

High Performance Cooling and EGR Systems as a Contribution to Meeting Future Emission Standards

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ABSTRACT

In relation to further tightening of the emissions legislation for on-road heavy duty Diesel engines, the future potential of cooled exhaust gas recirculation (EGR) as a result of developments in the cooling systems of such engines has been evaluated. Four basic engine concepts were investigated: an engine with SCR exhaust gas aftertreatment for control of the nitrogen oxides (NO_x), an engine with cooled EGR and particulate (PM) filtration, an engine with low pressure EGR and PM filtration and an engine with two stage low temperature cooled EGR also with a particulate filter. A 10.5 litre engine was calibrated and tested under conditions representative for each concept, such that 1.7 g/kWh (1.3 g/bhp-hr) NO_x could be achieved over the ESC and ETC. This corresponds to emissions 15% below the Euro 5 legislation level. It was found, as a consequence of the two stage low temperature EGR cooling, that not only could the fuel economy of the engine be improved compared to that with conventional EGR cooling but that this economy was similar to that of the SCR engine concept (when the urea solution consumption was taken into account). The required cooling performance was achieved via optimisation of the cooling system without an increase in the fan power requirement. It was also found that the engine with two stage low temperature cooled EGR could achieve NO_x emissions significantly less than 1 g/kWh (0.7 g/bhp-hr) over the legislated test cycles with consistent fuel economy.

INTRODUCTION

For more than fifteen years the development of heavy duty Diesel engines for commercial vehicles has been driven largely by ever more stringent exhaust gas emissions legislation. This trend has been seen worldwide, even though regional differences in the legislated levels and the test cycles exist.

Up until the year 2000, when the allowable levels stood at approximately 5 g/kWh (3.7 g/bhp-hr) of NO_x , the legislation could be achieved via conventional engine based means, such as increasing the fuel injection pressure, the air boost pressure ratio or an improved charge air cooling. With the introduction of NO_x emission limits of 3 g/kWh (2.2 g/bhp-hr) or lower two alternative technical solutions have been applied: cooled exhaust gas recirculation (EGR), which enables the engine out raw emissions to reach the legislated levels, or exhaust gas aftertreatment through selective catalytic reduction (SCR) of the NO_x , which allows higher engine out NO_x emissions and better fuel economy. However, with SCR an additional reductant such as urea solution is necessary, which must be taken into account when considering the engine operating costs. Comparisons using vehicles operated under real conditions show similar operating costs for both solutions [1].

It must be assumed that in some if not all countries the legislated NO_x levels will be further reduced. The effectiveness of the emissions reduction via engine based and/or aftertreatment based methods will need to be evaluated once more. In either case, the fuel economy of the engine plus the requirements for the cooling system will need to be evaluated.

The results presented in this paper go some way towards supporting this evaluation. Test results from a multi-cylinder engine show that, through the implementation of practical cooling system advances, not only can a cooled EGR based solution achieve lower NO_x levels, but that this is possible with acceptable operating costs. These cooling system advances and the components necessary to realise them, which are applicable not only to EGR but also to a great extent to SCR solutions, will be described in detail.

Emission Levels		Year									Units
		2004	2005	2006	2007	2008	2009	2010	2011	2012	
Europe	NO _x	5.0		3.5		2.0					g/kWh
	PM	0.10		0.02		0.02					
USA	NO _x	2.50		1.20		0.20					g/bhp-hr
	PM	0.10		0.01		0.01					
Japan	NO _x	3.38		2.00		0.70					g/kWh
	PM	0.18		0.027		0.01					

Figure1: NO_x and particulate matter limits for on-road heavy duty Diesel engines in Europe, the USA and Japan

LEGISLATION

Europe, the USA and Japan lead the introduction of commercial vehicle emissions legislation. In these countries the allowable levels of NO_x and PM have been reduced step by step (see Figure 1). Furthermore, it must be realised that China and India will introduce the European legislation with just a few years delay.

In Europe, with the introduction in 2008 of the Euro 5 legislation, the limit for NO_x will be 2.0 g/kWh (1.5 g/bhp-hr), whilst the limit of PM will remain unchanged from Euro 4 at 0.02 g/kWh (0.015 g/bhp-hr) [2]. The engines are tested over steady state (European Steady-state Cycle (ESC)) and transient (European Transient Cycle (ETC)) cycles. Currently, there is discussion about the possible limits for Euro 6: this could come into force

sometime after 2012 and is likely to result in lower legislated emissions limits. For this case a new transient cycle, the World Harmonized Transient Cycle (WHTC) is also in discussion.

In the USA from 2010 the lowest limit levels in the world will come into force: 0.20 g/bhp-hr (0.27 g/kWh) for NO_x and 0.01 g/bhp-hr (0.013 g/kWh) for PM [3]. These will be measured over the steady state (SET) and transient (HD-FTP) test cycles.

In Japan the New Long-Term Regulation (NLTR) is currently in force. The next reduction is planned for 2009, when the NO_x limits will be 0.7 g/kWh (0.52 g/bhp-hr) and the PM 0.01 g/kWh (0.007 g/bhp-hr) measured over a transient test cycle (JE05) [4].

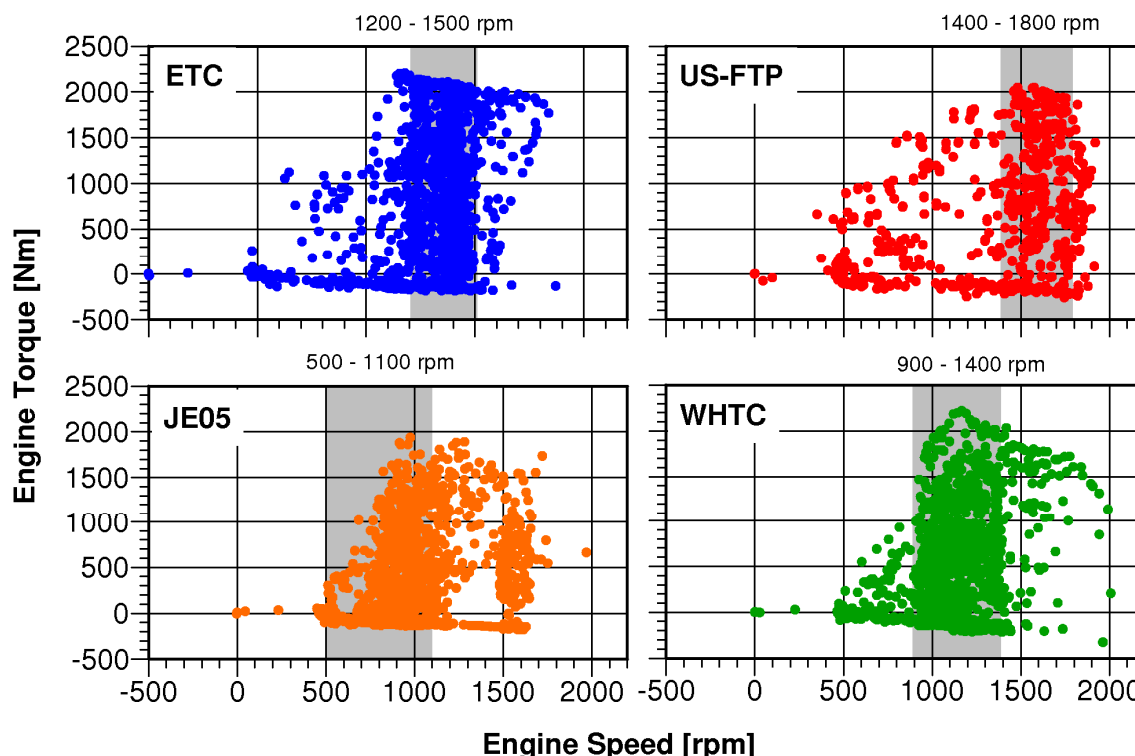


Figure 2: Transient test cycles for heavy duty Diesel engines with their dominant speed ranges (grey); engine size 12 litre, rated speed 1800 rpm, Japan: 25 tonne gross vehicle weight

The individual engine test cycles that are specified in order to measure the emissions levels have significantly different speed and load operating profiles (see Figure 2) [5]. This can result in different technical solutions reaching similar legislated emissions levels. The introduction of the WHTC would mean a reduction of the average operational speed and load when compared to the ETC. This would result in a lowering of the exhaust gas temperatures and possibly more difficult conditions for the correct operation of exhaust gas aftertreatment systems.

EMISSIONS REDUCTION AND ENGINE COOLING TECHNOLOGY

TECHNOLOGIES FOR EMISSIONS REDUCTION

The mechanisms of creation of NO_x and PM emissions lead to a conflict trade-off situation when trying to fulfil the emissions legislation. For example, whilst increasing combustion temperature leads to an exponential rise in the NO_x formation, the higher temperatures also lead to a more effective oxidation of soot hence lower emitted PM [6]. Engine based in-cylinder technologies have been repeatedly introduced to improve this trade-off. When it is no longer possible or economic to do this then exhaust gas aftertreatment technology is applied in order to achieve the legislation.

Engine Based Measures

Through improvements in the combustion processes, the fuel injection equipment, the boosting system and also the charge air cooling system, NO_x legislation down to 5 g/kWh (3.7 g/bhp-hr) could be achieved without a significant deterioration in the engine fuel consumption [6]. In combination with cooled EGR lower NO_x levels could be achieved [7, 8].

With cooled EGR part of the exhaust gas from the engine is returned and mixed with the intake air [9]. Due to its higher heat capacity and its lower oxygen content, the introduction of EGR leads to a reduction of the in-cylinder combustion temperatures, hence NO_x creation. This effect is magnified when the exhaust gas is cooled, which allows a further reduction in the NO_x and a better charge density for improved PM emissions. Consequently, the trade-off between NO_x and PM emissions has been improved step by step over the last years. In Figure 3 this development identifying the primary engine based technologies is represented by example at 9, 5 and 2 g/kWh (6.7, 3.7 and 1.5 g/bhp-hr) NO_x over the ESC.

Two different types of EGR systems are possible. In a high pressure EGR system, EGR is taken prior to the turbine and routed through an EGR cooler and valve to a mixing point between charge air cooler and intake manifold. Low pressure EGR systems pick up the recirculated exhaust gas after the particulate filter and return it upstream of the compressor.

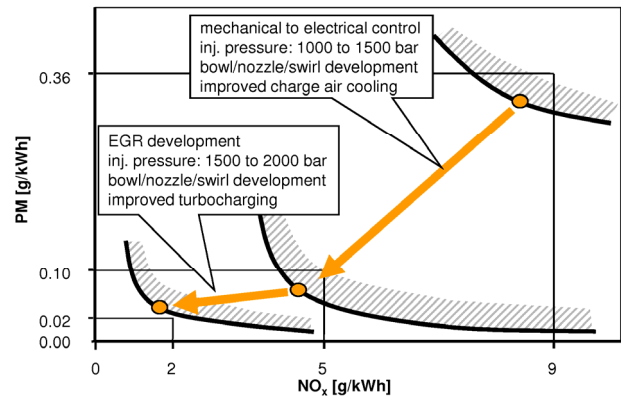


Figure 3: The development of the NO_x versus PM trade-off from 9 to 2 g/kWh and the corresponding technologies

Exhaust Gas Aftertreatment

A further possibility to reduce the NO_x and PM emissions is the application of SCR and a Diesel particulate filter (DPF).

With SCR, a urea solution (AdBlue®) [10,11] is injected into the exhaust line; as a result of the temperatures present there the solution then breaks down to form ammonia and over the catalyst this reduces the NO_x in the exhaust. The use of SCR allows the engine to be calibrated close to its optimum for fuel economy, which means that the engine-out NO_x levels are between 7 to 9 g/kWh for a tailpipe emission of 2 g/kWh. The amount of urea used is proportional to the amount of NO_x to be reduced: for Euro 4 engines this is between 4 to 6% by volume of the fuel consumption.

As a consequence of the lowered emissions legislation in the USA from 2007, DPF technology will be used in all applications. The particulate matter is trapped in the filter and then combusted during filter regeneration. The particle filter has been applied for many years to commercial vehicles but, until now, usually only on vehicles with sensitive applications, such as inner-city buses and delivery trucks.

Combined Solutions

Depending upon the legislation, combinations of different in-cylinder and aftertreatment technologies can be applied. With NO_x limits below 0.3 g/kWh (0.22 g/bhp-hr) and PM limits below 0.01 g/kWh (0.007 g/bhp-hr), as for example those in the USA from 2010, a combination of EGR, SCR and DPF is likely to be needed [9, 13].

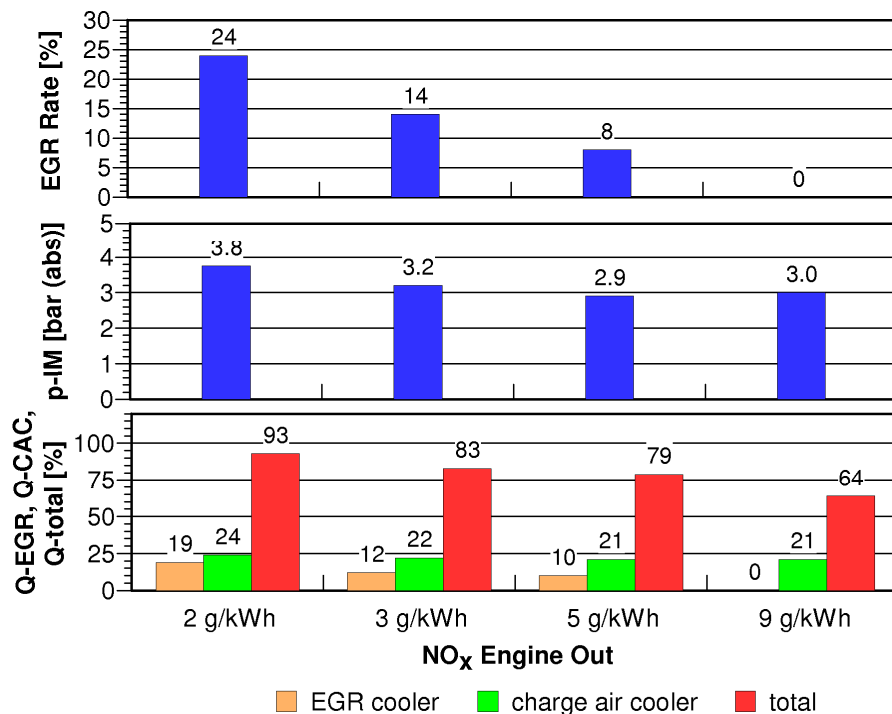


Figure 4: Required EGR rates and boost pressures to achieve different NO_x scenarios and the heat rejected (shown as the total, that from the recirculated exhaust gas and that from the charge air) as percentage of engine power; numbers given for the ESC C100 operating point

DEMANDS UPON THE COOLING SYSTEM

For a typical heavy duty Diesel engine (with between 1.6 to 2.0 litres per cylinder) the variation in EGR rate, inlet manifold pressure (p-IM) and heat rejection (from the EGR cooler (Q-EGR), the charge air cooler (Q-CAC) and in total (Q-total)) at close to rated power (point C100 on the ESC [2]) is shown in Figure 4 for a variety of engine out NO_x levels. With the reducing engine out emissions, represented by lower NO_x levels, the heat rejection from both the EGR cooler (because of increased EGR rates) and the charge air cooler (because of increased boost pressures for PM control etc.) increases. It is clear that such an increase in the required heat rejection is only possible through appropriate further developments in the cooling system.

DESCRIPTION OF THE CONCEPTS UNDER CONSIDERATION

In the following sections four concepts are described. These concepts were investigated in order to examine the requirements for engine and cooling systems at 2 g/kWh (1.5 g/bhp-hr) NO_x. Together with the concepts currently in use (SCR, high pressure EGR (EGR) and low pressure EGR (LP-EGR)) a fourth variant, where the recirculated exhaust gas is cooled much more (low-temperature EGR (LT-EGR)) was also investigated to determine how much improvement further development of the cooling system can bring.

THE “SCR” CONCEPT

In order to reach the cycle NO_x targets the SCR system has an assumed efficiency of between 70 and 80%. As such the engine out emissions lie between 7 to 9 g/kWh (5.2 to 6.7 g/bhp-hr) NO_x and the PM levels are less than 0.02 g/kWh (0.015 g/bhp-hr), such that a DPF is not required. The boosting system is assumed to be a single stage, fixed geometry, wastegate turbocharger.

The cooling system primarily consists of an engine cooling circuit with a coolant pump, a thermostat, a radiator, a charge air-to-air cooler and a fan with a viscous clutch (see Figure 5). Compared to a 5 g/kWh (3.7 g/bhp-hr) NO_x engine (Euro 3) there are no significant cooling system changes required.

THE “EGR” CONCEPT

Here cooled exhaust gas recirculation is used to achieve the NO_x limits “engine-out”: the exhaust gas is cooled using coolant from the engine cooling circuit. To achieve the PM limits a DPF effectiveness of 50 to 70% is assumed, such that engine-out PM levels of between 0.04 to 0.06 g/kWh (0.03 to 0.044 g/bhp-hr) can be accepted.

In the investigations reported here, the boosting system consisted of two stages, with charge air cooling after each stage: both of the charge air coolers were engine mounted. The cooling system (see Figure 6) consisted of

an engine cooling circuit with the coolant pump, the exhaust gas cooler (EGRC), the thermostat and radiator, an independent low temperature circuit with a separate coolant pump, a low pressure charge air cooler (LP-CAC), a high pressure charge air cooler (HP-CAC) together with their own radiator (LT-Radiator) and a fan with viscous clutch.

THE "LP-EGR" CONCEPT

In this concept EGR is routed through a low pressure EGR system (see Figure 7). The gas is cooled using the coolant from the main engine coolant circuit. Lower coolant temperatures for the EGR cooler are not desirable in order to avoid condensation prior to the compressor.

Like the two other EGR concepts the engine is equipped with a two stage turbocharging system with intercooling.

To avoid condensation in the LP-CAC, the charge air in the LP-CAC is cooled with engine coolant, whereas the HP-CAC uses low temperature coolant. By routing the EGR gas together with the charge air through the charge air cooler, low intake manifold temperatures can be achieved, comparable with the "LT-EGR" concept.

A drawback of this solution is the formation of acidic condensate inside the charge air cooler. The charge air cooler is typically made out of aluminium. Therefore special aluminium alloys are required to avoid excessive corrosion.

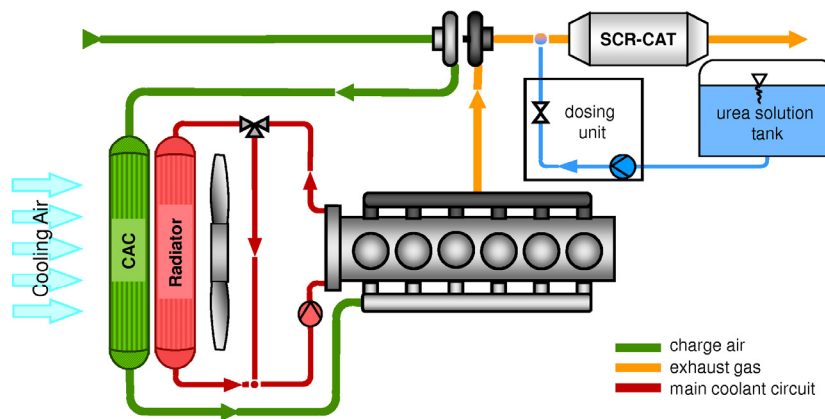


Figure 5: Schematic layout of concept variant "SCR" including the cooling system

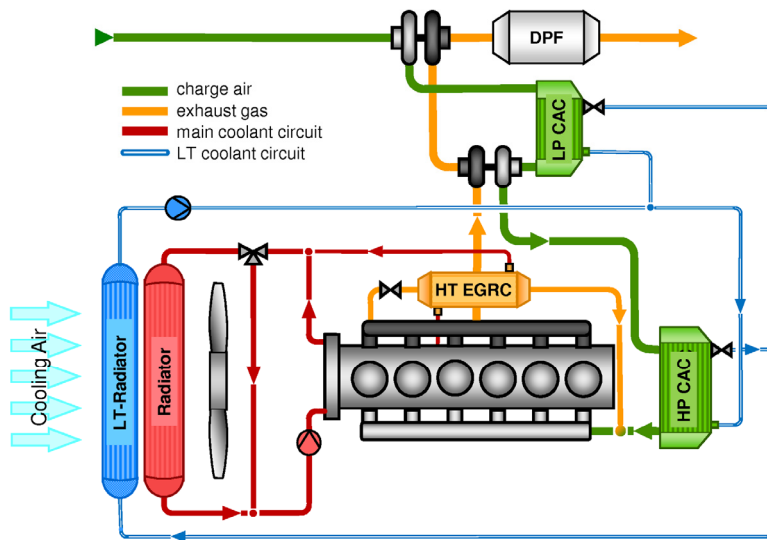


Figure 6: Schematic layout of concept variant "EGR" including the cooling system