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Carbon Dioxide Control Technologies for Diesel Engines

S Tarulescu[*], R Tarulescu and C I Leahu
Transilvania University of Brasov, Eroilor Boulevard Nr. 29, Romania

[*]Corresponding author e-mail: s.tarulescu@unitbv.ro

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Abstract. The main pollutants contributed by internal combustion engines are CO, NO_x unburned hydro-carbons (HC) and particulate emissions. In addition to this, all fuel burning systems emit CO_2 in large quantities and this is concerned with the Green House Effect which is going to decide the health of earth. In theory, on average, Diesel engines emit 20% less CO_2 than gasoline engines, but, depending to the fuel consumption, or engine regime, can reach high values. The paper presents researches on exhaust gases quality for an experimental single cylinder Diesel engine. The tests were made on an AVL single cylinder test bed for single cylinder engine (AVL 510 cc Single Cylinder Engine Type 5402). The quality of the exhaust gases, and the amount of CO_2 produced for different regimes and injection strategies, for this engine, were analyzed and compared with the theoretical principles. In conclusion, different CO_2 reduction strategies were compared, in order to find the optimal solutions.

1. Introduction

Global climate change is one of the most significant long-term policy challenges. In recent years, fuel consumption standards and greenhouse gas emission (GHG) standards limiting carbon dioxide, methane, and nitrous oxide have created a new challenge for engine and vehicle manufacturers [1]. Carbon dioxide does not directly impair human health, but it is a “greenhouse gas” that traps the earth’s heat and contributes to the potential for global warming [2].

Due to the last environmental regulations set emitted by the European Union, engine researchers are testing and developing various emission reduction strategies for compression ignition engines. Combustion resulting from compression ignition diesel engines contains high levels of nitrogen oxides (NO_x), particulate matter (PM2.5 and PM10), hydrocarbons (HC) and small quantities of carbon monoxide (CO) and carbon dioxide (CO_2) [5]. Diesel engines emit 20% less CO_2 than gasoline engines, but, depending to the fuel consumption, or engine regime, can reach high values.

Nevertheless, the amount of CO_2, which is linearly correlated with fuel consumption, produced on the road can be up to 30% higher than official measurements indicate, in particular for Diesel vehicles. The EU is actually working not only on tightening emission reduction rules (standard Euro 6 up to Euro 6d), but also on improving testing procedures for pollutant emissions and fuel consumption of light-duty vehicles. Compared to tests under laboratory conditions, light-duty vehicles have significantly higher emissions when actually on the road, and two new testing procedures are currently being developed in order to assess the performance of vehicles under real-life conditions: Real Driving Emissions (RDE) for measuring regulated pollutants, and the Worldwide Harmonized Light-duty Vehicles Testing Procedure (WLTP) for measuring CO_2 emissions [7].

CO_2 formation for Diesel engines is presented in equation 1 and 2 [3].

$$C_xH_y + zO_2 \rightarrow aCO_2 + bH_2O + cCO + heat \quad (1)$$

$$CO + \frac{1}{2} \cdot O_2 \rightarrow CO_2 + heat \quad (2)$$

Multiple hoses injection of fuel find important stand in improvement of combustion process. This technique is used in modern internal combustion engine through electronically operated fuel injection system [9]. Various parameters influence the performance of the compression ignition engine. The parameters like fuel injection pressure and advance crank angle plays an important role [10].

In order to reduce the emissions resulted by the Diesel engines, focused on the CO_2, different reduction strategies were compared, to find the optimal solutions. The measures that were applied are: using an injection strategy with two or three phases; varying the advance crank angle of combustion related to top dead centre (TDC).

To obtain data and optimize solutions for internal combustion engines, a research program were developed at Transilvania University of Braşov, ICDT - Research & Development Institute. The research stand is an AVL single cylinder test bed for gasoline and Diesel engines. For the present paper, the tests were made on a AVL CR Diesel Single Cylinder Research Engine 5402. The single cylinder can be setup in several configurations (with multipoint injection, with direct injection, with turbocharger). The mixture formation and combustion processes of the fuel can be monitored through the test bed component software, AVL FIRE Commander 7.06c - IAV [6].

2. Used equipments

The researches presented in the present paper were made on a AVL CR Diesel Single Cylinder Research Engine 5402 with following specifications:

- Bore: 85 mm; Stroke: 90 mm.
- Displacement: 510 cm^3. Compression ratio: 17:1.
- Maximum engine speed: 4200 rpm and Maximum firing pressure: 180 bar.
- Maximum BMEP: 14 bar at 2300 rpm supercharged.
- Maximum output: 19 kW at 4200 rpm supercharged.

The test bed have some other components and systems: AVL Engine Control Unit (AVL ETU 427); Coolant and conditioning Unit 577; AVL Fuel mass flow meter - Type Flex Fuel; AVL Fuel temperature control; Intake Air Consumption Measurement Device; Particle Evaluation - Micro Soot Sensor Continuous Measurement of Soot Concentration; AVL PUMA Open Test bed Automation (Figure 1).

The used software for intake and combustion process optimization is AVL FI2RE Commander 7.06c – IAV. AVL FIRE were developed to solve the most demanding flow problems in respect to geometric complexity and chemical and physical modelling. The software used for engine parameters monitoring is AVL Indicom software [6].

Figure 1. AVL PUMA Open Test bed Automation, for Engine test bed system

3. Research methodology

The tests were made in controlled laboratory conditions. The used fuel was Diesel Petrom Standard. The atmospheric temperature was constant maintained at 18 ºC.

The tests ware made for 25%, 50% and 75% loads and for 1500, 2000, 2500, 3000 and 3500 rpm engine speeds. The intake parameters are controlled by set the number of injections. In this case there were used two injection strategies (1. only one main injection; 2. one pilot injection and one main injection). The fuel mixture was adjusted by varying the amount of fuel injected per cycle (injection period - μs). The ignition time was set in crank angle degrees before top dead centre. The engine combustion quality was tested for 100 engine cycles.

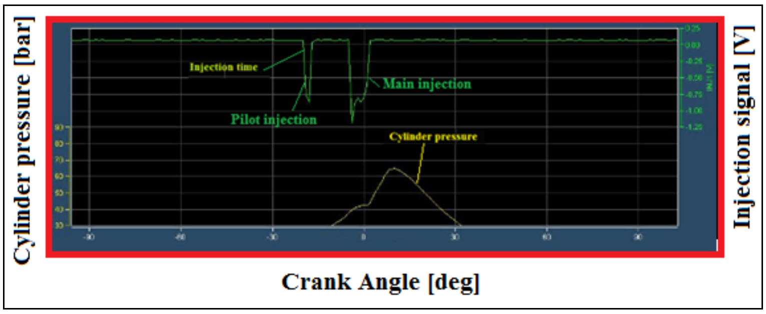

Figure 2. The combustion features for AVL CR Diesel Single Cylinder Research Engine 5402

The parameters changes were made to obtain an optimal single cylinder pressure curve and more optimal combustion (no detonations). In the Figure 2 are presented the combustion features for AVL CR Diesel Single Cylinder Research Engine 5402. The window presents the injection time (in function of engine crank angle and TDC) and engine cylinder pressure. Tests were done for five specific engine speeds and three engine loads by modifying the following parameters: number of injection phases per engine cycle and ignition time (spark moment) before top dead centre (TDC).

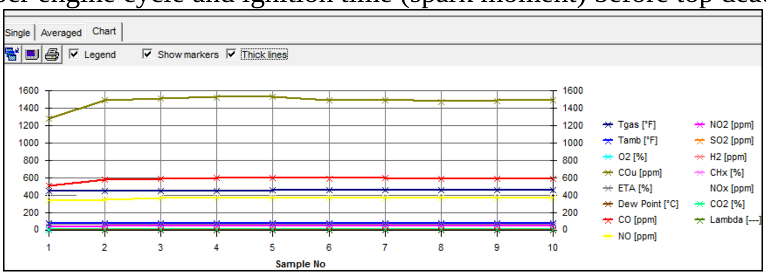

Figure 3. Interface for exhaust gas analyzer Model GA-21plus - parameters (test: 3500 rpm, 50% engine load and 2 injections phases/cycle and TDC advance -15 ºCA)

In order to control the quality of the exhaust gases for the tested engine it was used exhaust gas analyzer, Model GA-21plus. For each test were recorded values of the main pollutants (as seen in the example working page - Figure 3 and Figure 4) and especially the carbon dioxide level.

Analyzer Type: GA-21plus
Analyzer No: 21962063
Software Version: 12E12
Printed: 15.04.2016 by:

Bank properties:

Data read from analyzer No 21962063 on 15.04.2016 as online bank
Date: 15.04.2016 16:40:04 Measurements: 10
Period: 10 sec Fuel: LIGHT OIL
Reference oxygen O2R: 3%

Measurement results table

	Time	Tgas	Tamb	T1	T2	T3	T4	O2	CO2	COu	ambd	SL	ETA	IL	ETA1	ew Po	CO	NO	NO2	SO2	H2	CHx	NOx	RESS
	:mm:	°F	°F	°F	°F	°F	°F	%	%	ppm	---	%	%	%	%	°C	ppm	ppm	ppm	ppm	ppm	%	ppm	hPa
1	6:40:1	442,9	77,7	---	---	---	---	---	6,10	1283	2,52	32,5	67,5	0,0	67,5	0,0	509	338	40	0	0	---	378	0,03
2	6:40:1	445,8	77,5	---	---	---	---	---	6,00	1491	2,57	33,3	66,7	0,0	66,7	0,0	580	350	44	0	0	---	394	0,03
3	6:40:2	448,7	77,5	---	---	---	---	---	6,00	1516	2,57	33,5	66,5	0,0	66,5	0,0	590	363	45	0	0	---	408	0,03
4	6:40:3	450,7	77,9	---	---	---	---	---	6,00	1527	2,57	33,7	66,3	0,0	66,3	0,0	594	364	45	0	0	---	409	0,03
5	6:40:4	452,5	77,7	---	---	---	---	---	6,00	1529	2,57	33,9	66,1	0,0	66,1	0,0	595	365	45	0	0	---	410	0,03
6	6:40:5	454,6	77,7	---	---	---	---	---	6,10	1494	2,52	33,5	66,5	0,0	66,5	0,0	593	365	44	0	0	---	409	0,03
7	6:41:0	456,6	77,7	---	---	---	---	---	6,10	1497	2,52	33,7	66,3	0,0	66,3	0,0	594	368	44	0	0	---	412	0,03
8	6:41:1	457,9	77,7	---	---	---	---	---	6,10	1477	2,52	33,8	66,2	0,0	66,2	0,0	586	370	43	0	0	---	413	0,02
9	6:41:2	459,7	77,9	---	---	---	---	---	6,10	1487	2,52	34,0	66,0	0,0	66,0	0,0	590	370	43	0	0	---	413	0,04
10	6:41:3	460,7	77,5	---	---	---	---	---	6,10	1489	2,52	34,1	65,9	0,0	65,9	0,0	591	371	43	0	0	---	414	0,03

Figure 4. Exhaust gas analyzer Model GA-21plus - results (test: 3500 rpm, 50% engine load and 2 injections phases/cycle and TDC advance -15 ºCA)

Tests were made for a big range of engine speeds: 1500, 2000, 2500, 3000 and 3500 [rpm]. Also, the spark moment before TDC was set for two values: -15 and -20 [ºCA]. The engine load varies from 25% to 50% and 75% (the most common loads used in real exploiting conditions).
Engine parameters are centralized in Table 1.

Table 1. Engine power, torque and fuel consumption in function of engine speed and load

Load	*Engine speed*	*Power*	*Torque*	*Fuel consumption*
[%]	*[rpm]*	*[kW]*	*[Nm]*	*[Kg/h]*
25%	1500	1.860	11.848	0.727
	2000	1.445	6.895	0.732
	2500	1.376	5.486	0.839
	3000	1.256	4.000	0.941
	3500	0.466	1.274	0.997
50%	1500	3.561	22.670	1.131
	2000	3.921	18.722	1.288
	2500	3.670	14.020	1.333
	3000	3.854	12.269	1.465
	3500	3.849	10.506	1.628
75%	1500	3.770	24.000	1.208
	2000	5.062	24.148	1.568
	2500	6.249	23.862	2.008
	3000	6.127	19.500	2.037
	3500	6.746	18.407	2.346

4. Test results

For each test, there were measured the emissions to determine the exhaust gases pollution level in general and CO_2 level in particular. CO_2 concentrations for all four test sets are presented in Table 2 and in Figures 5, 6, and 7.

Table 2. The CO_2 concentration from exhaust gases for different intake strategies, in function of injection phase number/engine cycle and advance auto-ignition angle before engine TDC

CO_2 concentration from exhaust gases [%]			
Engine Load [%]	*25%*	*50%*	*75%*
Engine speed [rpm]	1 injection phase/engine cycle and TDC advance -15 [ºCA]		
1500	7.30	11.70	12.10
2000	5.10	9.50	11.50
2500	5.00	7.70	11.80
3000	4.30	6.90	10.70
3500	3.80	6.40	9.60
Engine speed [rpm]	1 injection phase/engine cycle and TDC advance -20 [ºCA]		
1500	6.50	11.50	11.99
2000	4.70	9.20	11.40
2500	4.70	7.60	11.69
3000	4.10	6.90	10.10
3500	3.80	6.40	9.40
Engine speed [rpm]	2 injection phases/engine cycle and TDC advance -15 [ºCA]		
1500	6.60	10.80	11.89
2000	4.70	8.70	10.40
2500	4.40	7.20	11.59
3000	4.10	6.70	10.10
3500	3.60	6.10	9.20
Engine speed [rpm]	2 injection phases/engine cycle and TDC advance -20 [ºCA]		
1500	6.20	11.40	11.70
2000	4.40	4.80	11.10
2500	4.30	4.90	11.30
3000	3.90	7.10	9.80
3500	3.40	4.30	9.20

CO_2 concentration in function of different strategies can be noticed more obvious in graphic representations. In Figures 5, 6 and 7 is presented carbon dioxide concentration for 25%, 50% and 75% engine loads in function of engine speed, for all four test sets.

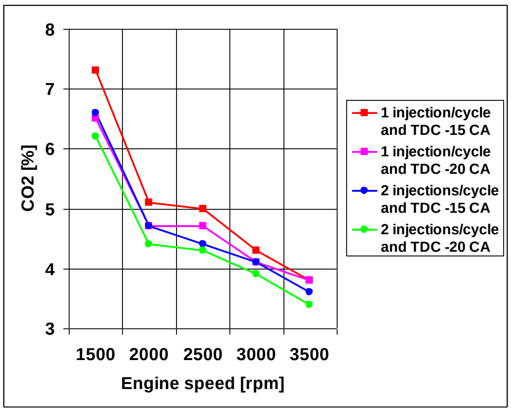

Figure 5. Carbon dioxide concentration for 25% engine load in function of engine speed, for all four test sets

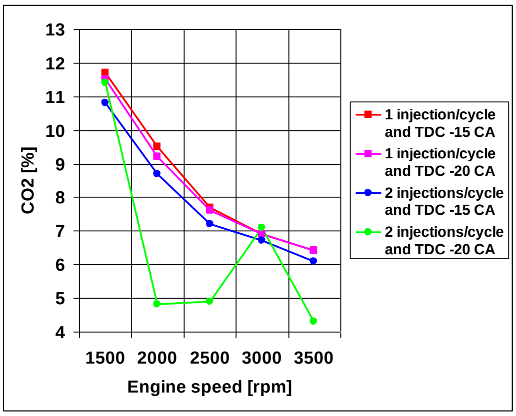

Figure 6. Carbon dioxide concentration for 50% engine load in function of engine speed, for all four test sets

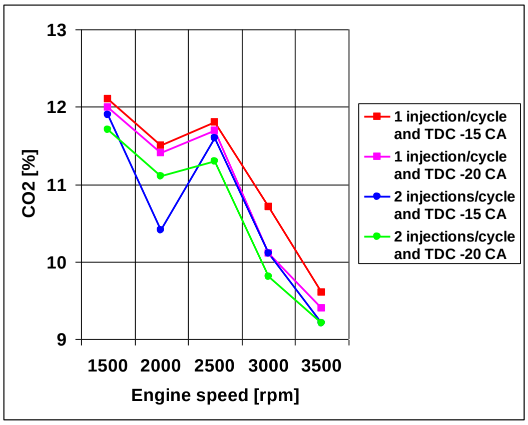

Figure 7. Carbon dioxide concentration for 75% engine load in function of engine speed. for all four test sets

The lowest values of CO_2 were recorded for two injection phases (one pilot injection and one main injection) strategy (In Figures 5, 6 and 7 these strategies are corresponding to the green and blue curves). Also, a selected value of -20 [ºCA] advance angle from TDC is the better solution than 15 [ºCA] (green curve).

It can be noticed that the most obvious differences are registered for 50% engine load and for 2000, 2500 and 3000 [rpm] engine speeds. The CO_2 concentration from exhaust gases will be minimum for higher engine speeds and for moderate engine loads (50% throttle valve open). Also, in order to decrease the CO_2 concentration, an optimal intake strategy is needed. After the research tests, we confirm the theory: a two phases injection strategy is the optimal solution, and a -20 [ºCA] advance angle (for this engine type) is the optimal solution in order to reduce CO_2 amount [4].

This strategies are efficient in order to reduce the other exhaust pollutants: CO, NO, NO_2 and HC (Table 3).

Table 3. The CO, NO, NO_2 and HC concentrations from exhaust gases for 3500 rpm and 50% engine load

Pollution diminish strategy	*CO [ppm]*	*NO [ppm]*	*NO_2 [ppm]*	*HC [ppm]*
1 injection phase/engine cycle and TDC advance -15 [ºCA]	620	523	35	53
1 injection phase/engine cycle and TDC advance -20 [ºCA]	423	349	29	44
2 injection phases/engine cycle and TDC advance -15 [ºCA]	353	337	26	25
2 injection phases/engine cycle and TDC advance -20 [ºCA]	363	314	13	23

5. Conclusions

The parametric optimization tests made for the Diesel Single Cylinder Engine 5402, a large set of data were collected in order to analyse the quality of exhaust gases. There ware collected values for the main pollutants (CO, NO, NO_2 and HC) and for CO_2 emissions. For this paper, the main objective was to test different strategies in order to reduce the CO_2 concentration from exhaust gases for a single cylinder Diesel engine. Four tests, corresponding to different functional strategies were made, using different engine regimes (by varying the engine speed, engine load and intake parameters).

After the data analysis, we can conclude that the optimal strategy for our engine is the two injection phases intake and a -20ºCA advance from TDC. For this strategy the amount of carbon dioxide is minimum. Also, most of the pollutants have lower values than other tested strategies.

In order to optimize engine functioning and for a high quality of exhaust gases we can take the following measures: using an injection strategy with two or three phases; varying the advance angle of the spark related to TDC; optimize the exhaust parameters; optimize the fuel quantity injected per engine cycle (depending on engine regime); control the fuel consumption.

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