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Effect of Injection Timing and Coolant Temperatures of DI Diesel Engine on Cold and Hot Engine Startability and Emissions

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Abstract: *From the problematic combustion phases for diesel engines, cold start is most one. A large volume of pollutants produced during this period. These high levels of emitted emissions resulted from misfiring and incomplete combustion due to the low engine temperatures. Many variables intervene in, some of it follows fuel properties; others follow lubricant properties and some of it due to engine operation conditions. Injection timing plays a dominant rule in engine start ability in cold and hot weathers. In this study tests were conducted on DI four cylinder diesel engine to clarify this effect. Four injection timing were chosen (12, 15, 20 & 23^{o}BTDC) to operate the engine, and their results were compared with engine operation at 17oBTDC (factory specification). Tests were conducted at four engine coolant temperatures (-10, 0, 25 & 50^{o}C) to evaluate injection timing effect. The study results indicated that increasing test temperature led to reducing starting time apparently. Combustion instability was significant mainly during starting at cold temperatures (-10 & 0^{o}C). Extremely high levels of HC, CO and opacity were experienced in the exhaust gas, mainly during cold starting. Combustion noise increased highly due to low starting temperature and retarded IT.*
Keywords: *injection timing, start ability, HC, CO, smoke opacity, noise, cold starting*

I. Introduction

Internal combustion engines face the challenge of the growing demands for it and at the same time the dilemma of reducing its negative impacts on the environment. Compression-ignition engines are the most employed propeller to power cars, trucks, constructing machines and electric power generation. In fact, diesel engines have reached a share of around 50% of the total number of new engines registrations in the last few years all over the world [1 & 2].

Despite all the progress made in diesel engine technology today, some of the combustion stages still cause high levels of emitted pollutants and need to be improved. Among these steps, engine starting is the most critical juncture of combustion. It is a problem for current DI diesel engines, especially in low ambient temperatures. Engine cold starting becomes the limiting factor for new methods of combustion [3 & 4]. The diesel engine cold start here refers to the sequence starting from of a diesel engine at room temperature. The diesel engine starting sequence is very transient process that can be divided into four distinct phases [5]:

1- Cranking phase: Cranking of the engine through the starter motor. The engine is cranked at a speed within the range of 150 to 300 rpm and depends on room temperature, engine characteristics, electrical motor characteristics and oil properties [6].
2- Start phase: As a minimum speed has been reached the starting phase begins with the first injections. The engine speeds increase up due to combustion until the assistance of the electrical motor is no longer necessary. During this phase, the load must be so that can overcome mechanical and frictional losses [7].
3- After-start phase: When engine speed is relatively high (around 900 rpm) but still unstable due to large load and combustion phasing variations [8].
4- Idle phase: when engine speed stabilizes at the nominal idle speed. Then, the engine warm-up until the coolant temperature is maintained around 80^{o}C [9 & 10].

Finally, during this whole sequence, the main concerns are the high emissions levels, since engine start can usually be achieved. Emission control is concerned with HC, CO, and smoke. These pollutants are emitted mostly at the beginning of the starting sequence [11]. In addition to these emissions, combustion noise which is another important, but often neglected emission that must be studied. The emitted engine noise radiated from diesel engines acquires more and more attention in recent years, as it is linked to the discomfort of the passengers and pedestrians [12 & 13].

Old cold start strategies for diesel engines were based on delivering a significant amount of fuel since it was supplied with mechanically controlled fuel pumps (where the possibilities for parameters adjustment were limited). Usually, more than full load fuel was delivered [14]. The supplied fuel quantity based on the assumption that the more the fuel provided, the more opportunity was given for fuel evaporation and combustion [15]. Injection strategies improvements (high injection pressure and quantity control of multiple injections) have allowed to reduce and control NOx, soot, combustion noise and specific fuel consumption in warmed up states [16 & 17].

Zahdeh (1990) [18] reported that low temperatures cause many problems, including the reduction in the stirring speed, which reduces the resulting energy and causes heat transfer losses, a result also found by [19]. Shayler (2005) [20] after conducted several tests and calculated motored friction at different temperatures, explained the drop in the cranking speed. The friction which is linked to the effective pressure (FMEP) can be increased by a factor of about three, depending on the engine design and its speed at temperatures ranges from -25^{o}C to 20^{o}C during the first period of operation. Han (2001) [21] linked between the unstable combustion and engine starting temperature, instantaneous engine speed and injection timing. Han identified the injection timing concerning a wide range of engine speeds, which helped in the suppression of misfire for heavy-duty diesel engines in use. He also has linked the failure of a mismatch between the injection parameters and instantaneous engine speed indicating that its strategies will be needed to control the injection timing variation. Experiments have shown that the reliable injection timing variation range become narrower with the little resistance and higher self-ignition fuel [22 & 23].

The present work aims to study and understand the behavior of cold engine starting and the associated problems that may arise as a result of the injection timing variation during this period. A multi-cylinder DI Fiat engine performance and emitted emissions are analyzed for cold starting period. The effects of ambient temperature also were explored. This investigation work is a part of continues efforts of the Energy and Renewable Energies Technology Center to improve the air quality in Iraq, and to enhance the used fuels and to reduce the resulted emissions of the engines currently used in the streets of various cities in Iraq [24-56].

II. Experimental Setup

All experiments were performed to measure the effects of the engine operation in cold environments. The used engine was a four cylinder DI Fiat engine. The engine is connected to a hydraulic dynamometer, and both are mounted on a test-bed. A 12V automotive battery supplies power to the engine control unit, fuel pump, and glow plug. In this study, the cranking rpm was chosen at 150 rpm; however, in the field, the cranking time is limited by the available battery energy and the time to overheat the cranking motor. The 1-minute continuous cranking period was chosen as a compromise of these factors. If the engine started and continued running after 1 minute (or less) of cranking, then this was considered a (start). If the engine failed to start or continue running after 1 minute of cranking, then this was seen as a "no-start" condition. This procedure was repeated at different target temperatures until three "start" were completed to ensure repeatability. Table 1 illustrates the tested engine specifications.

Table 1 Tested Engine Specifications

Engine type	4cyl., 4-stroke
Engine model	TD 313 Diesel engine rig
Combustion type	DI, water cooled, natural aspirated
Displacement	3.666 L
Valve per cylinder	Two
Bore	100 mm
Stroke	110 mm
Compression ratio	17
Fuel injection pump	Unit pump 26 mm diameter plunger
Fuel injection nozzle	Hole nozzle 10 nozzle holes Nozzle hole dia. (0.48mm) Spray angle= 160^{o} Nozzle opening pressure=40 Mpa

The experimental study focused on investigating the starting cold temperatures impact on the performance of variable injection strategies. Different IT combinations were assessed to explore the effect of pilot injection strategy on cold starting. Two retarded injection timing (15 & 12^{o}BTDC), and two advanced injection timing (20 & 23^{o}BTDC) were used to study the effect of injection timing on cold engine start. The results were compared with optimum injection timing (17^{o}BTDC).

The employment of a direct chilled coolant was the principal method of cooling that was capable of chilling down to -10^{o}C. The used coolant was a mixture of tap water and BS6580 ethylene glycol antifreeze at 50/50 mixing ratio. The tests were conducted in the coldest Iraqi winter days on the first morning to ensure the ambient air was at low temperatures.

Various thermocouples monitor the engine, but the one used to define test temperature measured the temperature at the liner, as this is the reading closest to the combustion chamber. Other temperatures could be a few degrees lower during cold start. For example, to achieve -10^{o}C liner temperature the chiller would be set to -14^{o}C, resulting in the pre-engine coolant, fuel and intake air temperatures around -10^{o}C. Four temperatures were tested in this study each one represents the minimum degree of a season. The -10^{o}C represents the ambient winter temperatures in northern of Iraq, and 0^{o}C represents the winter degree in middle and south Iraq. While 25^{o}C represent spring and autumn and finally 50^{o}C, represent summer temperature in all Iraq. The engine testing at the sub-zero testing environment often needs a large fuel excess, which causes significant accumulation of soot and unburned fuel in the combustion chamber. Spray impingement on walls/piston will be exacerbated by cool surface temperatures, in addition to water as ice may be presented.

A hot starting condition runs were performed after each cold starting test to evaluate the hot starting engine condition. The creation of a known starting condition for the next test was managed by taking several steps to clean the combustion chamber of any remaining fuel residue, and to draw fresh air into the chamber. The engine motored for two minutes after the IT strategy was determined, drawing cool clean air through the chamber. The engine was left after cold starting test to run till the coolant water, and lubricants reached ±75ºC and then it was shut down before the next hot starting test was initiated. This conditioning technique enabled to perform one test a day. The engine oil and the oil filter were changed after every ten tests to ensure no significant build-up contaminants in the lubricant oil.

The smoke opacity of the exhaust gas was measured with the partial flow opacity-meter type AVL 439. This device is suitable for dynamic testing measurements. Its response is time less than 0.1 s and its accuracy is 0.1% opacity. A Multigas Mode 4880 analyzer was used to measure the CO and HC pollutants. CO and HC levels were measured by a non-dispersive infrared (NDIR) and a flame-ionization detector (FID) techniques, respectively. Each analyzer was calibrated daily with zero gas before being tested. Calibration gasses (carbon monoxide (CO), propane (C3H8), and carbon dioxide (CO_2) are mixed with pure nitrogen (99.95%). All calibration were inducted at Science and Technology Ministry if Iraq.

Finally, combustion noise was measured with an overall sound pressure level meter 4615 Italy made. The combustion noise origin in a diesel engine caused by the high cylinder pressure rate rises, mainly after the ignition delay during the premixed combustion phase. The total error of the device was less than 0.76%. The combustion noise meter was placed about a half meter from the cylinder block in the four directions, and it was used without any low-pass filters. Table 2 represents the equipment, detection principle, and accuracy of measuring devices.

Table 2, Summary of equipment, detection principle and accuracy of measurements

Measuring item	Detection principle	Equipment (Maker)	Scale range	Accuracy
CO	NDIR (non-dispersive infrared)	Multigas Mode 4880	0-10% vol.	0.01%
CO_2	NDIR (non-dispersive infrared)	Multigas Mode 4880	0-25% vol.	0.01%
HC	FID (Flame ionization detector)	Multigas Mode 4880	0-1000 ppm	0.01%
NOx	CLD (Chemical luminescence detector)	Multigas Mode 4880	0-1000 ppm	0.02%
Overall sound pressure	Precision sound level meter 4615	Italy made	0-200 dB	0.76%
smoke opacity	partial flow opacity-meter	AVL 439	0-20 % vol.	0.24%

2.1 Experimental procedure

The experimental procedure included a group of cold and hot starting tests at variable injection timing, i.e. at different engine coolant and lubricating oil temperatures. Four injection timings (-10, 0, 25 & 50ºC) were studied. A preconditioning procedure was followed before every test, to ensure the removal of the particulate matter conjoined on the exhaust pipe walls. This procedure was conducted to prevent the blowout and released of these PM during the next experimental trials. This cleaning strategy was followed in the day before the cold-starting and the fully warmed-up tests.

2.2 Starting time

In this investigation, the engine starting time is defined as the time between the first battery voltage drop during cranking, and reaching specified engine speed of 1000 rpm. The starting time allows validating and optimizing all the measured parameters during the cold and hot starts.

2.3 Engine speed stability

The combustion process is the primary factor that determines the engine stability, where the idle stability affected negatively by combustion misfires. The high engine speed stability during cold starting period is one of the primary targets.

2.4 Properties of tested fuel

The conventional diesel fuel used was supplied by the Al-Doura Refineries – Baghdad and represents the typical, high sulfur (1% by weight) diesel fuel. The fuel properties are given in Table 3.

Table 3, diesel fuel used in recent study properties

specification	Diesel
Chemical formula	$C_{10.8}H_{18.7}$
Mole weight (g)	148.3
Density (g/cm^3 at 20^{o}C)	0.84
Boiling point (^{o}C)	180-330
Heat of evaporation (kJ/kg)	280
Lower heat value (MJ/kg)	42.5
Liquid viscosity (cP at 20^{o}C)	3.03
Surface tension (mN/m at 20^{o}C)	34.1
Flash point (^{o}C)	78
Stoichiometric air fuel ratio	14.4
Cetane number	49
Auto-ignition (^{o}C)	235
Carbon content (wt%)	87.4
Oxygen content (wt%)	0

II. Results and discussions

From a general point of view, to reach ignition conditions liquid fuel must evaporate, mix with air and react chemically promoted by the mixture temperature. All these processes must occur rapidly since in-cylinder conditions change both spatially along the combustion chamber and temporally with piston evolution. The slowest method would be the one that controls ignition. As a reference to the rate at which each of these processes occurs. Fig. 1 shows the effect of studied temperature on cold engine starting at factory injection timing (17^{o}BTDC). The required starting time reduced as the temperature is increased. Increasing temperature means higher combustion chamber temperature which reflects on better fuel atomization and vaporization. Low temperatures caused accumulation of fuel on the cold cylinder surfaces and reduction in fuel vaporization; as a result, starting engine deteriorated.

Hydrocarbons (HC) are volatile organic compounds of hydrogen and carbon. If the combustion is incomplete, unburned hydrocarbons will be exhausted from the combustion chamber. Misfires are the second reason for a high HC levels. As Fig. 2 represents, increasing temperature lowered engine HC emission highly, especially at 50^{o}C. The reduction in HC concentration between -10 to 50^{o}C was about 86.9%.

The same trend can be seen in Fig. 3, which states the CO emitted at studied temperatures. CO concentrations were increased highly at -10^{o}C. For comparison with CO emitted at 50^{o}C, the reduction was about 92.5%. The injected fuel mixes with air, but due to the poor air and engine temperatures, the fuel evaporation before the start of combustion is extremely low. Apart from the injected mass not exceeding around 10-20% is evaporated as References [2 & 5] clarified.

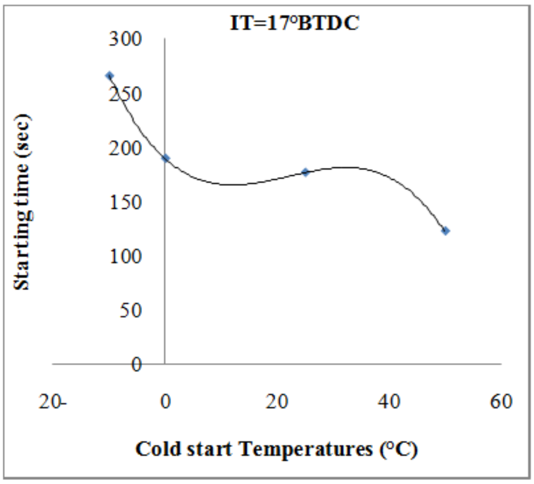

Fig.1, variable starting temperatures effect on engine starting time

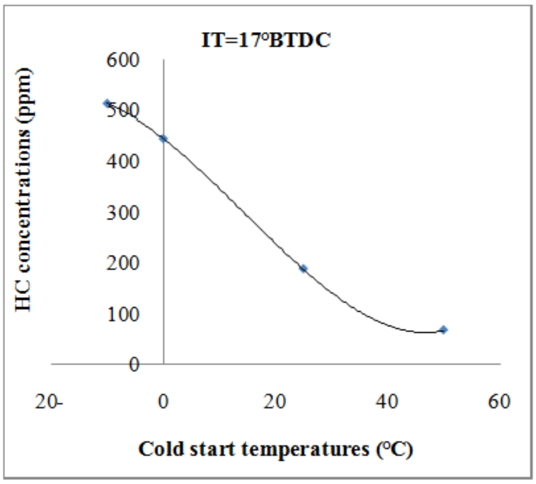

Fig. 2, variable starting temperatures effect on emitted engine HC concentrations

Most of the evaporation takes place during the injection period, and the rest of the injected fuel mass is expelled from the combustion chamber in the liquid state. If the released heat started to increase because of the ignition of the 10-20% of the injected mass, some additional evaporation would be caused by the heating resulted from combustion temperature increase. The combustion process should reduce the unacceptable limitations of evaporation in this process which is one of the main obstacles.

The few quantity of the fuel vapor is not enough not spread to other parts of the combustion chamber, and the heat release is tiny and inadequate to complement the mixture burning. While at a higher temperature, the liquid fuel could evaporate even at the piston wall and can burn and an increase in the concentration of carbon dioxide can be seen during the remainder of the combustion process.

Fig. 4 shows very high levels of smoke opacity during the tests, the measured opacity revealed a much lower increase in the coolant temperature. At high coolant temperature, the high air-fuel mixing prevents the formation of high soot inside the cylinder, resulting in less heat loss that promotes the oxidation of soot.

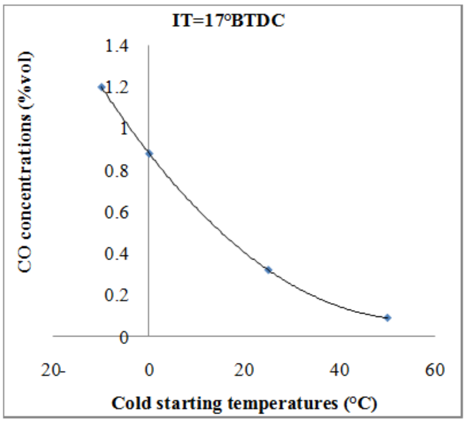

Fig. 3, variable starting temperatures effect on emitted engine CO concentrations

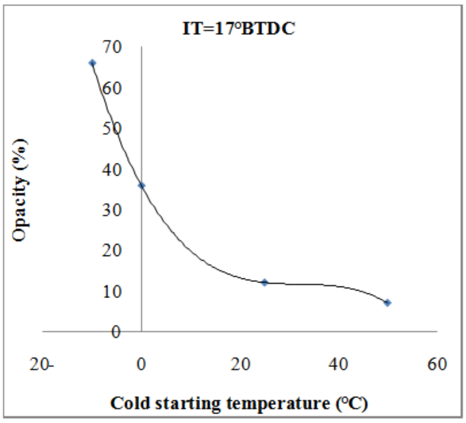

Fig. 4, variable starting temperatures effect on emitted engine smoke opacity

Engine noise increased with reduced temperature as Fig. 5 insures. At low temperatures lubricants with high viscosity and low lubrication effect increasing friction, accompanied with rough combustion where more misfiring which reflected by increasing engine noise. Increasing engine temperature improved the lubrication and combustion processes; hence, reducing engine starting noise. The reduction recorded was about 26.78%.

Fig. 6 illustrates the effect of injection timing on engine starting times at cold and hot starting temperatures. Factory injection timing is the optimum injection timing when the engine runs at stability manner. But at starting the engine, the figure ensures that advancing IT improved starting time for the engine at all studied temperatures. Advancing IT gives the air-fuel mixture more time to mix, and reduces self-ignition delay period. These factors improve cold and hot starting time. The injection timing is direct defines the combustion duration, so, retarding IT delays the ignition starting of combusting cycles, and if it were extended, no combustion would be achieved. This combustion failure is known as the misfiring cycle. Retarding injection timing causes a combustion duration increase which results in long and low fuel intensity diffusion burning. Due to this, severe combustion and longer starting time are required.

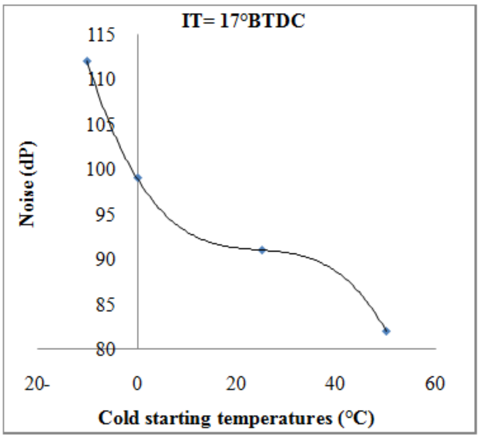

Fig. 5, variable starting temperatures effect on emitted engine noise

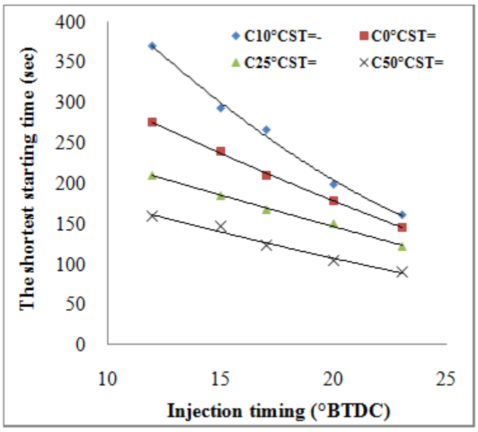

Fig. 6, Injection timing effect on the engine starting time

Advancing IT at starting the engine reduced the emitted HC concentrations as Fig. 7 manifests. The same former reasons mentioned for fig. 6 can be applied here. Advancing IT, also, increases combustion chamber internal pressure resulting in higher temperatures. Higher temperature equates to higher peak rate combustion temperatures and shorter burn duration. This increment in temperature results in better fuel atomization and evaporation. Finally, better combustion with lower HC concentrations was measured. A little compression temperatures occur at retarded timings causing a very poor self-sustaining combustion at reduced ambient temperature.

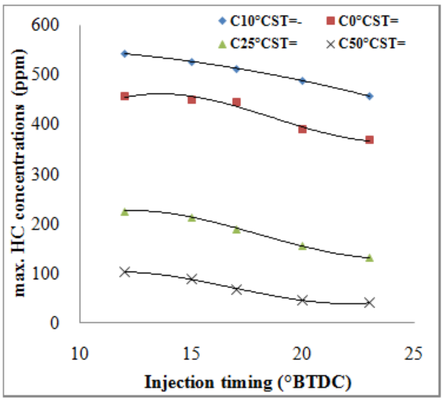

Fig. 7, Injection timing effect on engine maximum emitted HC concentrations

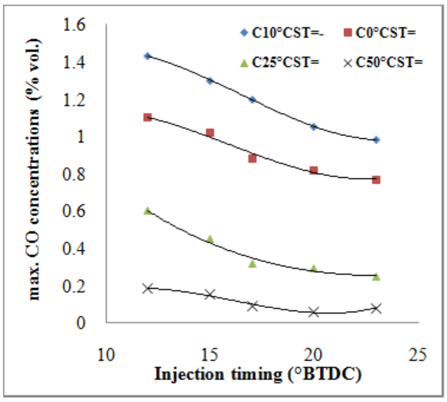

Fig. 8, Injection timing effect on emitted engine CO concentrations

CO produced from non-complete combustion that takes place at cold temperatures as Fig. 8 reveals. Advancing IT at starting engine improved combustion as indicated previously. Measured CO concentrations were reduced with advancing IT, indicating better combustion. It must be noticed that at 50°C and IT=23°BTDC, CO concentration slightly increased. This can be considered due to CO_2 dissociation caused by increased temperature inside the combustion chamber.

The effect of advanced IT effect appears clearly on smoke opacity as Fig. 9 represents. Advance in IT from 17 to 23°BTDC reduced opacity by 40.9% for starting the engine at -10°C while retarding IT from 17 to 12°BTDC increased opacity by 34.8%. This effect at engine hot starting temperatures stays the same as recorded measures at 50°C indicated. Advancing IT from 17 to 23°BTDC reduced opacity by 42.8%, while retarding IT to 12oBTDC increased opacity by 228%.

The engine noise is related to the cylinder pressure. The combustion noise (or the combustionroughness) is a good indication of the combustion chamber pressure rate increases during the combustion operation. This rate is affected by a variety of parameters as the injection timing and the fuel ignition delay. In cold-starting conditions, the injection timing and the fuel ignition delay behave in a different way compared with the warmed-up engine operation. The ignition delay impact is the most influential parameter where the combustion chamber's low temperatures prevent the fast fuel ignition. This condition leads to a more intense premixed phase for the combusted mixture, resulting in steeper cylinder pressure gradients, and then, higher combustion noise levels are experienced. Fig.10 demonstrates the starting combustion at low temperatures as -10°C is a severe operation, where misfire and hard starting likely happens. So, advancing IT improves combustion, and this appears clearly by engine noise reduction. Also, increasing starting temperature gives another effect as the figure reveals for 0, 25 and 50°C. At these starting temperatures retarding IT from 17 to 12°BTDC increased noise, while advancing IT from 17 to 23°BTDC increased noise, too.

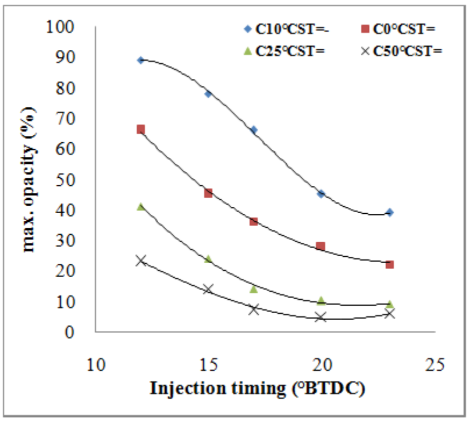

Fig. 9, Injection timing effect on emitted engine smoke opacity

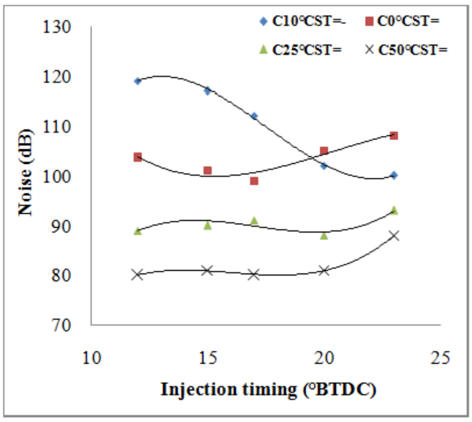

Fig. 10, Injection timing effect on emitted engine noise

Injection timing is an important role in the development of the fuel spray in the air-fuel mixing operation. The ignition delay becomes shorter when the coolant temperature increased due to lower heat loss to warm the cylinder walls. The engine low cranking speed has the dominant impact on combustion noise developed during the starting tests, which represents that the low cylinder pressure rates are being increased.

IV. Conclusions

Several aspects of cold and hot engine starting period operation have been investigated using a 17:1 compression ratio DI four stroke four cylinders Fiat diesel engine. Starting at cold and hot temperatures together with injection timing as factors influence engine startability and emissions were investigated. HC, CO, smokes opacity and combustion noise was measured in all conducted tests. Four variable injection timing and different coolant temperatures were used in the experiments. The following conclusions resulted:

1. Increasing tests temperature led to reducing starting time apparently. Combustion became more stable and starting time became shorter.
2. The range of optimum injection timings has a significant influence on startability and emissions.
3. At cold starting temperatures (-10 & 0oC), extremely high values of exhaust gas opacity due to combustion instability were experienced.
4. Lower starting temperatures result in higher combustion noise levels.
5. As the engine became hotter (at warm starting period), a reduction trend in the exhausted HC and CO levels were experienced.
6. The low starting temperature together with retarded IT appeared to have the dominant influence on combustion noise development and its absolute values.
7. Smoke opacity increased notably at low starting temperature together with retarded IT.

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Notation

^{o}BTDC	degreebefore top dead center
IT	injection timing
HC	unburned hydrocarbons
CO	carbon monoxide
CST	cold starting temperature
dB	decibel