán vortex sensor works by disrupting the air stream with a perpendicular bow. Providing that the incoming flow is laminar, the wake consists of an oscillatory pattern of Kármán vortices. The frequency of the resulting pattern is proportional to the air velocity. Figure 9.3 below shows a Von Kármán vortex street.

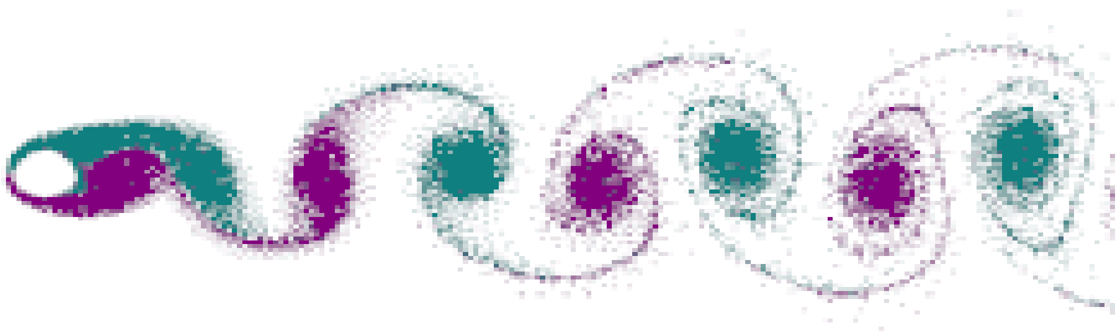

Figure 9.3 A Von Kármán Vortex Street

These vortices can either be read directly as a pressure pulse against a sensor, or they can be made to collide with a mirror which will then interrupt or transmit a reflected light beam to generate the pulses in response to the vortices. The first type can only be used in pull-thru air (prior to a turbo- or supercharger), while the second type could theoretically be used push- or pull-thru air (before or after a forced induction application like the previously mentioned super- or turbocharger). Instead of outputting a constant voltage modified by a resistance factor, this type of MAF outputs a frequency which must then be interpreted by the ECU. This type of MAF can be found on all DSMs (Mitsubishi Eclipse, Eagle Talon, and Plymouth Laser), many Mitsubishis, some Toyotas and Lexus, and some BMWs, among others [35].

9.6 Membrane Sensor

An emerging technology utilizes a very thin electronic membrane placed in the air stream. The membrane has a thin film temperature sensor printed on the upstream side, and one on the downstream side. A heater is integrated in the center of the membrane which maintains a constant temperature similar to the hot-wire approach. Without any airflow, the temperature profile across the membrane is uniform. When air flows across the membrane, the upstream side cools differently from the downstream side. The difference between the upstream and downstream temperature indicates the mass airflow. The thermal membrane sensor is also capable of measuring flow in both directions, which sometimes occur in pulsating situations. Technological progress allows this kind of sensor to be manufactured on the microscopic scale as micro sensors using microelectromechanical systems technology. Such a micro sensor reaches a significantly higher speed and sensitivity compared with macroscopic approaches. See also MEMS sensor generations.

9.7 Laminar Flow Elements

Laminar flow elements measure the volumetric flow of gases directly. They operate on the principle that, given laminar flow, the pressure difference across a pipe is linear to the flow rate. Laminar flow conditions are present in a gas when the Reynolds number of the gas is below the critical figure. The viscosity of the fluid must be compensated for in the result. Laminar flow elements are usually constructed from a large number of parallel pipes to achieve the required flow rating.

Chapter Ten

Nitrogen Oxide Sensor

10.1 Introduction

A nitrogen oxide sensor or NOx sensor is typically a high-temperature device built to detect nitrogen oxides in combustion environments such as an automobile, automotive truck tailpipe or smokestack.

10.2 Overview

The term NOx represents several forms of nitrogen oxides such as NO (nitric monoxide), NO_2 (nitrogen dioxide) and N_2O (nitrous oxide, also known as laughing gas). In a gasoline engine, NO is the most common form of NOx at around 93%, while NO_2 is around 5% and the rest is N_2O. There are other forms of NOx such as N2O4 (the dimer of NO_2), which only exists at lower temperatures, and N_2O_5, for example. However, owing to much higher combustion temperatures due to high cylinder compression and turbo or supercharging, diesel engines produce much higher engine-out NOx emissions than spark-ignition gasoline engines. The recent availability of Selective catalytic reduction (SCR) allows the properly equipped diesel engine to emit similar values of NOx at the tailpipe compared to a typical gasoline engine with a 3-way catalyst. In addition, the diesel oxidation catalyst significantly increases the fraction of NO_2 in "NOx" by oxidizing over 50% of NO using the excess oxygen in the diesel exhaust gases.

The drive to develop a NOx sensor comes from environmental factors that affect the surrounding environment containing nitrogen oxides. NOx gases can cause various problems such as smog and acid rain. Many governments around the world have passed laws to limit their emissions (along with other combustion gases such as SOx (oxides of sulfur), CO (carbon monoxide) and CO_2 (carbon dioxide) and hydrocarbons). Companies have realized that one way of minimizing NO x emissions is to first detect them and then employ some sort of feedback loop in the combustion process, minimizing NOx production by, for example, combustion optimization or regeneration of NOx traps.

10.3 Challenges

1. Harsh Environment

Due to the high temperature of the combustion environment, only certain types of material can operate in situ. The majority of NOx sensors developed have been made out of ceramic type metal oxides, with the most common being yttrium-stabilized zirconia (YSZ), which is currently used in the decades-old oxygen sensor. The YSZ is compacted into a dense ceramic and conducts oxygen ions (O_2) at the high temperatures of a tailpipe such at 400 °C and above. To get a signal from the sensor a pair of high-temperature electrodes such as noble metals (platinum, gold, or palladium) or other metal oxides are placed onto the surface and an electrical signal such as the change in voltage or current is measured as a function of NOx concentration.

2. High Sensitivity and Durability Required

The levels of NO are around 100–2000 ppm (parts per million) and NO_2 20–200 ppm in a range of 1–10% O2. The sensor has to be very sensitive to pick up these levels.

The main problems that have limited the development of a successful NOx sensor (which are typical of many sensors) are selectivity, sensitivity, stability, reproducibility, response time, limit of detection, and cost. In addition due to the harsh environment of combustion the high gas flow rate can cool the sensor which alters the signal or it can delaminate the electrodes over time and soot particles can degrade the materials.

Chapter Eleven

Oxygen Sensor

11.1 Introduction

An oxygen sensor (or lambda sensor, where lambda refers to air–fuel equivalence ratio, usually denoted by λ) is an electronic device that measures the proportion of oxygen (O_2) in the gas or liquid being analyzed.

It was developed by Robert Bosch GmbH during the late 1960s under the supervision of Dr. Günter Bauman. The original sensing element is made with a thimble-shaped zirconia ceramic coated on both the exhaust and reference sides with a thin layer of platinum and comes in both heated and unheated forms. The planar-style sensor entered the market in 1990 and significantly reduced the mass of the ceramic sensing element, as well as incorporating the heater within the ceramic structure [36]. This resulted in a sensor that started sooner and responded faster.

The most common application is to measure the exhaust-gas concentration of oxygen for internal combustion engines in automobiles and other vehicles in order to calculate and, if required, dynamically adjust the air-fuel ratio so that catalytic converters can work optimally, and also determine whether the converter is performing properly or not. Divers also use a similar device to measure the partial pressure of oxygen in their breathing gas.

Scientists use oxygen sensors to measure respiration or production of oxygen and use a different approach. Oxygen sensors are used in oxygen analyzers, which find extensive use in medical applications such as anesthesia monitors, respirators and oxygen concentrator so.

Oxygen sensors are also used in hypoxic air fire prevention systems to continuously monitor the oxygen concentration inside the protected volumes.

There are many different ways of measuring oxygen. These include technologies such as zirconia, electrochemical (also known as galvanic), infrared, ultrasonic, paramagnetic, and very recently, laser methods.

11.2 Automotive Applications

Automotive oxygen sensors, colloquially known as O_2 sensors, make modern electronic fuel injection and emission control possible. They help determine, in real time, whether the air–fuel ratio of a combustion engine is rich or lean. Since oxygen sensors are located in the exhaust stream, they do not directly measure the air or the fuel entering the engine, but when information from oxygen sensors is coupled with information from other sources, it can be used to indirectly determine the air–fuel ratio. Closed-loop feedback-controlled fuel injection varies the fuel injector output according to real-time sensor data rather than operating with a predetermined (open-loop) fuel map. In addition to enabling electronic fuel injection to work efficiently, this emissions control technique can reduce the amounts of both unburnt fuel and oxides of nitrogen entering the atmosphere. Unburnt fuel is pollution in the form of air-borne hydrocarbons, while oxides of nitrogen (NOx gases) are a result of combustion chamber temperatures exceeding 1300 kelvins, due to excess air in the fuel mixture therefore contribute to smog and acid rain. Volvo was the first automobile manufacturer to employ this technology in the late 1970s, along with the three-way catalyst used in the catalytic converter. Figure 11.1 below shows a three-wire oxygen sensor suitable for use in a Volvo 240 or similar vehicle.

Figure 11.1 a Three-Wire Oxygen Sensor Suitable for Use in a Volvo 240 or Similar Vehicle

The sensor does not actually measure oxygen concentration, but rather the difference between the amount of oxygen in the exhaust gas and the amount of oxygen in air. Rich mixture causes an oxygen demand. This demand causes a voltage to build up, due to transportation of oxygen ions through the sensor layer. Lean mixture causes low voltage, since there is an oxygen excess.

Modern spark-ignited combustion engines use oxygen sensors and catalytic converters in order to reduce exhaust emissions. Information on oxygen concentration is sent to the engine management computer or engine control unit (ECU), which adjusts the amount of fuel injected into the engine to compensate for excess air or excess fuel. The ECU attempts to maintain, on average, a certain air-fuel ratio by interpreting the information gained from the oxygen sensor. The primary goal is a compromise between power, fuel economy, and emissions, and in most cases is achieved by an air–fuel ratio close to stoichiometric. For spark-ignition engines (such as those that burn gasoline or LPG, as opposed to diesel), the three types of emissions modern systems are concerned with are: hydrocarbons (which are released when the fuel is not burnt completely, such as when misfiring or running rich), carbon monoxide (which is the result of running slightly rich) and NOx (which dominate when the mixture is lean). Failure of these sensors, either through normal aging, the use of leaded fuels, or fuel contaminated with silicones or silicates, for example, can lead to damage of an automobile's catalytic converter and expensive repairs.

Tampering with or modifying the signal that the oxygen sensor sends to the engine computer can be detrimental to emissions control and can even damage the vehicle. When the engine is under low-load conditions (such as when accelerating very gently or maintaining a constant speed), it is operating in "closed-loop mode". This refers to a feedback loop between the ECU and the oxygen sensor in which the ECU adjusts the quantity of fuel and expects to see a resulting change in the response of the oxygen sensor. This loop forces the engine to operate both slightly lean and slightly rich on successive loops, as it attempts to maintain a mostly stoichiometric ratio on average. If modifications cause the engine to run moderately lean, there will be a slight increase in fuel efficiency, sometimes at the expense of increased NOx emissions, much higher exhaust gas temperatures, and sometimes a slight increase in power that can quickly turn into misfires and a drastic loss of power, as well as potential engine and catalytic-converter (due to the misfires) damage, at ultra-lean air–fuel ratios. If modifications cause the engine to run rich, then there will be a slight increase in power to a point (after which the engine starts flooding from too much unburned fuel), but at the cost of decreased fuel efficiency, and an increase in unburned hydrocarbons in the exhaust, which causes overheating of the catalytic converter. Prolonged operation at rich mixtures can cause catastrophic failure of the catalytic converter. The ECU also controls the spark engine timing along with the fuel-injector pulse width, so modifications that alter the engine to operate either too lean or too rich may result in inefficient fuel consumption whenever fuel is ignited too soon or too late in the combustion cycle.

When an internal combustion engine is under high load (e.g. wide open throttle), the output of the oxygen sensor is ignored, and the ECU automatically enriches the mixture to protect the engine, as misfires under load are much more likely to cause damage. This is referred to as an engine running in "open-loop mode". Any changes in the sensor output will be ignored in this state. In many cars (with the exception of some turbocharged models), inputs from the air flow meter are also ignored, as they might otherwise lower engine performance due to the mixture being too rich or too lean, and increase the risk of engine damage due to detonation if the mixture is too lean.

11.3 Function of a Lambda Probe

Lambda probes provide feedback to an ECU. Where applicable, gasoline, propane and natural gas engines are fitted with three way catalysts to comply with on road vehicle emissions legislation. Using the lambda sensor signal, the ECU can operate the engine slightly rich of lambda = 1, this is the ideal operating mixture for a three way catalyst to be effective [37]. Robert Bosch GmbH introduced the first automotive lambda probe in 1976 [38], and it was first used by Volvo and Saab in that year. The sensors were introduced in the US from about 1979 and were required on all models of cars in many countries in Europe in 1993.

By measuring the proportion of oxygen in the remaining exhaust gas, and by knowing the volume and temperature of the air entering the cylinders amongst other things, an ECU can use look-up tables to determine the amount of fuel required to burn at the stoichiometric ratio (14.7:1 air: fuel by mass for gasoline) to ensure complete combustion.

11.4 The Probe

The sensor element is a ceramic cylinder plated inside and outside with porous platinum electrodes; the whole assembly is protected by a metal gauze. It operates by measuring the difference in oxygen between the exhaust gas and the external air and generates a voltage or changes its resistance depending on the difference between the two.

The sensors only work effectively when heated to approximately 316 °C (600 °F), so most newer lambda probes have heating elements encased in the ceramic that bring the ceramic tip up to temperature quickly. Older probes, without heating elements, would eventually be heated by the exhaust, but there is a time lag between when the engine is started and when the components in the exhaust system come to a thermal equilibrium. The length of time required for the exhaust gases to bring the probe to temperature depends on the temperature of the ambient air and the geometry of the exhaust system. Without a heater, the process may take several minutes. There are pollution problems that are attributed to this slow start-up process, including a similar problem with the working temperature of a catalytic converter.

The probe typically has four wires attached to it: two for the lambda output, and two for the heater power, although some automakers use the metal case as ground for the sensor element signal, resulting in three wires. Earlier non-electrically-heated sensors had one or two wires.

11.5 Operation of the Probe

1. Zirconia Sensor

The zirconium dioxide, or zirconia, lambda sensor is based on a solid-state electrochemical fuel cell called the Nernst cell. Its two electrodes provide an output voltage corresponding to the quantity of oxygen in the exhaust relative to that in the atmosphere.

An output voltage of 0.2 V (200 mV) DC represents a "lean mixture" of fuel and oxygen, where the amount of oxygen entering the cylinder is sufficient to fully oxidize the carbon monoxide (CO), produced in burning the air and fuel, into carbon dioxide (CO_2). An output voltage of 0.8 V (800 mV) DC represents a "rich mixture", which is high in unburned fuel and low in remaining oxygen. The ideal set point is approximately 0.45 V (450 mV) DC. This is where the quantities of air and fuel are in the optimal ratio, which is ~0.5% lean of the stoichiometric point, such that the exhaust output contains minimal carbon monoxide. Figure 11.2 below shows a planar zirconia sensor (schematic picture).

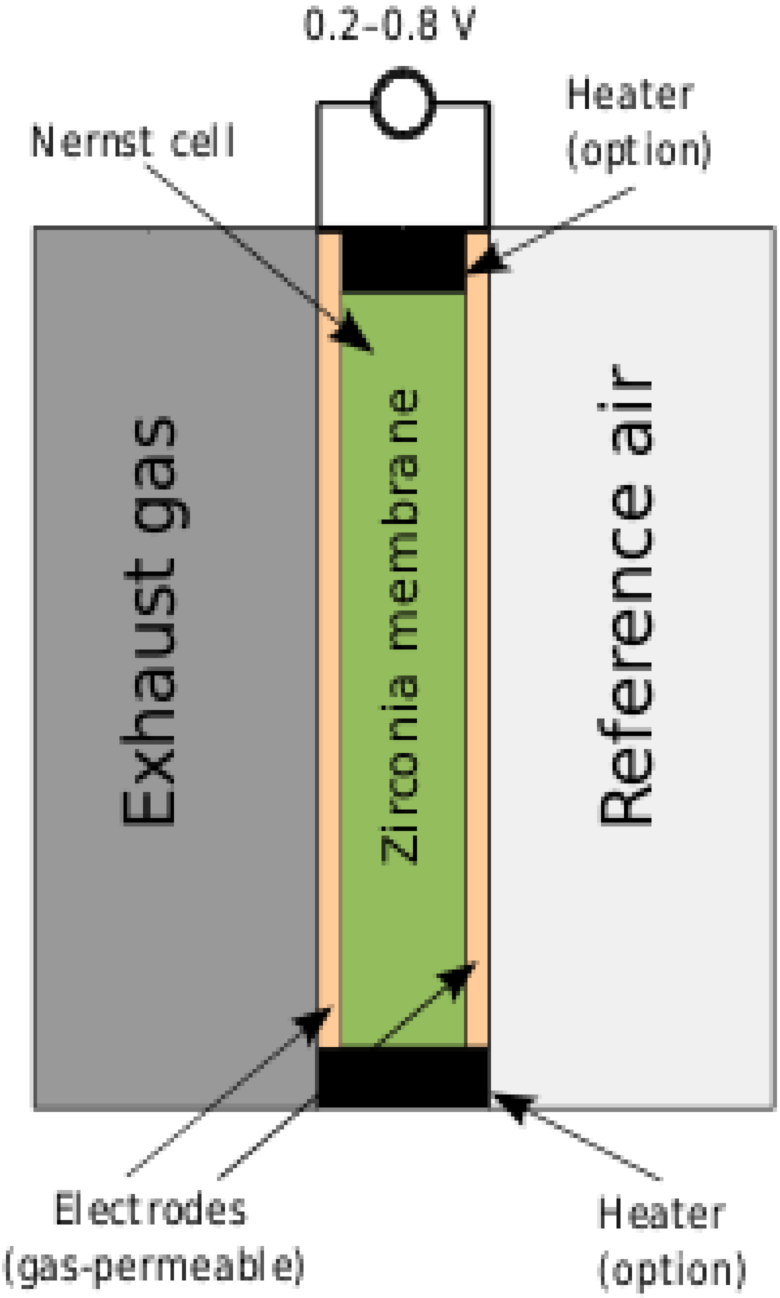

Figure 11.2 a Planar Zirconia Sensor (Schematic Picture)

The voltage produced by the sensor is nonlinear with respect to oxygen concentration. The sensor is most sensitive near the stoichiometric point (where $\lambda = 1$) and less sensitive when either very lean or very rich.

The ECU is a control system that uses feedback from the sensor to adjust the fuel/air mixture. As in all control systems, the time constant of the sensor is important; the ability of the ECU to control the fuel–air ratio depends upon the response time of the sensor. An aging or fouled sensor tends to have a slower response time, which can degrade system performance. The shorter the time period, the higher the so-called "cross count" [39] and the more responsive the system.

The sensor has a rugged stainless-steel construction internally and externally. Due to this the sensor has a high resistance to corrosion, allowing it to be used effectively in aggressive environments with high temperature/pressure.

The zirconia sensor is of the "narrow-band" type, referring to the narrow range of fuel/air ratios to which it responds.

2. Wideband Zirconia Sensor

A variation on the zirconia sensor, called the "wideband" sensor, was introduced by NTK in 1992 [40] and has been widely used for car engine management systems in order to meet the ever-increasing demands for better fuel economy, lower emissions and better engine performance at the same time [41]. It is based on a planar zirconia element, but also incorporates an electrochemical gas pump. An electronic circuit containing a feedback loop controls the gas-pump current to keep the output of the electrochemical cell constant, so that the pump current directly indicates the oxygen content of the exhaust gas. This sensor eliminates the lean–rich cycling inherent in narrow-band sensors, allowing the control unit to adjust the fuel delivery and ignition timing of the engine much more rapidly. In the automotive industry this sensor is also called a UEGO (universal exhaust-gas oxygen) sensor. UEGO sensors are also commonly used in aftermarket dyno tuning and high-performance driver air–fuel display equipment. The wideband zirconia sensor is used in stratified fuel injection systems and can now also be used in diesel engines to satisfy the upcoming EURO and ULEV emission limits.

Wideband sensors have three elements:

Ion oxygen pump,

Narrowband zirconia sensor,

Heating element.

The wiring diagram for the wideband sensor typically has six wires:

Resistive heating element,

Sensor,

Pump,

Calibration resistor,

Common.

3. Titanium Sensor

A less common type of narrow-band lambda sensor has a ceramic element made of titanium (titanium dioxide). This type does not generate its own voltage, but changes its electrical resistance in response to the oxygen concentration. The resistance of the titanium is a function of the oxygen partial pressure and the temperature. Therefore, some sensors are used with a gas-temperature sensor to compensate for the resistance change due to temperature. The resistance value at any temperature is about 1/1000 the change in oxygen concentration. Luckily, at $\lambda = 1$, there is a large change of oxygen, so the resistance change is typically 1000 times between rich and lean, depending on the temperature.

As titanium is an N-type semiconductor with a structure TiO_2-x, the x defects in the crystal lattice conduct the charge. So, for fuel-rich exhaust (lower oxygen concentration) the resistance is low, and for fuel-lean exhaust (higher oxygen concentration) the resistance is high. The control unit feeds the sensor with a small electric current and measures the resulting voltage drop across the sensor, which varies from nearly 0 volts to about 5 volts. Like the zirconia sensor, this type is nonlinear, such that it is sometimes simplistically described as a binary indicator, reading either "rich" or "lean". Titanium sensors are more expensive than zirconia sensors, but they also respond faster.

In automotive applications the titanium sensor, unlike the zirconia sensor, does not require a reference sample of atmospheric air to operate properly. This makes the sensor assembly easier to design against water contamination. While most automotive sensors are submersible, zirconia-based sensors require a very small supply of reference air from the atmosphere. In theory, the sensor wire harness and connector are sealed. Air that leaches through the wire harness to the sensor is assumed to come from an open point in the harness – usually the ECU, which is housed in an enclosed space like the trunk or vehicle interior.

11.6 Location of the Probe in a System

The probe is typically screwed into a threaded hole in the exhaust system, located after the branch manifold of the exhaust system combines and before the catalytic converter. New vehicles are required to have a sensor before and after the exhaust catalyst to meet U.S. regulations requiring that all emissions components be monitored for failure. Pre- and post-catalyst signals are monitored to determine catalyst efficiency, and if the converter is not performing as expected, an alert gets reported to the user through on-board diagnostics systems by, for example, lighting up an indicator in the vehicle's dashboard. Additionally, some catalyst systems require brief cycles of lean (oxygen-containing) gas to load the catalyst and promote additional oxidation reduction of undesirable exhaust components.

11.7 Sensor Surveillance

The air–fuel ratio and naturally, the status of the sensor, can be monitored by means of using an air–fuel ratio meter that displays the output voltage of the sensor.

11.8 Sensor Failures

Normally, the lifetime of an unheated sensor is about 30,000 to 50,000 miles (50,000 to 80,000 km). Heated sensor lifetime is typically 100,000 miles (160,000 km). Failure of an unheated sensor is usually caused by the buildup of soot on the ceramic element, which lengthens its response time and may cause total loss of ability to sense oxygen. For heated sensors, normal deposits are burned off during operation, and failure occurs due to catalyst depletion. The probe then tends to report lean mixture, the ECU enriches the mixture, the exhaust gets rich with carbon monoxide and hydrocarbons, and the fuel economy worsens.

Leaded gasoline contaminates the oxygen sensors and catalytic converters. Most oxygen sensors are rated for some service life in the presence of leaded gasoline, but sensor life will be shortened to as little as 15,000 miles (24,000 km), depending on the lead concentration. Lead-damaged sensors typically have their tips discolored light rusty.

Another common cause of premature failure of lambda probes is contamination of fuel with silicones (used in some sealing and greases) or silicates (used as corrosion inhibitors in some antifreezes). In this case, the deposits on the sensor are colored between shiny white and grainy light gray.

Leaks of oil into the engine may cover the probe tip with an oily black deposit, with associated loss of response.

An overly rich mixture causes buildup of black powdery deposit on the probe. This may be caused by failure of the probe itself, or by a problem elsewhere in the fuel-rationing system.

Applying an external voltage to the zirconia sensors, e.g. by checking them with some types of ohmmeter, may damage them.

Some sensors have an air inlet to the sensor in the lead, so contamination from the lead caused by water or oil leaks can be sucked into the sensor and cause failure [42].

Symptoms of a failing oxygen sensor includes:

Sensor light on dash indicates problem,

Increased tailpipe emissions,

Increased fuel consumption,

Hesitation on acceleration,

Stalling,

Rough idling.

11.9 Diving Applications

1. Electro-Galvanic Oxygen Sensor

The type of oxygen sensor used in most underwater diving applications is the electro-galvanic oxygen sensor, a type of fuel cell, which is sometimes called an oxygen analyzer or pp O2 meter. They are used to measure the oxygen concentration of breathing gas mixes such as nitrox and trimix [43]. They are also used within the oxygen control mechanisms of closed-circuit rebreathers to keep the partial pressure of oxygen within safe limits [44]. And to monitor the oxygen content of the breathing gas in saturation diving systems and of surface supplied mixed gas. This type of sensor operates by measuring the voltage generated by a small electro-galvanic fuel cell. Figure 11.3 shows an oxygen analyzer for breathing gas mixtures for diving.

Figure 11.3 an Oxygen Analyzer for Breathing Gas Mixtures for Diving

11.10 Scientific Applications

In soil respiration studies oxygen sensors can be used in conjunction with carbon dioxide sensors to help improve the characterization of soil respiration. Typically, soil oxygen sensors use a galvanic cell to produce a current flow that is proportional to the oxygen concentration being measured. These sensors are buried at various depths to monitor oxygen depletion over time, which is then used to predict soil respiration rates. Generally, these soil sensors are equipped with a built-in heater to prevent condensation from forming on the permeable membrane, as relative humidity can reach 100% in soil [45].

In marine biology or limnology, oxygen measurements are usually done in order to measure respiration of a community or an organism, but have also been used to measure primary production of algae. The traditional way of measuring oxygen concentration in a water sample has been to use wet chemistry techniques e.g. the Winkler titration method. There are however commercially available oxygen sensors that measure the oxygen concentration in liquids with great accuracy. There are two types of oxygen sensors available: electrodes (electrochemical sensors) and optodes (optical sensors).

1. Electrodes

Figure 11.4 below shows a dissolved oxygen meter for laboratory use.

Figure 11.4 a Dissolved Oxygen Meter for Laboratory Use

The Clark-type electrode is the most used oxygen sensor for measuring oxygen dissolved in a liquid. The basic principle is that there is a cathode and an anode submersed in an electrolyte. Oxygen enters the sensor through a permeable membrane by diffusion and is reduced at the cathode, creating a measurable electric current.

There is a linear relationship between the oxygen concentration and the electric current. With a two-point calibration (0% and 100% air saturation), it is possible to measure oxygen in the sample.

One drawback to this approach is that oxygen is consumed during the measurement with a rate equal to the diffusion in the sensor. This means that the sensor must be stirred in order to get the correct measurement and avoid stagnant water. With an increasing sensor size, the oxygen consumption increases and so does the stirring sensitivity. In large sensors there tend to also be a drift in the signal over time due to consumption of the electrolyte. However, Clark-type sensors can be made very small with a tip size of 10 µm. The oxygen consumption of such a micro sensor is so small that it is practically insensitive to stirring and can be used in stagnant media such as sediments or inside plant tissue.

2. Optodes

An oxygen optode is a sensor based on optical measurement of the oxygen concentration. A chemical film is glued to the tip of an optical cable, and the fluorescence properties of this film depend on the oxygen concentration. Fluorescence is at a maximum when there is no oxygen present. When an O2 molecule comes along, it collides with the film, and this quenches the photoluminescence. In a given oxygen concentration there will be a specific number of O_2 molecules colliding with the film at any given time, and the fluorescence properties will be stable.

The signal (fluorescence) to oxygen ratio is not linear, and an optode is most sensitive at low oxygen concentration. That is, the sensitivity decreases as oxygen concentration increases, following the Stern–Volmer relationship. The optode sensors can, however, work in the whole region 0% to 100% oxygen saturation in water, and the calibration is done the same way as with the Clark-type sensor. No oxygen is consumed, and hence the sensor is insensitive to stirring, but the signal will stabilize more quickly if the sensor is stirred after being put in the sample. These type of electrode sensors can be used for in situ and real-time monitoring of oxygen production in water-splitting reactions. The platinized electrodes can accomplish the real-time monitoring of hydrogen production in water-splitting device.

Planar optodes are used to detect the spatial distribution of oxygen concentrations in a platinized foil. Based on the same principle than optode probes, a digital camera is used to capture fluorescence intensities over a specific area.

Chapter Twelve

Throttle Position Sensor

A throttle position sensor (TPS) is a sensor used to monitor the air intake of an engine. The sensor is usually located on the butterfly spindle/shaft so that it can directly monitor the position of the throttle. More advanced forms of the sensor are also used, for example an extra closed throttle position sensor (CTPS) may be employed to indicate that the throttle is completely closed. Some engine control units (ECUs) also control the throttle position electronic throttle control (ETC) or "drive by wire" systems and if that is done the position sensor is used in a feedback loop to enable that control [46].

Related to the TPS are accelerator pedal sensors, which often include a wide open throttle (WOT) sensor. The accelerator pedal sensors are used in electronic throttle control or "drive by wire" systems, and the most common use of a wide open throttle sensor is for the kick-down function on automatic transmissions.

Modern day sensors are non-contact type. These modern non-contact throttle position sensor (TPS) include Hall Effect sensors, inductive sensors, magneto resistive and others. In the potentiometric type sensors, a multi-finger metal brush/rake is in contact with a resistive strip [47], while the butterfly valve is turned from the lower mechanical stop (minimum air position) to WOT, there is a change in the resistance and this change in resistance is given as the input to the ECU.

Non-contact type TPS work on the principle of Hall effect or inductive sensors, or magneto resistive technologies, wherein generally the magnet or inductive loop is the dynamic part which is mounted on the butterfly valve throttle spindle/shaft gear and the sensor & signal processing circuit board is mounted within the ETC gear box cover and is stationary. When the magnet/inductive loop mounted on the spindle which is rotated from the lower mechanical stop to WOT, there is a change in the magnetic field for the sensor. The change in the magnetic field is sensed by the sensor and the voltage generated is given as the input to the ECU. Normally a two pole rare-earth magnet is used for the TPS due to their high Curie temperatures required in the under-hood vehicle environment. The magnet may be of diametrical type, ring type, rectangular or segment type. The magnet is defined to have a certain magnetic field that does not vary significantly with time or temperature.

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