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Effect of coolant temperature on combustion and combustion noise fluctuations in a Diesel engine at idle conditions

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For a long time now, the reduction of noise and vibration is one of the major concerns of carmakers for their Diesel engines. Cold and idle conditions are considered to be the most critical conditions for both combustion noise and pollutant emissions. A better understanding of combustion process at these conditions gives better trade off between noise and pollutant emissions.
This paper presents the results of a study about the effects of engine coolant temperature and injection timings on the combustion process and on the combustion noise at idle condition. A modern direct-injection Diesel engine equipped with a common-rail injection system and piezoelectric injectors is used. It has been found that the combustion noise is very sensitive to both the coolant temperature and the dwell time between the pilot and the main injection, but its evolution does not follow a simple way. When the coolant temperature reaches $40°C$, there is a jump of combustion noise. In this case, the combustion of the pilot injection occurs at TDC, creating a high-pressure derivative and consequently a high combustion noise. The same phenomenon is observed with the change of dwell time between the pilot and the main injections. The combustion noise reaches its maximum level when the combustion of the pilot injection occurs at TDC.

Nomenclature

CNM	Combustion NoiseMeter (dBA)
ECU	Electronic control unit
$main$	Main injection
p_{cyl}	Cylinder pressure (Pa)
pil	Pilot injection
Q	Integral of the ROHR (J)
$ROHR$ or $dQ/d\theta$	Rate of heat release ($J/°CA$)
SOA/EOA	Start/End of Activation ($°CA$)
SOC/EOC	Start/End of Combustion ($°CA$)
t_a	Activation duration of the injection (μs)
Tc	Coolant temperature ($°C$)
TDC	Top Dead Center
V	Volume (m^3)
ϕ	Time lag between two injections (μs)
γ	Ratio of specific heat
θ	Crank Angle ($°CA$)

1 Introduction

For a long time now, the reduction of noise and vibration is one of the major concerns of carmakers for their Diesel engines [1]. Cold and idle conditions are considered to be the most critical from combustion noise point of view. It is also the case for the control of pollutant emission. Cold and idle conditions are considered to be the worst conditions in term of pollutant emission control. It is the case for the noise emission too. In such conditions, the piston and the chamber walls are cold, or at most not as hot as it could be in other conditions. The injection and the ignition occur in a cold environment which doesn't contribute positively to the combustion progress.
The wall and chamber temperatures are well known to be key parameters for the pollutant emissions. Ogawa et al. [2] showed that the increase in coolant temperature leads to lower HC emissions and higher NOx emissions. This result has also been observed by Torregrosa et al. [3] who found that an increase in the intake charge temperature leads also to a decrease in HC emissions and an increase in NOx emissions.
Torregrosa et al. [3] mentioned that the increase in coolant temperature or in intake charge temperature decreases the smoke emissions. The aim of the present work is to evaluate the effects of coolant temperature and injection parameters on the combustion process in regard to the combustion noise emission.

2 Experimental set-up and test conditions

Experiments have been made on a Common Rail Diesel engine [4]. The engine specifications are presented in Table 1.

Combustion system	Diesel Direct-Injection
Injection system	Common-Rail
Injectors type	Piezo-electric
Working cycle	4-stroke
Number of cylinder	4
Displacement	2000 cm^3
Valve system	2 In. / 2 Exh.

Table 1: Table of engine specifications

The engine is instrumented with cylinder pressure sensors (one per cylinder). The driving voltage applied to the injector #4 is measured to control the real injection timing. The dynamic pressure signal is measured with a relative pressure sensor mounted on a clamping adapter in the middle of the high-pressure pipe (injector #4). All measurements are performed over at least 100 cycles at a sample frequency of 204800 Hz. The control parameters of the engine are also recorded. The engine speed chosen for this study is the idle condition *i.e.* 800 rpm. The coolant temperature is changed from $Tc = 20°C$ to $Tc = 80°C$. Three injections per cycle were performed, two pilot injections and a main injection. Further experiments were done at hot conditions (*i.e.* $Tc = 90°C$) with only two injections per cycle. The aim is to study the influence of an increase in the dwell time between the two injections on the combustion and on the combustion noise emissions. The timing of main injection is kept constant equal to $360°CA$, the timing of the pilot injection being changed from around $348°CA$

to around $357°CA$. Moreover two charge conditions are considered: one with minimum engine torque ($23\ Nm$), another with double engine torque ($46\ Nm$) obtained by increased electrical consumption.

3 Data exploitation

3.1 Rate of heat release and combustion noise characterization

The cylinder pressure signal is used here to characterize the behavior of the combustion in the cylinder and the noise emissions. The combustion noise is commonly estimated from the cylinder pressure [5–10]. This procedure implies the application of three consecutive filters to the pressure signal, known as the AVL NoiseMeter treatment. The first filter that simulates the structure attenuation has been determined by Russell and Young [5] on a large range of Diesel engine. The second filter is introduced to avoid the influence of the chamber resonance on the cylinder pressure. Finally, the third filter takes into account the human ear response. The result of this procedure is a combustion noise level named CNM for Combustion NoiseMeter in dBA.

The cylinder pressure is also used to estimate the rate of heat release (ROHR). Numerous references can be found in the literature on the modeling of the rate of heat release [11–15]. The ROHR is calculated here from the first thermodynamic principle and the perfect gas law. The expression of the ROHR is given by Eq (1):

$$\frac{dQ}{d\theta} = \frac{\gamma}{\gamma - 1} \cdot p_{cyl} \cdot \frac{dV}{d\theta} + \frac{1}{\gamma - 1} \cdot V \cdot \frac{dp_{cyl}}{d\theta} \quad (1)$$

The instantaneous volume of the combustion chamber V is defined from the geometrical parameters of the engine. Thus, an analytical expression for V and $dV/d\theta$ is known. The derivative of the cylinder pressure $dp/d\theta$ is determined with a classical derivative formula.

3.2 Injection times and ignition delay

The Fig.1 shows the parameters estimated from the voltage signal and the rate of heat release. The actual activation duration of the injector, t_a, is obtained from the signal voltage (see Fig.1):

$$t_a = EOA - SOA \quad (2)$$

The dwell time ϕ between the successive activations of the injector is also considered:

$$\phi = SOA_2 - SOA_1 \quad (3)$$

The start and the end of combustion (SOC and EOC) are derived from the rate of heat release and used to determine the ignition delay t_{ig}:

$$t_{ig} = SOC - SOA \quad (4)$$

4 Results

4.1 Effects of the coolant temperature

The coolant temperature is changed from $Tc = 20°C$ to $Tc = 80°C$. The injection system is driven by the ECU, but a false coolant temperature ($Tc = 90°C$) is fixed on the ECU, disregarding the true coolant temperature, in order to maintain the same injection strategy for the different conditions. However, in our experiments, the rise of the coolant temperature comes along with a decrease of the indicated torque (-15%), and so leads to a slight reduction of the injection durations (by nearly -10 %). The decrease of the indicated torque with the increase in Tc expresses a decrease in the engine charge due, for example, to a reduction in friction stresses or in the pressure drop in the coolant circuit induced by a decrease in the fluid viscosities.

The changes occurring in the injection and the combustion are summarized in Fig.2. For each condition, the injection phases are well distinguished. The start of activation is progressively shifted to earlier crank angle value for the three injections. With the scale chosen for this graph, the decrease of the activation duration is too week to clearly be noticed. The combustion phases cannot be differentiated so easily, particularly for the coldest conditions (bottom of the chart). For $30°C < Tc < 60°C$, only two combustion phases actually occur in the combustion chamber. The partitioning in three distinct combustion phases is effective only for $Tc = 80°C$. The combustion of the pilot injections

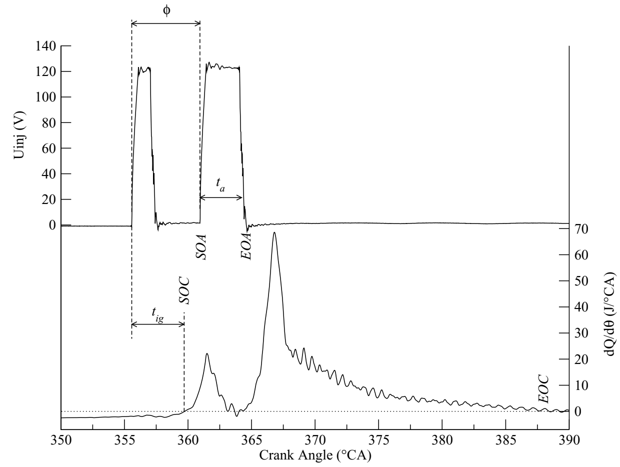

Figure 1: Definition of the start of activation (SOA), end of activation (EOA), activation duration (t_a), time lag between two injections (ϕ) and ignition delay (t_{ig})

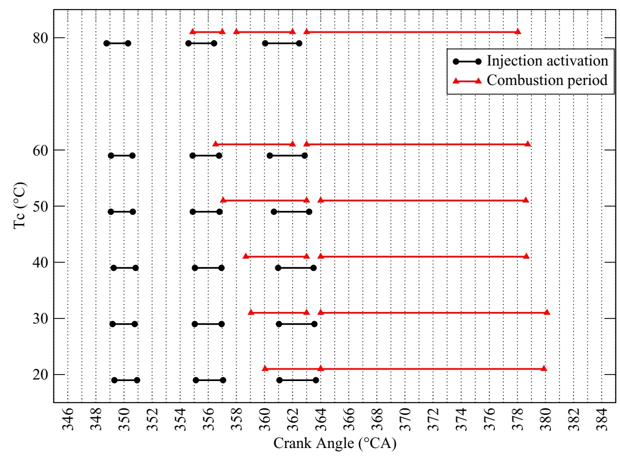

Figure 2: Chart of the injection and combustion timings

is significantly modified by the elevation of the coolant temperature in terms of phasing, duration and intensity. When the coolant temperature is increased from $20°C$ to $80°C$, the ignition delay diminishes from $10.4°CA$ to $6.0°CA$, thus t_{ig} reduces about $4°CA$ whereas the injection timings only change of about $0.7°CA$.

The injection durations decrease by nearly 10% for Tc varying from $20°C$ to $80°C$, but the maximum of ROHR and the integral of the ROHR decrease by almost 40% with the increase in coolant temperature. The Fig.3 illustrates these decreases for the four cylinders. These important decreases are due to the changes of thermodynamic conditions in the cylinder.

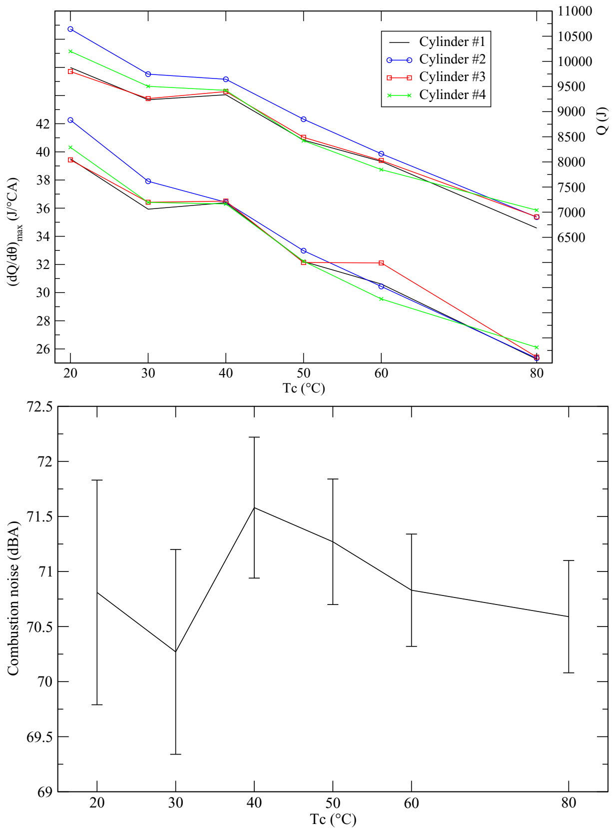

Figure 3: Evolution of the maximum of ROHR, of the integral of ROHR and of the combustion noise with the increase in coolant temperature

Usually, pretty good correlations are found between the CNM levels and the maximum of ROHR values (or the maximum of cylinder pressure derivative) [5–10]. This is true at constant coolant temperature for cycle-to-cycle fluctuations. When the coolant temperature changes, the tendency observed for the combustion noise is very different to that observed for the ROHR. As shown in Fig.3, from $20°C$ to $30°C$ and from $40°C$ to $80°C$, the combustion noise decreases slightly and regularly with the increase of coolant temperature, but from $30°C$ to $40°C$, combustion noise greatly increases ($+1.5$ dBA).

The increase in CNM level at $40°C$ seems quite surprising because, in general, the increase of engine temperature permits a quicker fuel ignition in the chamber, and as a result the combustion noise is lower. By analyzing the cylinder pressure derivative shown in Fig.4, it can be seen that when the coolant temperature is between $20°C$ and $30°C$, due to the very low temperature of cylinder wall, the combustion of pilot injections is so delayed that it takes place after the top dead center (TDC *i.e.* $360°CA$) when the piston is moving down, and consequently the cylinder pressure derivative is quite small. When the coolant temperature reaches

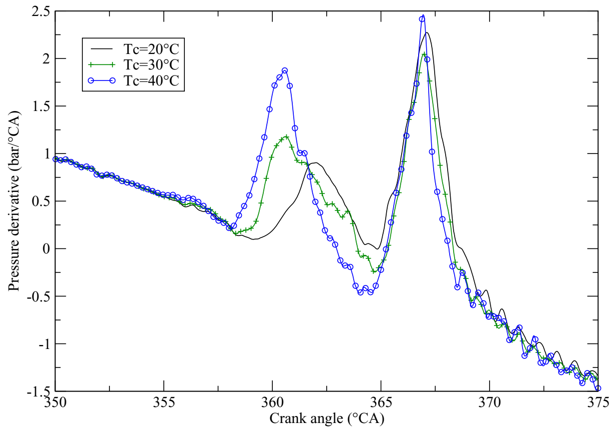

Figure 4: Cylinder pressure derivative analysis at different coolant temperatures - $Tc = 20, 30$ and $40°C$

$40°C$, the combustion of pilot injections takes place just at the position of TDC, where the thermodynamic conditions are the worst for the combustion noise. It results in a much higher pressure derivative, which explains why the CNM level at $40°C$ is higher than that at $30°C$. The pressure derivatives related to the combustion of the principal injection are similar for the 3 coolant temperatures. Beyond $40°C$, when the coolant temperature increases, the combustion of pilot injections occurs more and more before the TDC so the cylinder pressure derivative decreases. Moreover, an increase in engine temperature leads to a reduction in combustion ignition delay which is favorable to combustion noise. This is why the combustion noise decreases with the increase in coolant temperature in the range beyond $40°C$.

The standard deviations of the CNM at very low temperature ($20°C - 30°C$) are higher than those beyond $40°C$, this means a high cycle-to-cycle ignition instability at very low temperature.

As can be seen in Fig.5, the ROHR shape is changing too when Tc increases. In fact, at low temperature, the pilot and the main combustion are very close and cannot really be differentiated. When the temperature increases, the maximum of ROHR of the pilot combustion increases too. At hot temperature, three local maximum for the ROHR corresponding to the three injections were obtained. This indicates that the fuel mass injected during the first pilot injection does not really burn in the chamber, except when $Tc = 80°C$.

4.2 Effects of the injection timing

In this second part, experiments were done at hot conditions (*i.e.* $Tc = 90°C$) with only two injections per cycle. The timing of main injection is kept constant equal to $360°CA$, the timing of the pilot injection is changed from around $348°CA$ to around $357°CA$. The effect of the injection timing is tested for two charge conditions

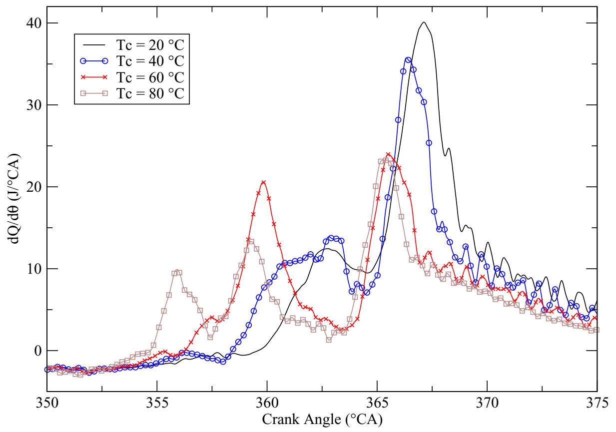

Figure 5: Change in the ROHR shape with the increasing coolant temperature

(simple and double charge condition). The change of the charge condition is compensated by the ECU with slight modifications of injection durations. The ECU acts in fact on the injection durations to change the fuel mass injected by cycle.

The change in the combustion induced by the different injection timings is shown in Fig.6. Excepting the case of a very late pilot injection, the ROHR clearly shows distinct combustion phases. Main combustion remains located around $366°CA$ and pilot combustion advances in the same way as the SOA_{pil}.

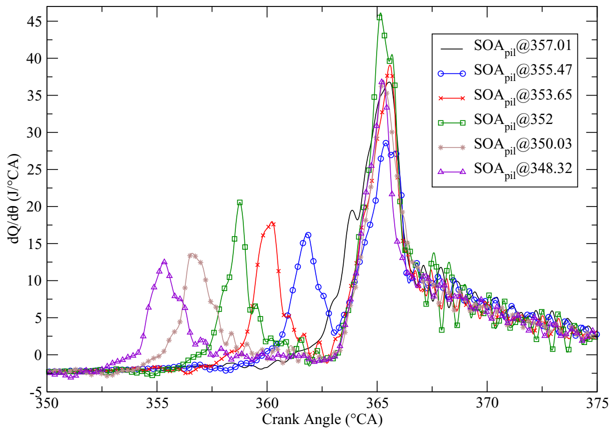

Figure 6: Evolution of the ROHR for several crank angle of SOA_{pil} (crank angle of SOA_{main} = constant, simple charge condition)

As shown in Fig.7, the ignition delays are high for advanced pilot injections. This is merely due to the low cylinder pressure and low temperature. These thermodynamic conditions are not favorable to a rapid ignition. The ignition delay decreases continuously with the increase of the SOA of pilot injection up to $356°CA$. After that (pilot injection near TDC), a slight increase in ignition delay can be noticed for both charge conditions. This result was also obtained by Kook et al. [16] who showed that the average in-cylinder temperature decreases earlier than the in-cylinder pressure near TDC. As the ignition delay is well correlated to the inverse of the gas temperature, the ignition delay finally increases.

The combustion noise levels and the maximum of

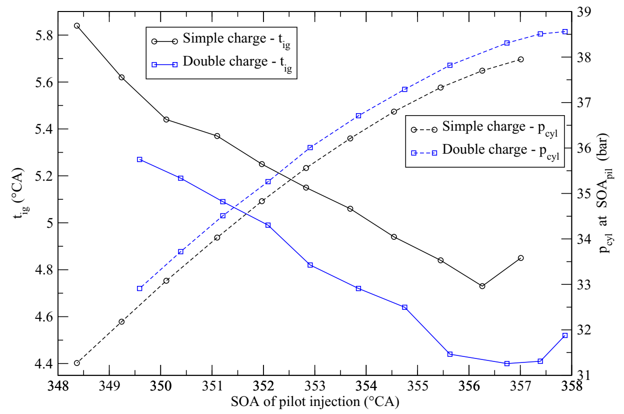

Figure 7: Evolution of the mean ignition delay and the mean cylinder pressure at SOA_{pil} with the injection timings (for simple and double charge)

ROHR are shown in Fig.8. The correlation between the maximum of ROHR and the CNM is quite clear in this figure. For $SOA_{pil} \leq 353°CA$, the ignition takes place

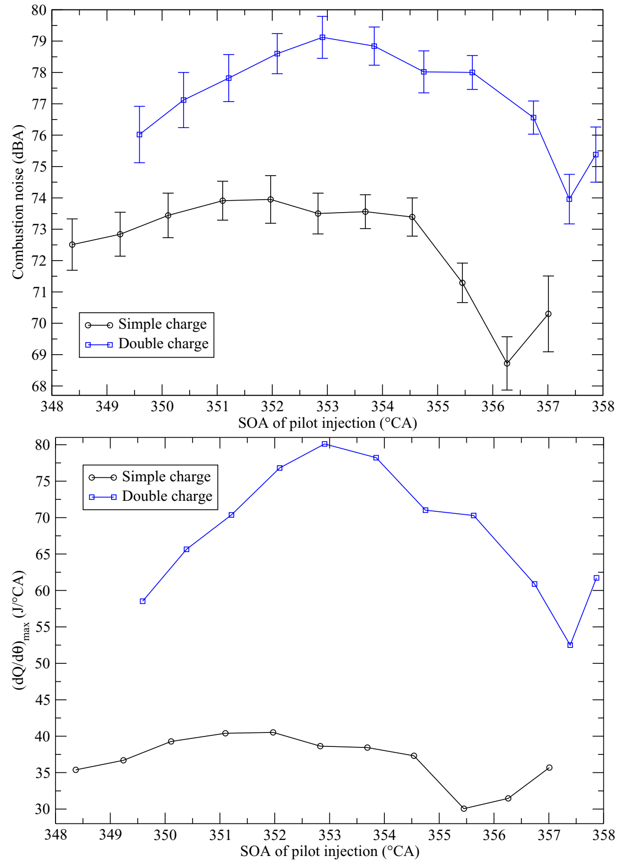

Figure 8: Combustion noise and maximum of ROHR versus SOA of pilot injection for simple and double charge

before the TDC (see Fig.6). Thus, as SOA_{pil} increases from $348.32°CA$ to $352.86°CA$, the ignition moves closer to the TDC which implies an increase in maximum of pressure derivative and in combustion noise. For SOA_{pil} $> 353°CA$, the ignition of combustion takes place after the TDC. In these cases, a higher SOA_{pil} implies a combustion far from the TDC, thus a lower pressure derivative due to the fact that the piston is moving down. This explains why the combustion noise decreases quickly with SOA_{pil}. The minimum of CNM and of $(dQ/d\theta)_{max}$ occurs when the ignition delay is the shortest. The SOA_{pil} varies about $9°CA$ in these experiments, but the variations of the $(dQ/d\theta)_{max}$ or of the integral of ROHR remain respectively around 25% and 12%.

5 Conclusion

The effects of engine coolant temperature on combustion noise have been studied on a modern direct-injection Diesel engine working at idle condition with two pilot injections and one main injection. It has been found that, for coolant temperature $\leq 70°C$, the combustion does not take place for the first pilot injection. When the engine is hot ($Tc \geq 80°C$), combustion occurs for each injection so three combustion phases are observed. It has been found that combustion noise does not change linearly with the coolant temperature. In the ranges below $30°C$ and above $40°C$, the combustion noise decreases slightly and regularly with the increase in coolant temperature, but from $30°C$ to $40°C$, there is a jump of combustion noise ($+1.5\ dBA$). This phenomenon is due to the fact that when the coolant temperature reaches $40°C$, the combustion of pilot injections takes place at TDC creating a very high cylinder pressure derivative. Beyond $40°C$, when the coolant temperature increases, the combustion ignition delay decreases, and the combustion of pilot injections occurs more and more before the TDC so the cylinder pressure derivative decreases, leading to a reduction of the combustion noise.

The effect of the dwell time between the pilot injection and the main injection has also been studied at hot idle condition. It has been found that when the start of activation of the pilot injection (SOA_{pil}) is around $353°CA$, the combustion noise reaches its maximum level. This is also due to the fact that, at $353°CA$, the combustion ignition of the pilot injection occurs at the TDC. When SOA_{pil} is in the range beyond $353°CA$, the ignition of combustion occurs after the TDC. In these cases, higher SOA_{pil} means a combustion far from the TDC, with the piston being moving down, creating lower pressure derivative. This explains why the combustion noise decreases with the increase of SOA_{pil} at this range.

References

[1] S. Wang, C. Chalu, F. Gautier, "Optimization of combustion noise of modern Diesel engines for passenger cars", *SAE Paper no 2007-01-2379* (2007)

[2] H. Ogawa, K.A. Raihan, K. IIizuka, N. Miyamoto, "Cycle-to-cycle Transient Characteristics of Diesel Emissions during Starting", *SAE Paper no 1999-01-3495* (1999)

[3] A.J. Torregrosa, P. Olmeda, J. Martin, B. Degraeuwe, "Experiments on the influence of inlet charge and coolant temperature on performance and emissions of a DI Diesel engine", *Experimental Thermal and Fluid Science. Vol. 30*, 633-641 (2006)

[4] B. Fasolo, A.M. Doisy, A. Dupont, F. Lavoisier, "Combustion System Optimization of a New 2 Liter Diesel Engine For EURO IV", *SAE Paper 2005-01-0652* (2005)

[5] M.F. Russell, C.D. Young, "Measurement of Diesel combustion noise", *In Autotech '85* (1985)

[6] M.F. Russell, R. Haworth, "Combustion Noise from High Speed Direct Injection Diesel Engines", *SAE Paper no 850973* (1985)

[7] S. Kohketsu, K. Mori, T. Kato, K. Sakai, "Technology for Low Emission, Combustion Noise and Fuel Consumption on Diesel Engine", *SAE Paper no 940672* (1994)

[8] G. Galinsky, G.T. Reader, I.J. Potter, R.W. Gustafson, "Effect of various working fluid compositions on combustion noise in Diesel engines", *Proceedings of the Intersociety Energy Conversion Engineering Conference, Vol. 3*, 1157-1162 (1994)

[9] M. Kondo, S. Kimura, I. Hirano, Y. Uraki, R. Maeda, "Development of noise reduction technologies for a small direct-injection Diesel engine", *JSAE Review, Volume 21 Issue 3*, 327-333 (July 2000)

[10] G.T. Reader, C.E. Bowen, I.J. Potter, "Combustion Noise from a Diesel Engine Operating with High Concentrations of Intake Carbon Dioxide", *SAE Paper no 1999-01-2713* (1999)

[11] Heywood, J.B., "Internal Combustion Engine Fundamentals", McGraw-Hill, New York (1988)

[12] M. Klein, L. Eriksson, J. Åslund. "Compression ratio estimation based on cylinder pressure data", *Control Engineering Practice, Vol. 14*, 197-211 (2006)

[13] C.E. Goering, "Engine heat release via spreadsheet", *Transactions of the ASAE, Vol. 41, no 5*, 1249-1253 (1998)

[14] M.F.J. Brunt, H. Rai, A.L. Emtage, "The Calculation of Heat Release Energy from Engine Cylinder Pressure Data", *SAE Paper no 981052* (1998)

[15] M.F.J. Brunt, K.C. Platts, "Calculation of Heat Release in Direct Injection Diesel Engines", *SAE Paper no 1999-01-0187* (1999)

[16] S. Kook, C. Bae, P.C. Miles, D. Choi, L.M. Pickett, "The Influence of Charge Dilution and Injection Timing on Low-Temperature Diesel Combustion and Emissions", *SAE Paper no 2005-01-3837* (2005)