

# Experimental Analysis of Water Injection in Heavy Duty Diesel Engine for NO<sub>x</sub> Reduction

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**ABSTRACT:** Emission from Diesel engine includes Oxides of Nitrogen and Particulate Matter both of these are harmful to environment as well as human health so it's important to reduce these pollutants at the source itself. There are many methods to decrease the nitrogen oxide emission of a diesel engine. Formation of NO<sub>x</sub> depends on the combustion temperature. Hence the technology of injecting water into the intake of heavy-duty Diesel Engine to reduce peak combustion temperature hence reduce the formation of NO<sub>x</sub> is found to be most effective. In this paper computation fluid dynamics investigation is carried out to analyze the effect of direct water injection under various injector configuration on water evaporation, combustion, performance, and emission characteristics of direct injection engine.

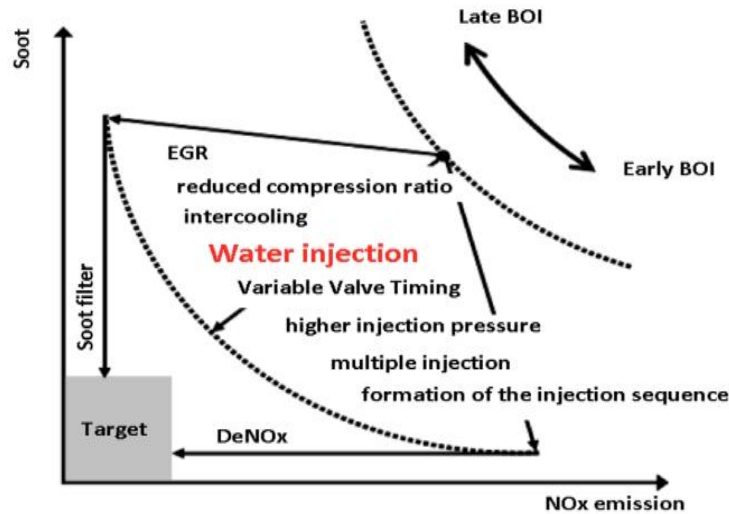
This paper gives the review of 3D CFD analysis to find the water spray characteristics. The experiment includes European Steady State Cycle (ESC) and European Transient Cycle (ETC) emission to study emission reduction using water injection. The water to fuel ratio in this experiment was varied between 3% to 16%.

**KEYWORDS:** Emission, Diesel engine, water injection, NO<sub>x</sub> emission.

## I. INTRODUCTION

Along with reduction of combustion noise the reduction of nitrogen oxide is a major goal in developing future contemporary diesel engine. The basic constituents of fossil fuels are carbon and hydrogen. The complete combustion in engine cylinder will lead to formation of carbon dioxide and water. However, many factors lead to incomplete combustion leading to formation of harmful products like CO, HC, NO<sub>x</sub>. In case of diesel engine amount of available oxygen is more than the theoretical required oxygen. Due to this excess oxygen in engine cylinder, nitrogen oxide is formed due to reaction on nitrogen and oxygen [1]. Emission of diesel engine are typically characterized by a NO<sub>x</sub>-PM trade-off as shown in Figure 1.

It can be seen that by variation of the engine operation parameter such as injection timing NO<sub>x</sub> emission can be decreased but particulate emission increases and vice versa [2]. Reducing both the components does not seem possible with standard operation parameters. Therefore, some measures like exhaust gas recirculation, Reduced compression ratio or intercooling allows a slight lowering of both emission components. Unfortunately, this comes with an increase in fuel consumption due to delay combustion phasing. Therefore, Water injection seems to be an appropriate method to reduce NO<sub>x</sub> emission.



**Figure 1:** NOx-particulate trade-off and different measures of emission reduction

There are three important methods of injecting water in Diesel engine. Emulsion, IN-cylinder injection, Fumigation. The emulsion system consists of two immiscible liquid, one being finely dispersed into other. In water/diesel type of emulsion system water droplets are dispersed in diesel fuel. In, IN-cylinder injection water injection is fully controlled electronically. In the process of fumigation water is fumigated into the air intake [3]. It is found that by injecting 0.03Kg of water per every Kg of air-mass, about 50% of NOx can be reduced [1].

## II. METHODOLOGY

3D CFD analysis using CONVERGE was carried out in-order to assess the water spray characteristics. Initially the experiment was carried out without water injector. Further to this water injector was used to inject the desired quantity of water in engine cylinders to reduce NOx emission. The selection of water injector was based on the simulation result to inject the required quantity of water. Test were carried out by European Steady State Cycle (ESC) and European Transient cycle [1].

**TABLE 1:** Number of tests conducted and water injected quantity

SI. NO	Case	Injection Timing(deg)	Injection Duration(ms)	Injection quantity(mg/cycle)
1	Base-ESC	WOWI	-	-
2	ESC-1	240°BTDC	6ms	8.6
3	ESC-2	240°BTDC	3ms	8.4
4	Base-ETC	WOWI	-	-
5	ETC-1	240°BTDC	3ms	8.4

Initially, the experiment was conducted without injecting water in the engine cylinder, Base ESC test on a 3-cylinder common rail direct injection diesel engine. Then modifications were made in same engine to integrate a water injector to inject a desired quantity of water. Two ESC test cycles were performed which inject water for 6ms (8.6 mg/cycle), injected at 240° BTDC. Reduction of NOx was found in all 13 modes. But it was found to increase in smoke in full load points and in ideal modes, so it was decided to cut down the water injection from 6ms to 3ms (8.4mg/cycle) at 240° BTDC. The same test was then performed for ETC cycle by injecting water for 3ms (8.4 mg/cycle) at 240° BTDC.

**III. EXPERIMENTAL SET-UP**

Experiment was performed on 3-cylinder, direct injection, turbocharged, diesel engine. Figure 2 shows the test setup with water injection system.



**Figure 2:** Test setup with water injection system.

**TABLE 2:** Test engine specifications

Engine Power	115HP
Rated Engine Speed	2700 rpm
Peak Torque	320 Nm
NO. of cylinder	3 Cylinder, Inline configuration
Fuel injection system	1600 bar, common rail direct injection

**TABLE 3:** Water injector specification

1	Spray quantity	20 mg/stroke (max)
2	Number of holes	6
3	Size of hole	140 microns
4	Injection pressure	10 bars
5	Peak Voltage	40 v
6	Peak current	12 A
7	Hold Voltage	12v
8	Hold current	4A

**IV. ENGINE INTAKE SYSTEM**

For 3-D CFD simulation the engine speed was kept constant at 2400 rpm. As the engine was three-cylinder engine three shots were used for each cylinder one water injection shot. As the firing order of engine was 1-2-3, so accordingly the ignition was selected as  $0^{\circ}$ - $240^{\circ}$ - $480^{\circ}$ . The results were generated with respect to the crank angles.

Selection of injector position is very important to achieve good water spray quality. 1<sup>st</sup> injector position was selected such that spray is perpendicular to the air-EGR mixture flow field. 2<sup>nd</sup> position was selected near the EGR mixing point along the flow field. Third position of injector was a combination of position 1&2 except that position 1 spray is directed opposing to flow field. For all the three positions 3-D CFD simulation was performed



V. EXPERIMENTAL RESULTS

1. European Steady State Cycle

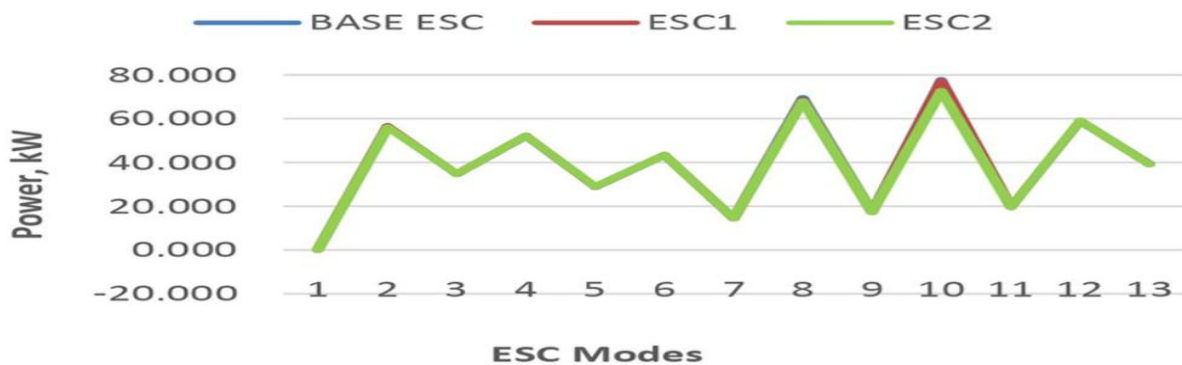
Comparison of base ESC cycle, ESC-1, ESC-2 cycle is shown in fig 1-a. Base ESC is the test performed without water injection system. The ESC-1 test it was conducted with 3ms of water injection in all modes (shown in table), ESC-2 test was conducted with 6ms of water injection (at idle mode, A100, B100, C100and B75 water was cut off). The fig 1-a shows power will not be affected by the water injection quantity. The minute fluctuation at 10<sup>th</sup> mode is not due to the water injection but due to the fuel flow variation.

Although the fuel flow rate needs to be maintained constant, there in minute fluctuation in the fuel flow rate.

SL.NO	Modes	Speed(rpm)	NOx multiplier	Soot production constant
1	Idle	800	1	300
2	A100	1725	0.16	4500
3	B50	2075	0.14	1100
4	B75	2075	0.1	1600
5	A50	1725	0.235	1500
6	A75	1725	0.175	2000
7	A25	1725	0.25	1900
8	B100	2075	0.105	2300
9	B25	2075	0.34	1600
10	C100	2425	0.105	1700
11	C25	2425	0.8	6500
12	C75	2425	0.23	1800
13	C50	2425	0.225	1650

TABLE 4: Emission constant used in this study.

Figure 1-a: Comparison of power



Same as that of power the torque also fluctuates slightly at 10<sup>th</sup> mode due to variation in fuel flow rate, as shown in fig 1-b.

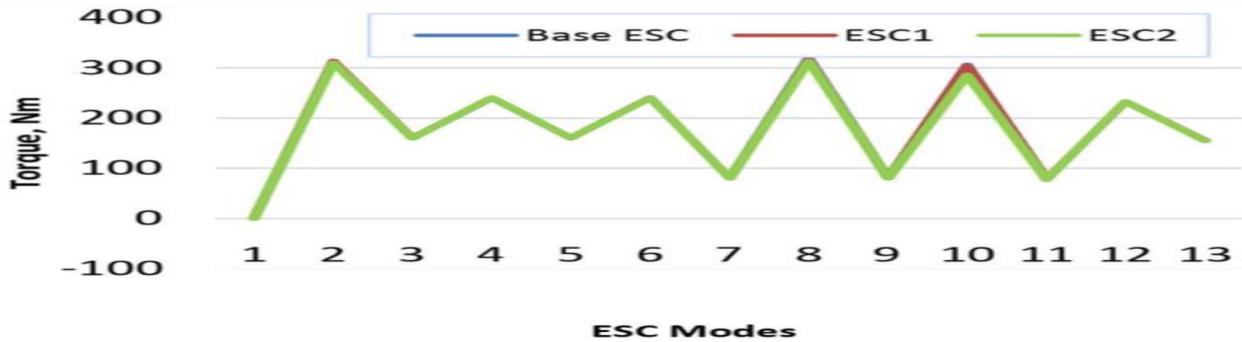


Figure 1-b: Comparison of torque

The fluctuation in fuel flow rate also results in increase in BSFC as BSFC depends on fuel flow rate and power generated. As power generated increases in 10<sup>th</sup> mode BSFC also increases, shown in figure 1-c.

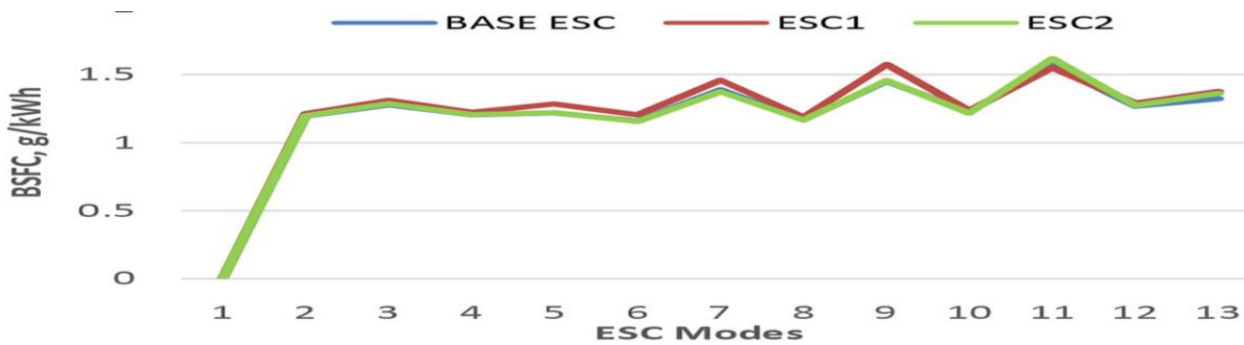


Figure 1-c: Comparison of BSFC

Figure 1-d shows the mass flow rate of fuel and mass flow rate of water. Water flow rate varies from 9% to 25% of fuel flow. This is because fixing the water injection quantity in all the operating modes.

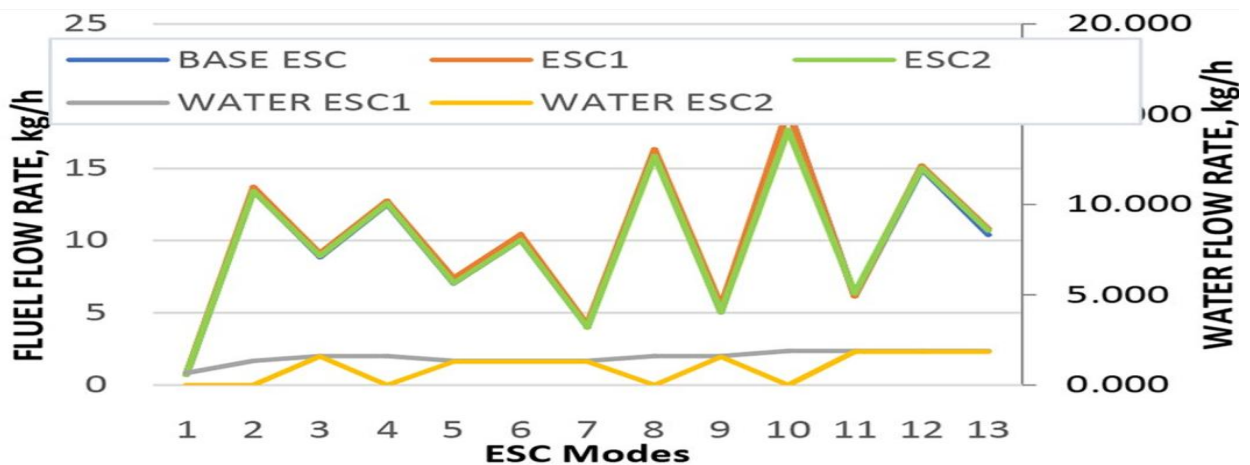


Figure 1-d: comparison of fuel flow rate and water flow rate

In engines equipped with turbocharger the intake air temperature increases due to compression. But this heating is not fully adiabatic as the temperature goes on increasing with increasing in compressor blade temperature which increases

due to increase in temperature Of compressor shaft which is exposed to hot exhaust gases. To take care of this engine equipped with turbocharger is provided with an intercooler. In this test the engine is provided with water injector to decrease the intake manifold temperature. This is because of trapped mass in WI the specific heat capacity increases.

Figure 1-e shows the comparison between ESC, ESC-1, and ESC-2 cycles. It can be observed that the temperature of intake charge in base ESC and ESC-1 is same, but ESC-2 cycle shows increase in temperature of intake charge because of cut-off of water injection at idle and full load points.

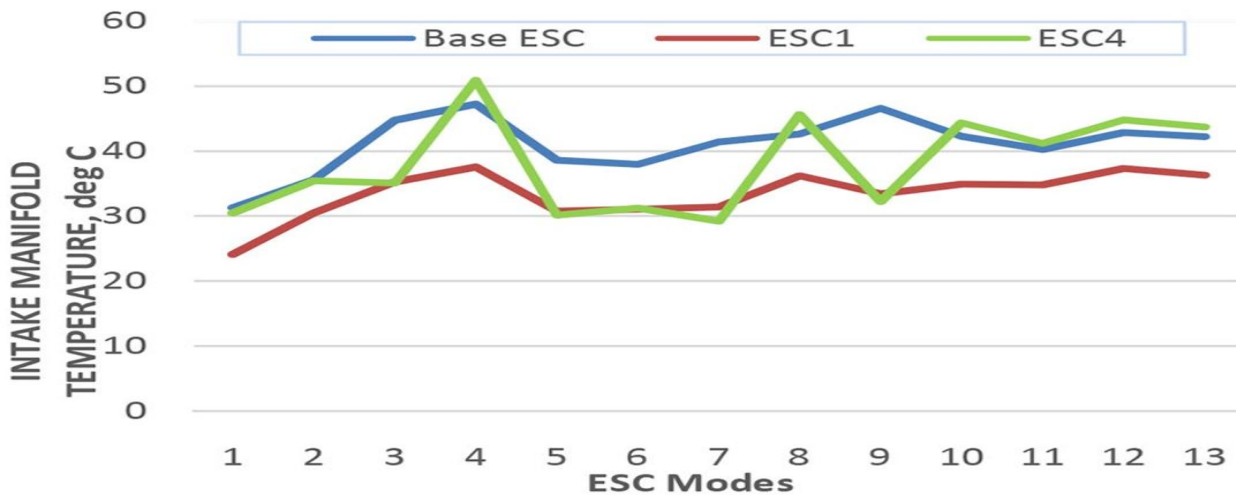


Figure 1-e: Comparison of intake manifold temperature

Figure 1-f shows comparison between exhaust manifold temperature between ESC, ESC-1, and ESC-2 test cycles. The reduction in exhaust manifold is due to the heat lost through the walls. As the water vapor has higher convective coefficient air, hence more heat exchange between in-cylinder gas content and the wall.

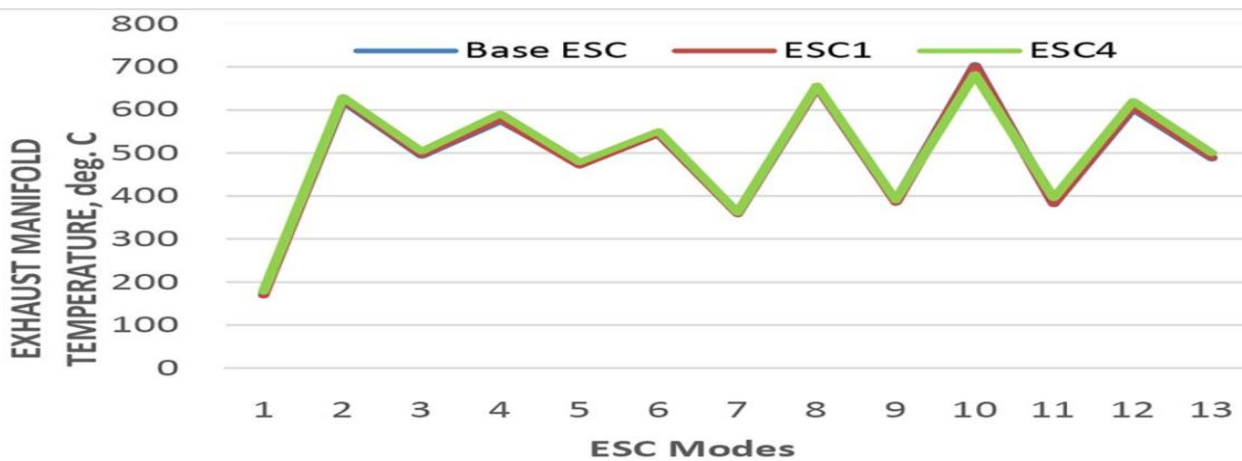


Figure 1-f: Comparison of exhaust manifold temperature

NOx formation depends on combustion chamber temperature, NOx reduces with increase in water injection. There are many reasons for reduction on combustion chamber temperature with water injection such as, with increase in water injection specific heat capacity increases, increase of heat loss at the wall, water cooling effect. Figure 1-g shows comparison of NOx emission for ESC, ESC-1, and ESC-2 cycles.

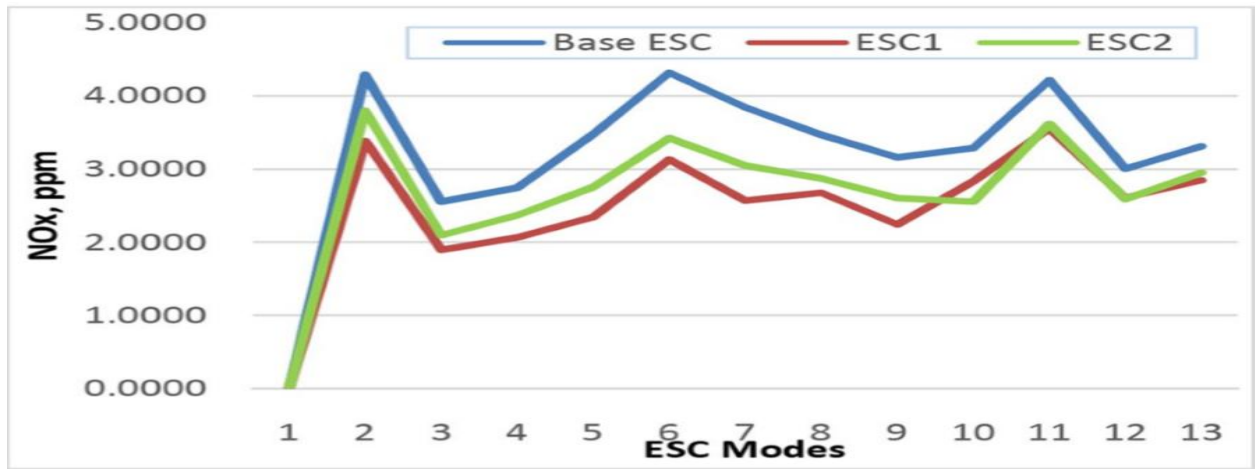


Figure 1-g: comparison of NOx emission

Figure 1-h shows the smoke emission comparison. As injection increases soot formation. This is the why base ESC shows less soot than ESC-1 and ESC-2. The reason behind that is when combustion temperature reduces, oxidation of soot reduces due to increase in wetness, the unburnt HC absorbs the soot core.

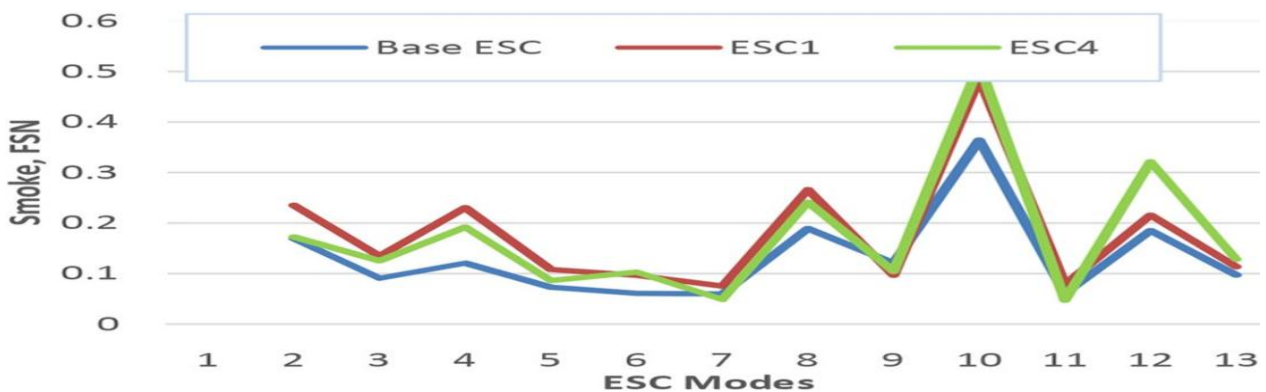


Figure 1-h: comparison of smoke emission

## 2. European transient cycle

8.4mg of water was maintained for transient cycle. As that of European steady state cycle in European transient cycle, for every cycle injector was made to inject in three pulse and each pulse was separated by 240° BTDC.

Figure 2-a shows comparison of power for base ETC and ETC-1 cycle, from figure it is clear that there is no change in power. Figure 2-b shows the comparison of torque for base ETC and ETC-1 cycle which shows there is no change in torque.

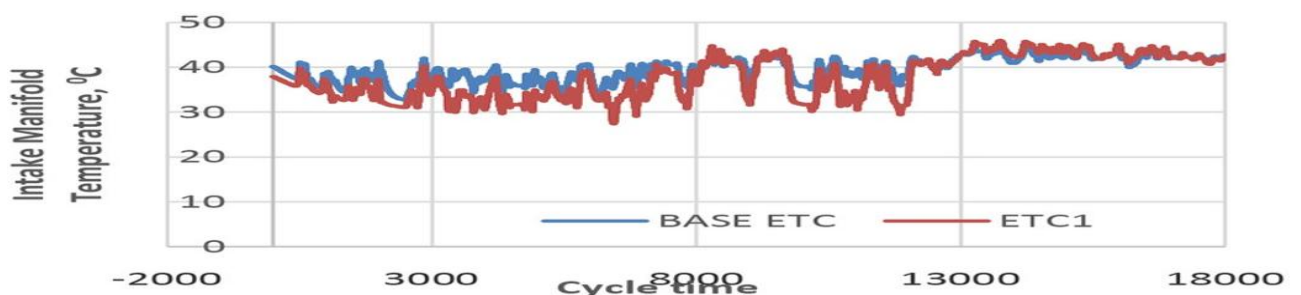


Figure 2-a: comparison of power

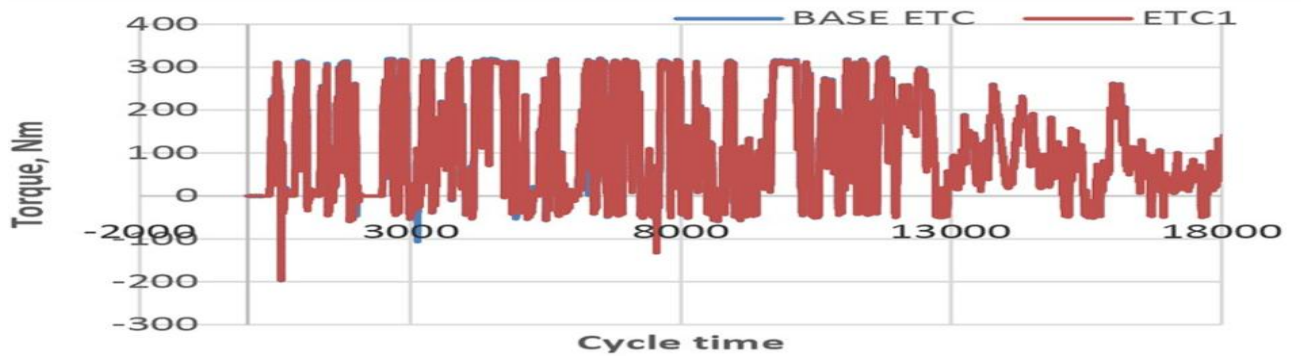


Figure 2-b: comparison of torque

figure 2-c and figure 2-d shows intake manifold and exhaust manifold temperatures. The intake manifold temperature decreases with water injection. The exhaust manifold shows no change in temperature as heat is lost through the wall.

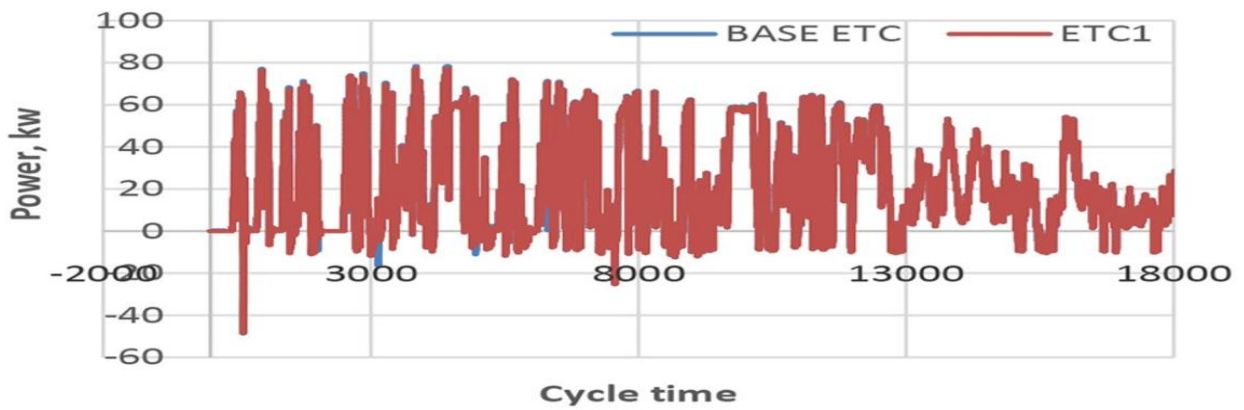


Figure 2-c: Comparison of intake manifold temperature

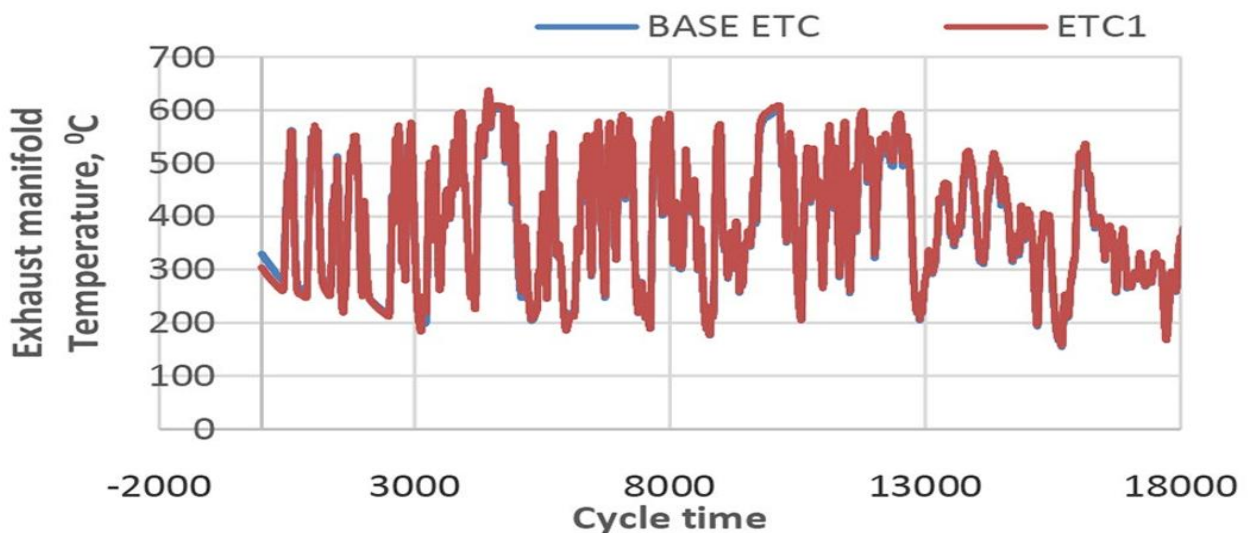


Figure 2-d: Comparison of exhaust manifold temperature



Figure 2-e shows NO<sub>x</sub> emission for base ETC and ETC-1 test, figure shows reduction in NO<sub>x</sub> formation in ETC-1 test due to injection of water which reduces the combustion chamber temperature

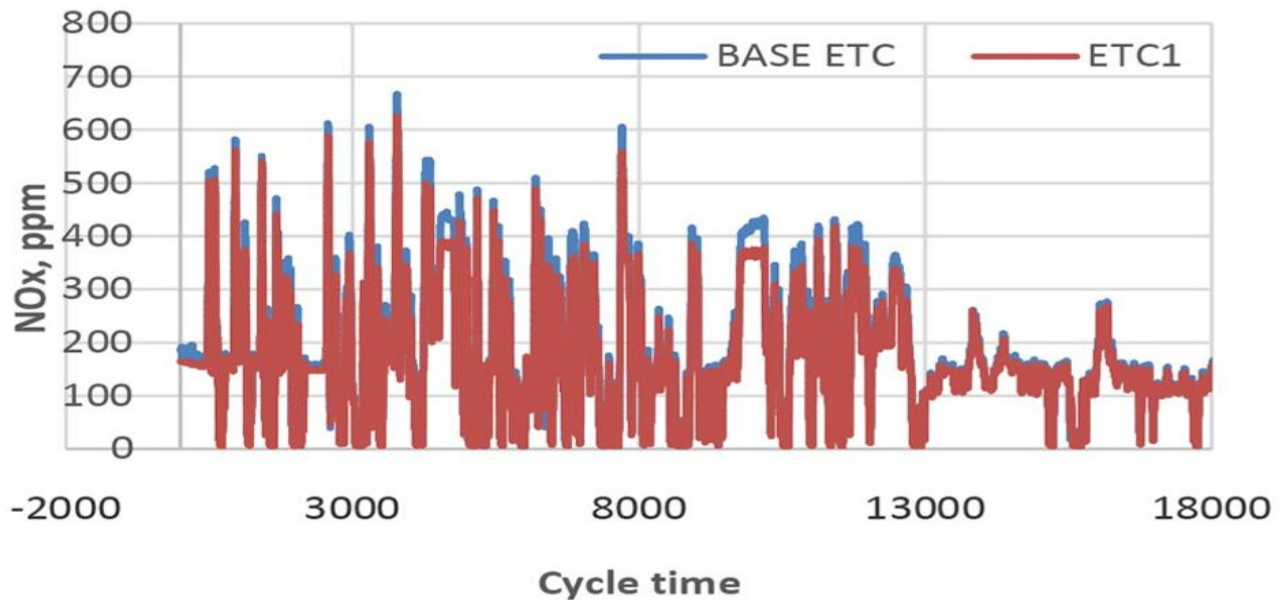


Figure 2-e: Comparison of NO<sub>x</sub> formation

### V. COMPARISON OF EXPERIMENTAL AND SIMULATED RESULTS

From ESC-1 and ESC-2, ESC-2 mode is selected for comparison of experimental and simulated results. Figure VI-a shows comparison of experimental and simulated injection cases. Figure VI-b shows comparison of airflow rate. In figure VI-c shows NO<sub>x</sub> emission comparison for simulation and experiment, at point 2,4,8,10 water is cut off simulation result shows no reduction in NO<sub>x</sub> emission, but experimental result shows reduction in NO<sub>x</sub> emission due influence of water injected in previous cycle. In figure VI-d at points where water injection was cut-off, simulated curve shows lower emission of smoke while experimental curve shows increase in smoke emission corresponding to reduction in NO<sub>x</sub> emission.

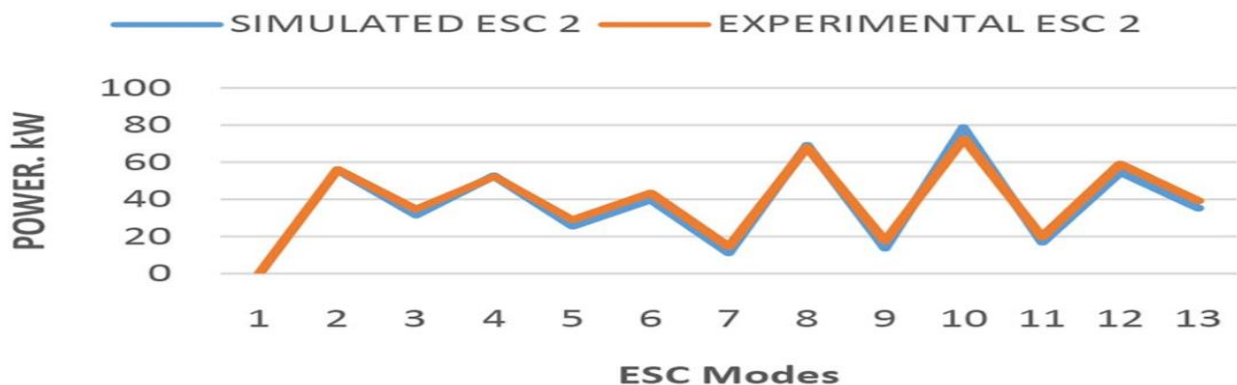


Figure VI-a: Comparison of power for experimental and simulated ESC Test

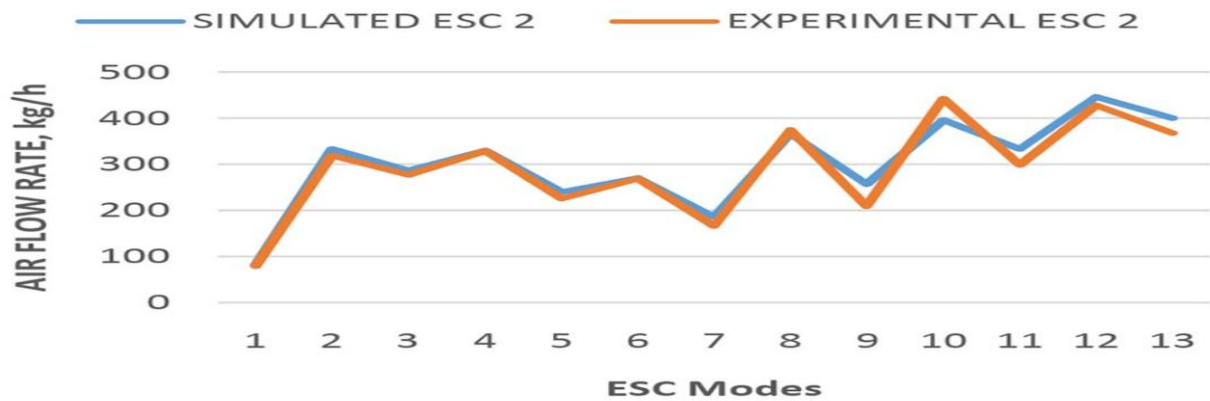


Figure VI-b: Comparison of air flow rate for experimental and simulated ESC test

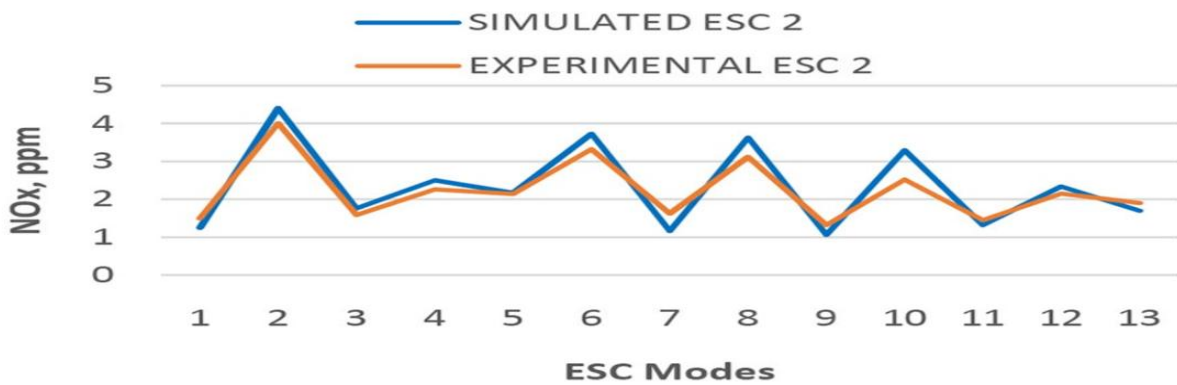


Figure VI-c: Comparison of NOx emission for experimental and ESC test

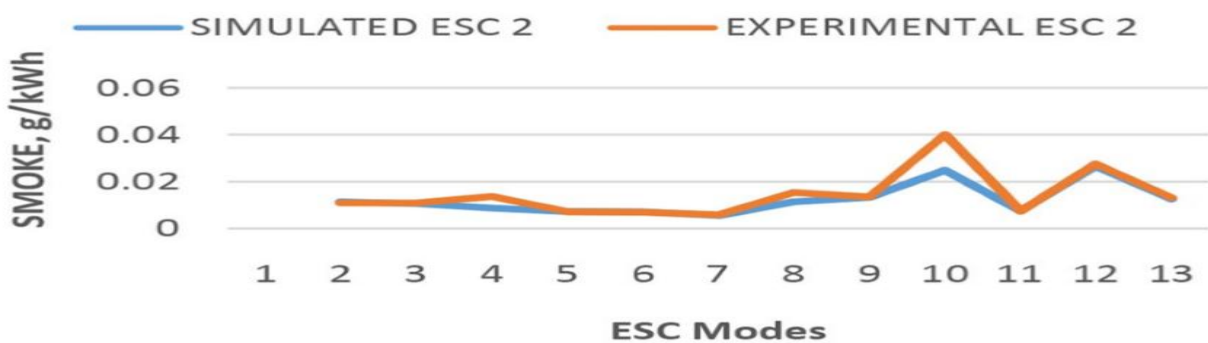


Figure VI-d: Comparison of smoke emission for experimental and ESC test

## VI. CONCLUSION

Experiment was performed using a 3-cylinder DI diesel engine at different operating points. 3D CFD analysis helps us to select the best injector position, and as from the experimental result 2 position of injector was selected as best position. It helps us to analyze the influence of water on NOx formation.

The primary conclusion was 8.4mg/stroke of water for 3ms need to be injected for effective reduction of NOx emission. Water was injected in each cylinder using injector controlled by an ECU unit. Two test cycles were

performed ESC and ETC. Initially ESC test was performed by keeping the water injection for 6ms(8.4mg/stroke), it was observed that NO<sub>x</sub> was reduced by 15% but there was increase in smoke formation, thereafter ESC test was performed by injecting water for 3ms(8.4mg/stroke). In this cycle the modes were smoke was increase water injection was cut-off i.e. at idle and full load points. This resulted in 13% reduction of NO<sub>x</sub> and comparatively lower increase in smoke than ESC-1. For ETC also 3ms (8.4mg/stroke) of water was injected for which the overall smoke reduction obtained was 7%.

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