# 9 Conclusions

## 9.1 Nature of the PM emission problem

Particulate matter is a complex part of diesel exhaust emissions. The soot portion in PM is essential, but it should be emphasised that diesel particulates are not purely soot. Hydrocarbons, ash, and sulphates adsorbed into the carbon core of the particle are also present. Nanoparticles in diesel PM do not necessarily have a carbon fraction. Droplets of sulphuric acid, hydrocarbon, and water may also exist. Profound understanding of diesel combustion is essential when the further reduction of the PM emissions of diesel engines is being planned.

Current emission regulations limit only the smoke number or the mass of the PM emissions. Besides the regulations, the number of particles is also of interest. The smallest nanoparticles in particular are of concern in research into the health effects of diesel PM. Diesel PM seems to increase heart and respiratory diseases, although the correlation is weak. Hydrocarbons in particulates contain carcinogenic PAH compounds. Therefore the amount of PAH might be regulated in the future. More specific knowledge about the health effects of diesel PM is being gained constantly.

The majority of diesel engines are in road vehicles. Therefore, it is logical that the interest in the diesel PM problem has risen during the past few years especially in on-road applications. In urban areas, road traffic is a major source of particulates. In addition, people there are in close proximity to vehicles and their exhaust fumes. Off-road high-speed engine applications are also significant PM sources. Their PM emission reduction measures typically follow the ideas utilised in on-road applications after a few years' delay. In medium-speed engines, the interest in PM emissions seems to be lower. Current IMO regulations do not limit PM emissions. Therefore, the EU may extend their inland waterway regulations to all marine engines. In most of the studies concerning the PM emissions of medium-speed engines, only the smoke number is measured. Although the efforts that are being made to reduce visible smoke are creditable, it is only part of the PM problem.

In the USA, the public opinion of diesel engines is much more critical than in Europe. This can be partly explained by the bad reputation of dirty and noisy old diesel engines. In particular, a diesel-powered passenger car is still a rarity in the USA. At the same time, the development of high-speed direct injection diesel engines has been fast. Because of the low fuel consumption of diesel engines, higher $NO_x$ and PM emissions compared to spark-ignited engines are accepted in Europe, which is not the case in the USA. On the other hand, this situation reminds European manufacturers that diesel engines are not satisfactory as regards PM emissions. The development work must be kept up, if the European industry also wants to sell light-duty diesel engines to the USA.

Environmental groups in Germany have criticised the local automotive industry in a "No diesel without filter" campaign, stating that the industry has not adopted particulate filters for diesel cars. The policy of independent companies has begun to change, partly because of the internal competition within the industry. Maintaining the relatively good reputation of modern diesel engines is important to manufacturers. If environmentalist groups turn public opinion against diesel engines, it could be difficult to restore their reputation, even despite major technical improvements.

It is contradictory that the PM reduction technology in passenger car engines is advanced but that these engines operate with poor efficiency under most driving conditions. In addition, these engines can often be considered as being too powerful for their normal purpose. The use of hybrid diesel-electric powertrains would improve vehicle efficiency. The engine can be smaller and operate at loads where good efficiency is achieved. On the other hand, hybrid powertrains may increase weight, space requirements, and costs.

Heavy-duty high-, medium-, and low-speed engines usually use the energy of fuel for transportation or electricity production more efficiently than passenger car engines. Typically, they work at high loads and for long periods. For example, the total mass of PM emissions during the voyage of a cargo ship may be large, but not when considering the mass of freight carried. In harbour areas and coastal waters the emission problems are emphasised.

## 9.2 In-cylinder measures

Mastering diesel combustion is a core task in PM reduction. However, it must be emphasised that low PM formation is only one factor in diesel process optimisation. For example, the effects on other exhaust gas components, fuel consumption, and engine noise must also be considered. Basic measures in the diesel process development towards smaller PM emissions are similar in principle in engines of different sizes and applications. Fuel injection technology and controlling the mixing of the fuel and air are essential. Common-rail fuel injection is an example of a technology which is suitable for diesel engines of all sizes. Pilot injection and post-injection are easy to implement with a common-rail. Some measures are easier to realise in medium- and low-speed engines, because of the larger size of the engine components and there being more time during the work cycle.

An efficient measure to reduce $NO_x$ emissions is internal or external exhaust gas recirculation (EGR). Unfortunately, EGR usually increases PM emissions. The drawback with PM emissions can be reduced using cooled external EGR. One strategy can be to reduce $NO_x$ emissions by EGR and PM by after-treatment methods. The negative effect of the increased EGR can also be reduced by optimising the injection parameters. In practice, this means utilising the capabilities of the modern common-rail injection technology, such as high injection pressure, smaller nozzle holes, and multiplied injection.

An important development step in turbocharging technology is putting into use variable geometry turbochargers (VGT), which have improved transient performance. They are becoming standard products in passenger cars. A VGT system must be optimised in combination with the EGR. Efficient charge air cooling is a basic measure in modern diesel engines. Other alternatives are the use of waste-gate turbochargers or two-stage turbocharging.

During transient conditions, sufficient combustion air must be available to avoid momentary and local enrichment and excessive soot and PM formation. Full-authority control of turbocharging, fuel injection equipment, and EGR – if applied – offers new opportunities to control transient PM emissions.

Especially in medium- or low-speed engines, one $NO_x$ reduction method is water injection. This can be realised by injecting water directly into the combustion chamber, humidifying the charge air, or mixing the water with diesel fuel. In many studies, water-fuel emulsion has shown better PM reductions than direct water injection. Water in the fuel drop may enhance drop atomisation. The emulsion must be prepared on-board, because the fuel and water separate in a few minutes. All these solutions need additional systems for water. Water is not suitable for applications, such as on-road vehicles in a cold climate, where freezing cannot easily be avoided. On the other hand, water-based technologies are well suited to large marine engines, especially if seawater can be used.

Lubrication has an increasing contribution to particulate emissions, mainly because of the particulate reducing measures already taken in fuel properties and combustion control. The chemical structure of the lubrication oil affects the SOF composition of the PM through the deposition of lubricant-based hydrocarbons into the particles. A significant reduction of particulate emissions can be achieved by an appropriate choice of base oil and additive. Polyalphaolefin (PAO)-based lubricants produce fewer emissions compared to mineral-based lubricants.

The total number of particulates increases with the decreasing kinematic viscosity of lubricating oil. Ageing of the lubricating oil may cause a substantial increase in particulate emissions. Using detergent additives, such as polymers and dispersants, can diminish this lubricant ageing effect.

The results of studies where lubricating oil is blended with fuel indicate that calcium and barium are the most effective metallic additives to enhance oxidation and suppress soot formation. Some studies have also shown that metal additives may reduce the accumulation mode and increase the nucleation mode of PM formation.

The composition of lubricating oil and additives may have an effect on exhaust after-treatment devices. The quantity of ash deposited on the DPF seems to depend on the sulphated ash level in the fresh lubricant. The sulphur from lubricating oil can accumulate into oxidation and $NO_x$ catalysts and lead to the contamination of catalysts.

Insulation of the combustion chamber with thermal barrier coatings is one possible measure to affect cycle temperatures and, thus, PM emissions. However, this solution is not widely used. The effects of coatings on PM emissions are speculative. Durability and the extra costs of coatings may also be drawbacks.

## 9.3 Combustion development

Modification of the diesel combustion process is the subject of intensive research. Much effort is being put into research of homogenous charge compression ignition process (HCCI). In principle, PM emissions decrease with increased premixing of the charge. The main problem of the HCCI is to keep the process controllable at high loads. HCCI combustion also leads to high HC and CO emissions. Therefore it is probable that the path towards the HCCI will be made stepwise, increasing the premixing in the regular diesel process. This idea is known as premixed charge compression ignition (PCCI), which may be more realistic than pure HCCI also in the long run. There are various concepts which utilise partial premixing. The borderline between a regular diesel process and a premixed process is often inexact.

Modern optical methods have revealed a new detailed insight into spray combustion. Moreover, PAH and soot chemistry modelling with chemical kinetic codes have revealed the "soot formation regimes" with respect to local air-to-fuel ratios and local temperatures. The minimising of soot and particulate matter by avoiding these soot formation regimes during combustion looks promising.

Normal diesel fuel is highly sooting only within a temperature range from about 1600 K to 2400 K when the local air-to-fuel ratio is smaller than 0.5. For example, benzene has a large soot formation regime and oxygenates like DME a small regime.

Increasing air entrainment into the fuel spray increases the minimum local air-to-fuel ratio. It can be seen that this decreases soot formation during combustion. Air entrainment into the spray could be increased by increasing the gas density or by using very small nozzle holes. However, there is now a clear target for combustion development: controlling the local air-to-fuel ratio and local temperature. Local fuel-to-air mixing in the combustion event depends on several variables. The shape of the combustion chamber and flow field characteristics, the characteristics of the fuel injection system, the possible extended use of inert gas (EGR), and the engine speed and load conditions have to be taken into account when optimising the mixing process. Optical methods and CFD simulations are necessary tools for this kind of combustion development.

The most accurate modelling of soot formation can be performed by CFD simulation. The current CFD codes are able to predict correct trends and in-cylinder conditions that are most likely to increase soot formation. The principal problem in soot emission prediction is that, despite extensive research efforts, soot formation and oxidation mechanisms are still poorly understood.

Semi-empirical or phenomenological models are the most common approach for soot modelling with practical CFD simulation. The models must often be calibrated according to a certain case. Then they are expected to perform reasonably well in simulations for similar kinds of engines and operating conditions. Soot models have been implemented as additional features in codes such as STAR-CD and KIVA.

### 9.4 Fuel properties and alternative fuels

Diesel fuel will maintain its status as the most common fuel in compression ignition engines, at least in the near future. The EU has set a goal of replacing 20% of transport fuels with alternative fuels by 2020. The replacement fuels are primarily biofuels, natural gas, and hydrogen (Commission of the European Communities

2002c). The world's crude oil reserves are still large and it is expensive to change infrastructure. Most probably, the substitution of diesel fuel will be slow.

Diesel fuel properties can be improved greatly in such a way that engine modifications are not needed. Thereby the modified fuel is also suitable for old engines, which decreases the emissions of the whole engine fleet. The ongoing process of reducing the sulphur content of diesel fuel is the single most important task. The future limits on on-road diesel fuel sulphur content seem satisfactory, but the greatest reductions after they have been implemented could be brought about for heavy fuels. The sulphur content affects not only $SO_x$ emissions, but also PM emissions and after-treatment devices. In 2006, there will be a 15 ppm sulphur limit for on-road diesel fuel in the USA. The same limit will apply to off-road fuel in 2010. On the other hand, the IMO's world-wide sulphur limit for heavy fuels is 45,000 ppm, and this has not even been ratified yet. The use of Orimulsion or other similar fuels should replace, for example, coal, but not cleaner fuels than Orimulsion. Governments should promote the purification of heavy fuels from sulphur and ash. The health benefits from reduced pollution have been assessed as being remarkably greater than the expense involved in the purification of heavy fuels.

One important characteristic of diesel fuel is its aromatic content, because aromatics play a major role in the particulate formation process. If very low emissions are demanded, the optimisation of aromatic content, cetane number, and density must be performed.

Oxygenating fuels is a widely researched PM reduction measure. Alcohol can be mixed with regular diesel fuel without any engine modifications, although some additives may be required to keep the mixture stable and some properties above certain limits. Oxygenated fuels have shown good results in PM reduction. Oxygenates will most likely be added to diesel fuel in the future.

The group of possible alternative fuels for compression ignition engines is large. Many of them promise lower emissions than diesel fuel. The most interesting alternative fuels, especially as regards PM emissions, are Fischer-Tropsch, natural gas, DME, DEE, and hydrogen. Biofuels (biodiesel and ethanol) are also an interesting option, because they are renewable and increase $CO_2$ emissions only a little.

Biodiesel should be researched more under difficult conditions and in different climates. In other respects, it seems usable already, except for its price. In addition, future development steps are to find the best additives and to optimise engines for biodiesel. Ethanol is the other option to utilise renewable sources. As ethanol works poorly in CI engines, its future in them could be as a blended component and oxygenate. Both biofuels have shown evident PM emission reductions.

Natural gas is the main alternative fossil energy source to crude oil. It can be utilised in several ways: as CNG or LNG without processing, as Fischer-Tropsch, DME or DEE synthetic fuels, or as pure hydrogen. All of these have shown low PM emissions. Refining natural gas into different liquid forms (F-T and DEE) makes fuel handling easier. It is very unclear whether the refined products are better than their source in performance. Historically, Fischer-Tropsch fuel has been used much and its widescale commercial production is emerging. The problems related to F-T fuel should be minor, except perhaps production costs. Emission results with DME have been very good, but the costs of special handling systems and manufacturing may overrun the benefits. From this point of view, DEE seems more applicable, but not much is known about its behaviour under different circumstances or its production costs. LNG seems feasible only for large ships and probably stationary power plants, but CNG can be used in more various applications. In short, fuels in liquid form can be used with existing technology, while gaseous fuels require new infrastructure and more engine modifications.

The feasibility of hydrogen as a fuel in internal combustion engines depends on progress in storage, handling, and fuel cell technology. If fuel cells improve, it is more reasonable to use hydrogen in them instead of internal combustion engines. Experience with gaseous fuels, before the introduction of the hydrogen economy, can be gained from CNG or DME. Basically, the future of alternative fuels depends very much on policy and the value we place on a cleaner environment.

The use of cleaner alternative fuels should be promoted by tax reliefs, lower port charges, fairway dues, and other economic instruments. The wide utilisation of new alternative fuels needs investment in the production and distribution infrastructure. The best way to start with alternative fuels is to blend them with diesel or heavy fuels, or use them in dual-fuel engines. In this way the experience gained with them increases and the investments are made gradually, which is also the policy of the EU.

The question whether the diesel engine is the application in which the fuel is converted to mechanical or electrical energy most efficiently is also important. Some fuels are better suited to spark-ignited engines. However, when regular diesel fuel is used as an ignition fuel, most fuels can also be used in compression-ignition engines, although two fuel systems are needed.

## 9.5 After-treatment devices

Diesel oxidation catalysts are reliable devices for reducing CO and HC emissions. They are also said to lower PM emissions by reducing the soluble organic fraction. They are commonly used in on-road diesel engines, but commercial products for medium-speed engines are also available. The high sulphur content of the fuels used in medium-speed engines causes harmful sulphur oxide formation in the oxidation catalyst, which drastically weakens the feasibility of DOC.

$NO_x$ reduction catalysts have primarily an indirect effect on PM emissions. The engine can be optimised for low PM, while the increased $NO_x$ emissions are reduced with an after-treatment system. SCR catalysts are already in use in medium- and low-speed engines. Although they are mainly targeted for $NO_x$ reduction, they may also decrease PM emissions. The SOF of the particulates may be reduced with the SCR, but some studies have shown that even the carbon fraction of the PM is reduced. The carbon reduction mechanism is not explained in those studies, and therefore it could be worthy of further research. SCR catalysts have also been widely tested in heavy-duty trucks. An SCR system needs regular urea refilling. This is problematic in applications such as passenger cars, which are used by private citizens. The distribution infrastructure must also be built. Instead of SCR, lean $NO_x$ catalysts or $NO_x$ adsorbers are more feasible for passenger cars, because they do not need any additives.

Diesel particulate filters (DPFs) have been developed for high-speed diesel engines. The most common filter type is a wall-flow monolith filter. Particulate filter systems have shown their efficiency and reliability under real-life conditions. In new light-duty road vehicles, particulate filters are already common. Today there are no filters on the market large enough for medium-speed engines. The largest filters are suitable for about 500 kW engine power. It is possible to use several filter units in parallel, but in large medium- and low-speed engines the system would become too expensive.

DPF is usually a device that both captures and oxidises particles. The major technological challenge in diesel particulate filters is the oxidation of the collected particles, not the filtration itself. The oxidation process is known as filter regeneration. There are various filter regeneration methods which can also carry out the regeneration under difficult engine operating conditions, especially at low loads and speeds. However, some increase in fuel consumption is hardly avoidable when using DPFs because of increased exhaust gas back pressure and the additional energy needed for the regeneration.

The integration of different after-treatment systems into the same unit is a growing trend. In most applications, a DOC is usually placed upstream of the DPF in the same housing. A more challenging task is to achieve simultaneous reduction of $NO_x$ and PM emissions in a single compact unit. However, some products of this type are commercially available.

In summary, the feasible after-treatment methods for medium- and high-speed diesel engines are different. The particulate filters developed for passenger cars can also be rather easily adapted for heavy-duty road vehicles and thus for off-road applications using high-speed diesel engines. $NO_x$ emissions are primarily reduced by engine design measures such as EGR. In medium- and low-speed engines, the strategy could be the opposite to that in high-speed engines. Until larger particulate filters possibly come on to the market, PM emissions must be reduced by internal engine measures. This also helps maintain good fuel economy, because it is rather easy to achieve a low fuel consumption and low PM emissions simultaneously. For further PM reductions, a water scrubber system or an electrostatic precipitator can be an alternative. $NO_x$ emissions are removed by SCR catalysts.

## 9.6 Cost-effectiveness of the measures

Because there are a number of technically feasible measures for diesel PM reduction, the cost-effectiveness is an essential question. The extra costs of cleaner engines are usually transferred to customers. Tax incentives can be used to compensate for the increased costs and speed up the appearance of low-emission technologies on the market.

Different in-cylinder measures have highly variable costs. For example, the costs of new turbocharger technology or fuel injection systems, which are already on the market, are easy to calculate. Some engine process modifications need expensive research and development work, and the results are still uncertain.

In refineries, expensive investments are often needed to produce improved fuels. If a completely new fuel must be brought on to the market, it would be far more expensive. For engine manufacturers, an important issue is the possible engine modifications for the new or improved fuel.

The utilisation of after-treatment devices implies extra engine costs. After-treatment devices themselves cost money, but engines may also need some modification in order to work optimally with an after-treatment system. During the life cycle of the engine there may be extra maintenance costs. Most devices also increase fuel consumption.

The correlation between diesel PM and health effects is not comprehensively known. Even if the correlation could be estimated, it would be difficult to calculate exactly how much the improved health of people saves money.

In summary, it is not easy to draw conclusions about costs. Sometimes it is difficult to compare the effectiveness of different PM reduction methods even if their cost-effectiveness is excluded. The reductions achieved using the same methods vary greatly from each other in different studies. This suggests that an optimisation of the measures in different types of engines and operating conditions is necessary.

## 9.7 Probable measures to fulfil future emission regulations

There are concerns that future emission limits would force the use of such expensive measures for their fulfilment that diesel engines could suffer in the competition with gasoline engines. Hence, the feasibility of several proposed future emission standards will be evaluated before their implementation. The PM emission regulations cannot be directly compared with each other, because the test cycles are usually different. Therefore, it is not possible to estimate the methods necessary for reaching the limits only by based on the PM value.

According to Johnson (2003), the Euro 4 limits in 2005 for passenger cars and light-duty trucks can be reached without the DPF using only internal engine measures in the weight class under 1.7 tonnes. The possible Euro 5 limits in 2010 seem to require both $NO_x$ and PM after-treatment. The DPF will probably become necessary in order to fulfil the regulations in Japan in 2005. In the US Tier 2 regulations applicable from 2006, both $NO_x$ and PM after-treatment may be necessary.

The Euro IV limits in 2005 for heavy-duty on-road diesel engines will probably demand the use of either DPF or $NO_x$ after-treatment. In some cases, even the DOC may fulfil the PM limits. The PM emission limits are the same in Euro V and Euro IV, but the $NO_x$ limits are tightened in Euro V. After 2007 in the USA, the PM emission limits for heavy-duty highway diesel engines will be tightened remarkably. To fulfil these limits a particulate filter will be necessary. $NO_x$ limits might be reached without after-treatment. In 2010 in the USA the $NO_x$ limits will be tightened further and make $NO_x$ after-treatment also necessary. (Johnson 2003; Pfeifer et al. 2003)

The European Stage III standards and US Tier 3 standards in 2006–2008 for off-road engines can be reached using only internal engine measures. In Europe, particulate filters and $NO_x$ reduction catalysts for off-road engines will not become necessary until the Stage IV regulations come into force in 2011–2012. In the USA, the proposed Tier 4 regulations for non-road engines in 2011–2014 would probably also demand a DPF. The proposed PM limits in the Tier 4 regulations would be slightly stricter than in the Stage IV standard.

Currently, there are no PM emission limitations for marine engines. In practice, some harbours have their own limits. Because visible smoke degrades the image of the whole shipping business, manufacturers and ship owners demand a certain level of cleanliness. The first limits (Tier 1, Tier 2, and Stage III) for waterway vessels can easily be achieved by internal engine measures. The limits for inland waterway vessels in the Stage IV proposal, which should come into force after 2010, will require extensive after-treatment such as DPF and SCR. That should not be a technical problem because even present marine engines equipped with an SCR can achieve $NO_x$ emissions under 2 g/kWh.

In power plants, there are generally no space or weight limitations on after-treatment devices. The only limitations are the costs. Thus, electricity produced in diesel power plants may become too expensive to be competitive, at least in some areas. On the other hand, regulations for other thermal power plants are also tightening.

Individual states or cities can enact local emission reduction programmes in addition to emission limits for the whole EU, USA, or Japan. There are also strict emission regulations in some other countries. For example, in Switzerland the use of a particulate filter is mandatory in diesel equipment in tunnel construction and on other large construction sites. (Schäfer-Sindlinger & Vogt 2003)

Recent diesel combustion research has revealed that non-sooting spray combustion is possible. However, much research and development work is needed before new combustion technologies can be applied.

## 9.8 Recommendations for minimising PM emissions

The reduction of PM without negative effects on fuel consumption or other emission components is essential. Using technologies available today, much can be done. Recommendations are presented below.

All engine size classes:

- Oxygenated fuel with ash, sulphur and aromatics content as low as possible.
- Oxidation catalyst, which is assumed to oxidise hydrocarbons in PM.
- Common-rail or electronic unit injector system with high injection pressure and multi-phase injection.
- Turbocharging with efficient charge air cooling. Controllable turbochargers and two-stage turbocharging.
- If EGR is used for $NO_x$ reduction, it should preferably be cooled.

- Optimisation of parameters such as injection timing, combustion chamber shape, swirl motion, controllable valve timing, and lift.
- Full-authority control of turbocharging, fuel injection, and EGR.
- Extensive combustion process development, including simulation and optical measurements.

High-speed diesel engines:

- Wall-flow monolith particulate filters for soot reduction in PM, available for engines up to about 500 kW; over 90% PM reduction.
- Alternatively, a combined $NO_x$ and PM reduction system.
- Retrofit of the DPF for old high-speed diesel engines.

Medium- and low-speed diesel engines:

- Combustion process optimisation for low PM emissions, increased $NO_x$ reduced by SCR catalysts.
- PM reduction with electrostatic precipitators, water scrubbers, or disposable filters.

It must be highlighted that it is economically unrealistic to use all the recommended measures in one engine. Current and future emission regulations can be achieved without using all possible measures. The benefits and costs of reducing PM emissions further, below the maximum allowed, must be considered on a case-by-case basis.