This article clarifies the origins of diesel particulate matter (DPM) in exhaust emissions and uses those insights to derive principles to manage these levels.

Managing diesel particulate matter

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Emission legislation for non-road vehicles was introduced in the late 1990s and moved from a “stake-in-the-ground” state to various stages where engine manufacturers had been excelling in complying with the standards and the target dates set. The development of legislation in the USA and Europe had been very similar and had followed the same stepped approach in reducing the emission targets.

The pending introduction of legislation in South Africa to control and reduce the exposure of mine workers to diesel particulate matter (DPM) is the first response to this international legislation, and is particularly pertinent as DPM has been classified as a carcinogenic. It also follows a “stake-in-the-ground” approach where certain levels of DPM exposure are set, and a systematic reduction in these exposure levels is required over the next five years.

Fuel mixture is either drawn into the combustion chamber (by virtue of the difference between atmospheric pressure and internal pressure generated by the intake stroke) or forced into the combustion chamber by either a turbo or a supercharger. The force generated from the combustion of the fuel-air mixture is transformed into linear motion in the pistons and connecting rods. This linear motion is then transformed to rotational motion through the crankshaft. Additional mechanical power can be tapped off at various locations e.g. end of the crankshaft, auxiliary gears, etc. to drive external auxiliary components such as oil and fuel pumps.

Various by-products are produced during the combustion process of an engine (either spark-ignition or compression-ignition type). Apart from the energy released from combustion, carbon monoxide (CO), hydrocarbons (HC), nitrous oxides (NOx), sulphates (SOx), etc. are also produced. Diesel fuel typically has more carbon atoms in its chemical composition than petrol compounds do (petrol is typically defined by C9H20, while diesel fuel is typically defined by C14H30). This longer chain of carbon atoms in diesel fuel results in higher energy density and is part of the reason why the engine is so efficient, but it also provides a different profile of exhaust gas constituents. Fig. 1 provides a graphical representation of the characteristics of the combustion process and the chemical make-up of the different stages.

NOx, HC, CO, sulphates (SOx), various carbon compounds and particulate matter (in this case diesel particulate matter, or DPM) are classified as toxic. DPM is a complex mixture of solid and liquid materials which include dry carbon particles (elemental and organic carbon, commonly known as soot), engine lubrication oil ash, hydrocarbons which are absorbed and condensed on the carbon particles (called soluble organic fractions, or SOF), water and sulphuric acid.

DPM has a very small particle size (0.01μm to 1μm) and can penetrate deep into the lungs when inhaled. The
reason for the pending legislation in South Africa becomes evident when considering that DPM was recently classified as a carcinogenic and is also known to increase the risk of heart and respiratory disease.

Engine designs for non-road vehicles have changed dramatically as a result of emission legislation introduced by the US Environmental Protection Agency (EPA) standards and, in Europe, through the European Association of Internal Combustion Engine Manufacturers (Euromot), from 1999 onwards.

Engine manufacturers realised that this seemingly insurmountable task was not that difficult to achieve and that a lot of other positive spin-offs could result from these developments. Some examples of these combined advantages are lower hydrocarbon emissions and lower oil consumption when the sealing interface between the piston and cylinder liner and the moving parts of the valve train were improved.

Another example is improved power output in combination with lower fuel consumption when the injection pressures were increased and additional holes were introduced in the diesel injector tips to improve the injector spray pattern to enhance the combustion process. A further example is electronic control of the amount and the timing of diesel injection for controlled combustion (the key to lower emissions) and this again has led to increased power output and lower fuel consumption.

In summary, all of these developments had a net effect of much improved performance and efficiency from engines with much smaller footprints. By the end of 2007, the NOx emissions had been reduced by 57% and the PM emissions by 71% by internal modifications and improvements.

This also marked the introduction of external additions to the exhaust-end of the engine, commonly referred to as “exhaust after treatment” (EAT) systems, to meet the new requirements by 2012 and 2014. Examples of EAT devices are the diesel oxidation catalyst (DOC), the selective catalytic reducer (SCR) and the diesel particulate filter (DPF). These devices can be used either individually and independently or as a combination of devices, depending on the engine output and configuration. For example, one would typically use only a DOC on an engine with power output of less than 56 kW. That would be ample for the engine to comply with the EU Stage IV/US EPA tier IV emission legislation. For engines with outputs of between 56 and 100 kW, a combination of a DOC and SCR or DPF and SCR can be used, again depending on the legislation and the application, etc. Fig. 2 is a schematic illustration of the possible combinations of EAT systems.

These external measures can further reduce the toxic emissions and the collective effect of these improvements is a 96% reduction in toxic emissions. Fig. 3 is a graphical representation of this development in emission legislation. Other improvements brought about the emission legislation to reduce these toxic and carcinogenic emissions include:

- Atomising the fuel more finely in the injection process.
- Higher injection pressure (from 200 bar 20 years ago to the current 2500 bar in a common rail).
- Multi-hole injectors (from a single-hole to the current five-hole injector).
- Optimal controlled combustion.
- Improved combustion chamber design to control the flame path.
- Exhaust gas recirculation (EGR), an induction technique to force un-burnt fuel from the exhaust gas back into the combustion chamber.
- Forced induction techniques like turbochargers.
- Charge air coolers to reduce the temperature of the intake air.
- Improved sealing of the piston ring to cylinder bore interface.
- Electronic control of the injection process by adjusting the rate and timing of injections. Modern engines have multiple (up to five) injections per compression stroke, the last injection even after top dead centre!
- Diesel oxidation catalyst (DOC). This unit is treated with a catalyst and it promotes chemical oxidation of CO to CO$_2$, and HC and SOF portion of diesel particulates to CO$_2$ and H$_2$O. However, it also oxidises sulphur dioxide (SO$_2$) in the exhaust emissions to sulphate particles (SO$_4^{2-}$) and sometimes sulphuric acid (H$_2$SO$_4$), and may increase total particulate emissions significantly. It also oxidises nitrogen monoxide (NO) to nitrogen dioxide (NO$_2$), (as harmful as NO), but it is then used to significantly enhance the regeneration process of the diesel particulate filter or certain types of selective catalytic reducers.
- Selective catalytic reducers (SCRs). This unit uses an aqueous urea solution to generate ammonia gas (NH$_3$) which then reacts with NO to form N$_2$ and H$_2$O.
- Reducing the sulphur content in diesel fuel. This development has had a direct impact on decreased sulphate production and thus soot formation. Sulphur content in diesel fuel has decreased from as high as 5000 ppm to the 50 ppm commonly available at present and Sasol has recently announced the availability at selected pump outlets of 10 ppm from 2014.
- Diesel particulate filters (DPFs). This unit is designed to collect diesel particulate matter and by its nature must be cleaned fairly often. Regeneration techniques are used and engine manufacturers use heat management systems (HMS) to increase the exhaust gas temperature by either late injection or injection during the exhaust stroke, a fuel burner after the turbo, temporary reduction of power by closing off the intake temporary, special catalytic coating on the filter to take advantage of the NO$_x$ from the DOC passing through, etc. This burns off the soot and oxidises it to CO$_2$ and N$_2$ (see Fig. 2).
- Exhaust gas temperatures (EGT) should be high enough during the normal duty cycle to trigger regeneration and, if not, external energy sources such as heaters, diesel fuel burners, etc. are used. Catalytic coatings are used on the surface of the DPF to enhance the process chemically.
- Non-catalysed filters are used when the EGT during a typical load cycle are in the region of 600°C.
- Base metal catalysts are used when the EGT is between 390°C and 600°C, and noble metal catalysts are used when the EGT is between 325°C and 390°C.
- Continuous regenerating technology is used when the EGT are between 260°C and 325°C.

Fig. 4 provides an example of the chemical reaction which takes place in a typical exhaust system after treatment. The HMS will select which type of DPF regeneration option to choose (EGT dependent), and Fig. 5 indicates an example of a continuous regenerating method.

The pending introduction of legislation in South Africa on reducing the production of DPM in the mines has led to the systematic introduction of low sulphur diesel (500 ppm to 10 ppm) in the country since 2007. Low sulphur diesel (50 ppm) is already available in the country and ultra-low sulphur diesel (10 ppm) will be introduced from 2018 onwards (as per II Government Gazette No. 34089). Some suppliers (like Sasol) are already supplying 10 ppm diesel to some parts of the country and it can be expected that availability of this diesel at all fuel stations will increase dramatically from 2015 onwards. The use of 50 ppm diesel fuel (and, eventually, 10 ppm) is not a statutory requirement, which also means that diesel with 500 ppm (and more) sulphur content is still widely available.

Many of the diesel engines operating in SA’s mines are not emission-optimised and the level of their diesel particulate emissions will probably fall far above the level to be set by government. There are, however, a few small adjustments (which result in large gains) which can be made on the mines to lower the DPM levels instead of going through the expensive exercise of installing devices such as diesel particulate filters. Apart from being expensive and cumbersome to maintain, these also introduce a lot of additional waste heat into the environment.

This country’s pending legislation recognises that managing the quality of emissions of underground diesel-driven machines requires proper control and interventions to reduce the levels from the initial target in 2014 to the proposed new levels in 2017. Optimal combustion is the key to maintaining and improving DPM levels, and the following pointers are important to manage:
- Change diesel from 500 ppm to 50 ppm sulphur content. This small change will reduce the DPM levels dramatically. When and where possible, change over to diesel with sulphur content of 10 ppm. It is important to measure the effect of all the interventions as you will be required to submit proof of improvements. In addition, downstream benefits include a reduction in the corrosive environment as there will be ten
times less chance of sulphuric acid forming in the surrounding air in the mines, and a longer life for the infrastructure underground.

- Immediately attend to any visible exhaust smoke (an indicator of uncontrolled combustion and hence unwanted DPM!). The remedies for this can be quite simple, and include:
  - Dirty or clogged air filters. The stoichiometric ratio of fuel to air is disturbed as the same pre-programmed amount of fuel is injected and there would be a clear deficit in the amount of air.
  - Dirty or faulty fuel injectors. These would normally squirt diesel in uncontrolled amounts into the combustion chamber, leading to uncontrolled combustion. A sticky injector which opens and closes in 3 ms instead of 2 ms supplies 50% more diesel than required, and it transforms into a blowtorch resulting in uncontrolled combustion, excessive smoking and holes in pistons.
  - Dirty diesel (water ingress, dirt ingress, etc.) has the same impact on the controlled process as described here. Any foreign particle in the diesel fuel will leave the combustion chamber combusted into some sort of particle and will be classified as diesel particulate matter.
  - Maintenance issues such as diesel injection timing, incorrect valve settings, etc. Incorrect timing of the point of injection will result in either lack of power, excessive smoking due to incomplete combustion and an EGT which will send out wrong information to the control system. Incorrect valve settings can result in incomplete combustion as the valves might not be able to open and close properly and at the correct point and, if too tight, can result in burnt valves and lead to incomplete combustion.
  - Internal bypass of oil (admittedly more expensive and time consuming). This can happen through various means such as worn or collapsed piston rings, worn valve stems or valve stem seals, worn seals on the turbocharger, etc. Oil can then bypass these areas and end up in the combustion chamber, where it will form part of the combustion process.

- Maintain the fuel supply system to prevent the ingress of dirt and water to ensure optimal combustion by using correct fuel filters, fuel pre-filters, water traps, ventilators, etc. Any foreign particle translates into particulate matter in the environment. Fig. 6 indicates a typical set-up to prevent dirt ingress. It is neither difficult nor expensive to set up.

- Set up a programme to ensure that every non-certified engine is replaced over time by an emission-certified engine. There is a major reduction in DPM levels between an EPA Tier I (EU stage I) engine, an EPA Tier II (EU stage II) engine and an EPA Tier III (EU stage III) engine. This is brought about by improvements in engine design and fuel consumption. Note that there is also a considerable saving to be made on oil and diesel consumption in addition to the obvious reduction in diesel particulate matter.

It is, therefore, not so difficult to set up a program to manage DPM. It is, however, important that the rules of the game are known and that strategies can be set up to manage the outcome.

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