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Strategies for Low Engine Speed Torque Enhancement of Natural Gas Engine: Valve Overlap and Compression Ratio

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Abstract

For a long time diesel engines are used as prime movers for commercial vehicles. However, since last two decades, countries are promoting natural gas vehicles to improve air quality. Since then, natural gas based commercial vehicles and their powertrains have witnessed fast development, principally driven by need to meet emission standards.

A widely used CNG commercial vehicle is passenger mass transport bus. In some cities, authorities impose maximum speed limit for such buses considering safety. This limit may be as low as 40km/hr. Thus, with low vehicle speeds, frequent stops and starts, and traffic conditions, such vehicles demand high torque output at slow engine speed. In here, various approaches for improving the torque of engine are briefly summarized. The objective is to observe effect of valve overlap and compression ratio for improving torque at low engine speeds as very limited literature exists that focuses on low engine speed zone.

Use of turbocharger, direct injection, electronic wastegate control, VVT, etc. have potential for torque improvement. The extent of their impact on low speeds is not clearly evaluated. Naturally aspirated six cylinders engine is simulated and virtual output is verified against experimental data from test bed at full throttle, to verify effective representation of model, so that numerical simulation of different technologies can be performed before experimental activity. Further testing is done with a few different compression ratios and valve overlaps. It is seen that there is scope for optimizing torque and power at low engine speed zone.

Keywords*; *Natural gas engines, valve overlap, compression ratio

I. INTRODUCTION

Many towns are full of vehicles of all categories. Energy consumption details show that personal vehicles need more energy than public transport for persons travelled [1]. For cost efficiency, drive is to operate trucks on alternate energy than conventional fuels [2]. City buses operating on natural as will be a big leap of emission reduction [3]. As market matures, OEMs shall use platform technology, thus minor changes shall serve worldwide needs [4]. Light and small commercial vehicles sector shall grow in recent times [5]. These designs shall replicate latest powertrains scenario and shall adopt alternate fuel, advance transmission etc. [6]. Using CNG as an alternate fuel shall reduce pollution and gain acceptance as green transport fuel [7]. Different attributes of natural gas help to have ease of designs, controls, better economics, combustion etc. [8]. As refueling infrastructure develops, number of CNG vehicles will increase, reducing emission. Advances related to compression ignition, compact storage etc. will be seen in newer vehicles [9]. Bio-Methane can be used instead of natural gas as fuel, but needs purification first for dense energy content, for practical usage on vehicle [10].

Commercial vehicle’s market in India saw growth of approximately of 23% in 2010-2011 while a compound annual growth of approximately 9.3%, with about hundred different models. Lowering operating costs will be crucial and natural gas versions of these vehicle will be available. Share of natural gas powered vehicles will be about 22%. Enforcement for use of natural gas as commercial vehicle fuel will increase share of CNG vehicles in future [11]. In addition to emissions regulation on engines, vehicle safety concerns formalized in form of a standard is published, called the bus body code that defines different specification and acceptability

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conditions covering eight aspects of comfort and passenger safety [12]. Vehicle's technology evolves as part of OEM's undertaking that highlights initiative to improve engines operating on alternate fuels. This is primarily driven by Government's directive natural gas policy in India. Vehicle manufacturers now offer their most popular models in natural gas option. Such vehicles are made available throughout the nation [13].

II. ENGINE MODIFICATIONS FOR LOW SPEED TORQUE ENHANCEMENTS

The reference engine, available for experimentation consists of six cylinder that is naturally aspirated, operating on natural gas. This engine at present powers a mass transit bus used for city transport. Important specifications of this engine can be observed in table 1 below.

Table 1 Specifications of base engine

Bore & Stroke (mm)	97 & 128
Numbers of cylinders	6 Cylinders, In-line
Order of firing	1 5 3 6 2 4
Rated speed (Max Power)	2500 RPM
Swept volume (Cc)	5675 Cc
Aspiration	Naturally Aspirated
Compression ratio	12.5:1 +/-1

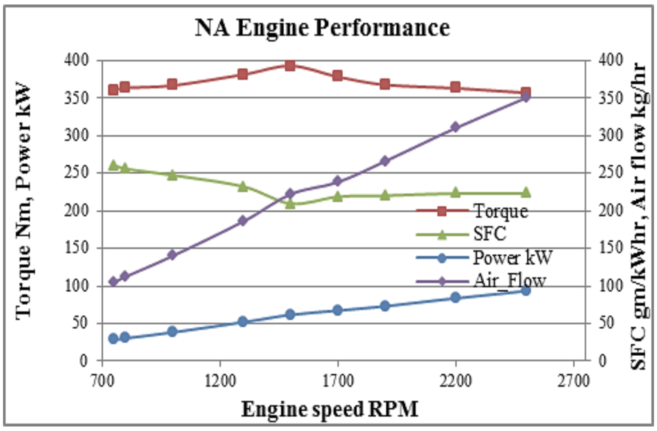

Figure 1 Base engine performance in form of a graph

Enhancing torque output at low engine speeds needs changes to basic hardware. Since the engine under study is on offshoot of a diesel engine, there are practical design limitations. Engine output at different speeds can be seen in the above figure 1. Other important engine operating parameters are also recorded simultaneously.

III. EFFECT OF VARIOUS APPROACHES TO ENHANCE ENGINE OUTPUT

Several approaches for increasing engine output are categorized by the nature of their functioning. Table 2 provides a brief summary of various such approaches adopted by researchers. It gives an insight of different findings about particular approach has on engine performance.

Table 2 Various approaches to engine output enhancements

Sr. No	Parameter	Effect
1	Turbocharging	Provides significant increase in torque and power, helps to recover wasted exhaust energy
2	Changes to engine	Downsizing helps gain efficiency
3	Variable Valves Timings	Increases engine power output by as much as about 15 - 20%
4	VVT & higher compression ratio	High volumetric efficiency observed with lesser valve overlap, with various compression ratios,
5	Electronic Wastegate Control	Enhanced engine power output
6	Induced Swirl or Tumble air motion	Enhanced swirl leads to higher pressure drop and reduces volumetric efficiency of engine
7	Direct injection with Jet ignition	Enhances engine efficiency by approximately 4 – 5 %.

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8	Higher compression ratio in HCNG engines	High torque, enhanced fuel efficiency, but some practical limitations.
9	In-cylinder combustion pressures	High in cylinder pressures in diesel engines as compared to natural gas versions

IV. SIMULATION AND ENGINE TESTING

So as to verify the effects of various methods of torque enhancement on engine slow speed torque, it is decided to initially simulate a model of engine and then validate it by comparing it to engine tests data, recorded from testbed.

As a part of virtual testing, one dimensional model of engine under consideration is built in software GT ISE. Once the model converged, it was capable to predict engine performance based on changes in valve overlaps, different valve timings, different compression ratios etc. Schematic virtual representation of engine under consideration can be seen here, in figure 2. Actual components of engine and their arrangements are numerically represented. Geometric attributes and limiting conditions are applied as inputs to the model. Simulation runs are then conducted at wide open throttle to observe various parameters at different engine speeds

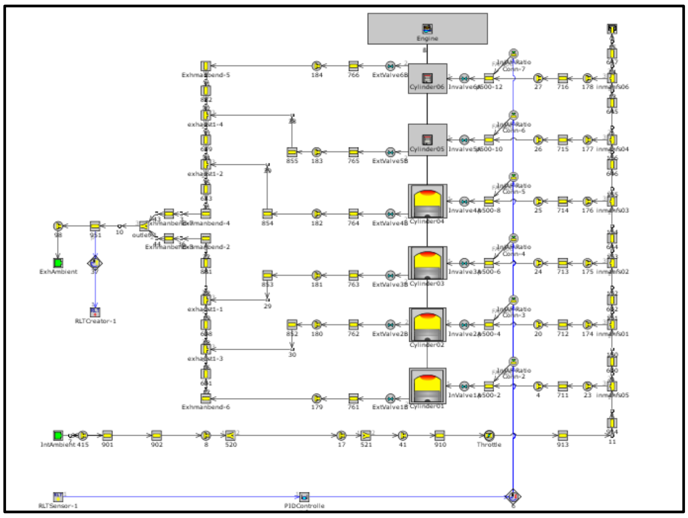

Figure 2 Base natural gas engine as modeled in software

Closeness of measured and simulated values is expected as it assures resemblance of actual engine and simulated model. Thus, 1D simulation of test engine, available for consideration was completed using the various dimensions and parameters from base engine specifications. The output of simulation model was compared with engine data available from engine test bed.

Similarly, table 3 highlights measured as well as simulated values for critical engine performance parameters for engine speeds corresponding to maximum power and maximum torque. It can thus be said that as these values match closely and model is a true representation of engine under consideration, based on which other virtual trials can be carried out.

Table 3 Test data and simulation output comparison

Parameter	**Test Data**	**Sim. Data**	**% diff.**
2500 RPM @ Max Power			
Torque	357.11	356.76	0.10
Power	93.44	93.401	0.04
Air flow (kG/hr)	355.65	348.29	2.07
Fuel flow (kG/hr)	22.09	21.53	2.54
BMEP	7.91	7.89	0.25
Brake thermal eff	30.5	30.65	-0.49
1500 RPM @ Max Torque			
Torque	392.96	389.26	0.94
Power	61.69	61.11	0.94
Air flow	221.9	216.03	2.65
Fuel flow	13.38	13.13	1.87
BMEP	8.71	8.43	3.21
Brake thermal eff	33.9	33.05	2.51

This validated model will now serve as base onto which different technologies such as different compression ratios, valve timings etc. shall be iterated to verify the extent by which engine output is affected and to optimize it for better low speed torque.

Figure 3 shows indicates similarity between measured and simulated values of engine power and

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torque. One observes the closeness of different parameters that assures model is well adapted and calibrated to be representative of engine under consideration. Different outputs based on these try-outs and iterations can be assumed to be valid for comparing enhancement or decline in engine output.

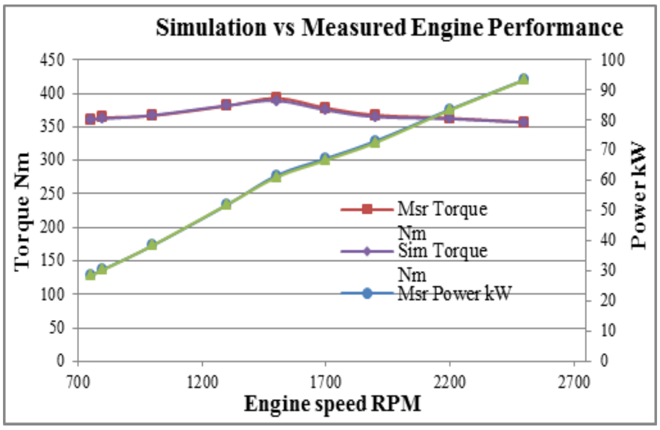

Figure 3 Simulated and measured engine torque and power

Valve Timing Study: - The present valve timings were considered as base starting point and further investigation were proposed based on changes to these base valve overlap and valve timings. Considering the physical limitations of un-machined camshaft, it was only possible to orient the final machining of cam profile by about nine degrees on either side of stock cam. Accordingly simulation cases were setup with different valve overlaps and different advance or retard of individual valve timings. In all about eight cases were considered. With different valve opening and closing times and different overlaps. To effectively find out the effect of valve overlap on different engine parameters, a valve overlap sweep was performed across simulation of different valve overlap timings. For topic under consideration valve overlap sweep is performed from 60 degrees to 90 degrees.

Valve timings have been crucial to engine performance as they are principal elements to determine the mass of air that can be inducted into the engine. Volumetric efficiency depends on valve timings to a considerable extent. In an attempt to observe the effect of different valve timings on low speed torque, a model of engine under consideration is made and its closeness of representing the actual engine is evaluated. Once satisfactory representation was assured, the valve overlap was varied on both sides of original overlap and effect on low speed

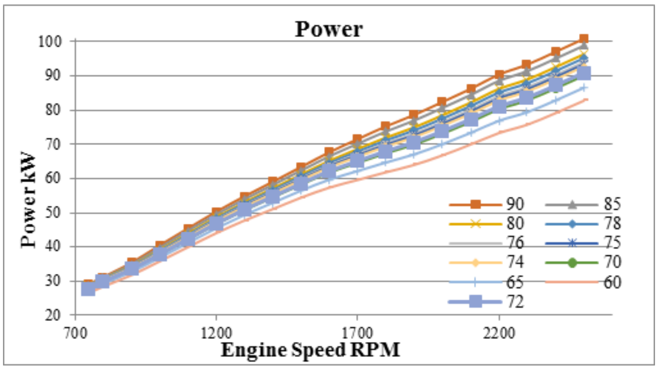

Figure 4 Power

There can be seen improvement in engine power as the valve overlap increases. Refer figure 4. The effect of different overlaps is more prominent as the engine speed increases. At lower speeds, the difference is not much spread out. As the overlap increases, engine torque too increases. The curves for power and torque follow a normal acceptable trend across different overlaps.

This suggests that engine is effectively able to breathe incoming air. The trend is similar to fuel flow as the ratio of air and fuel is constant across the different engine speeds under consideration.

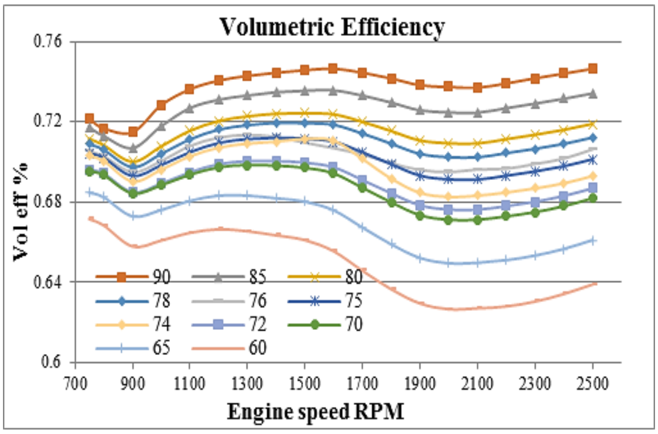

Figure 5 Volumetric efficiency

In the figure 5, it is observed that the volumetric efficiency increases as the overlap increases. The extent of increase especially at low engine speeds is to be noted and can be one of the factors to consider while enhancing engine torque at low engine speeds. Overall it is can be concluded that the engine is able

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to better exchange the air and products of combustion as the overlap increases.

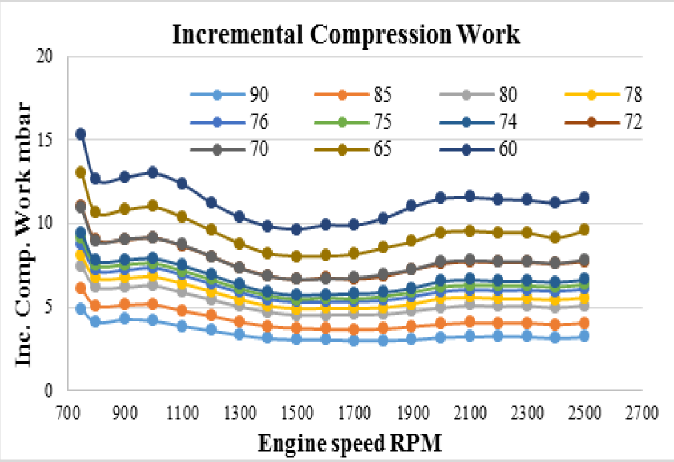

Figure 6 Incremental compression work

As a specific comparison of the effect of valve overlap on engine compression, a factor representing increased work at the starting of compression stroke, principally due to the air and fuel mixture being forced out of the cylinder, before the intake valve closes is studied. Refer figure 6. It is seen that as the valve overlap reduces the incremental compression work done by piston also reduces.

On the similar lines potential loss of engine output on account of early opening of the exhaust valve, before the end of exhaust stroke i.e. before the piston reaches BDC, represented as EVO losses is simulated and output is observed in figure 7.

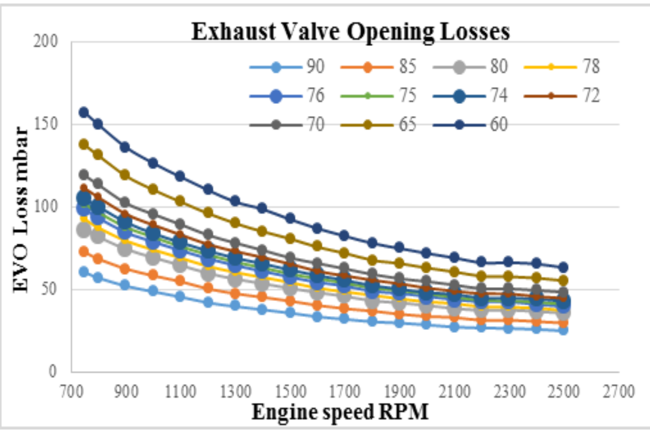

Figure 7 Exhaust valve opening losses

It can be seen that as the valve overlap increases the exhaust valve opening losses tend to reduce. Similarly, they tend to reduce as the engine speed increases.

Compression ratio: - Compression ratio signifies the extent to which the fluid is compressed once after it is introduced in the cylinder. Change in compression ratio affects engine performance, mean effective pressure, engine efficiency and other parameters in any internal combustion engine.

As mentioned above a one dimensional, virtual model of engine was made and its output is compared with engine performance data from engine test bed. Once the representation of model to actual engine was in established, different compression ratios were simulated to observe their effect on critical engine parameters. Observations are as below: -

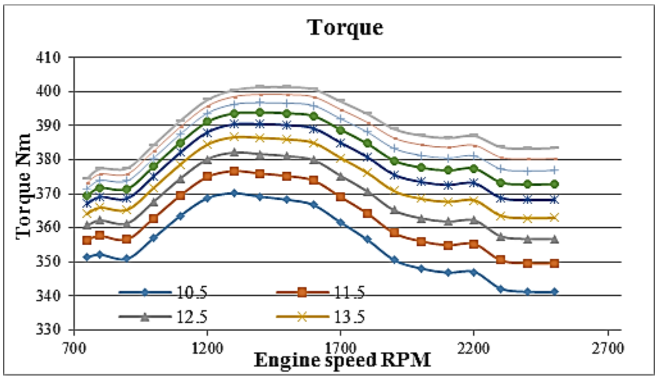

Figure 8 Torque

It can be seen from the figure 8 that torque increases as the compression ratio increases, there is a noticeable increase in engine torque, across the entire speed range. Increasing the compression ratio thus helps to enhance the engine output.

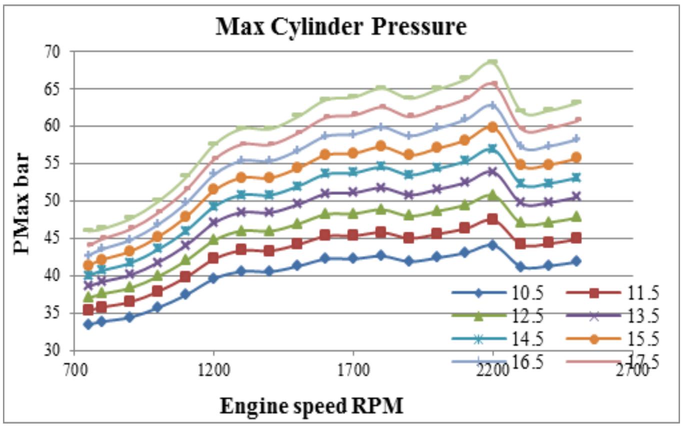

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Figure 9 Max cylinder pressure

Average maximum cylinder pressures increases as the compression ratio increases. It is seen from figure 9 that it also increases with increase in engine speed. Values for different compression ratio follow a similar trend. Higher the cylinder pressure, higher is the output of engine, which translates into better torque. It can thus be observed that the torque at low engine increases with increase in compression ratio.

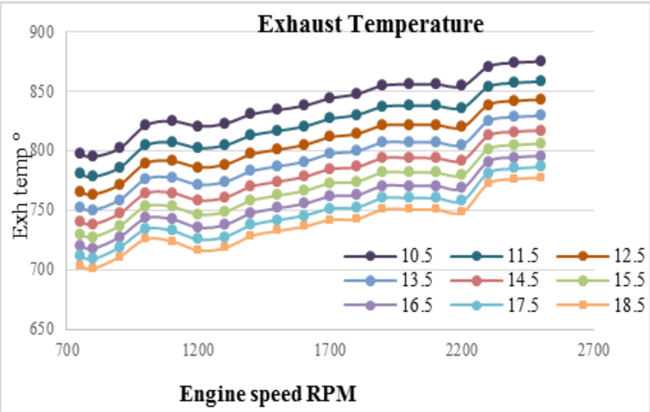

Figure 10 Exhaust temperature

The exhaust temperature measured as close as possible to exhaust port indicate that exhaust temperatures reduce as the compression ratio increases, however, as the engine speed increases, the exhaust temperatures also increase. The trend is similar across different compression ratios. Refer figure 10. It shows that as the compression ratio increases, the engine is better able to utilize the energy available from fuel to convert it to useful work. On the similar lines, it can also be observed from the specific fuel consumption that higher compression ratio, better is the efficiency of engine and better the output.

The brake thermal efficiency chart too suggests that as the compression ratio increases, the engine is better able to utilize the fuel and useful output is enhanced. From 10.5:1 to 18:5:1 there is about 3% improvements in brake thermal efficiency, across the entire engine speed range. The exhaust energy represented as a part of total percentage. It is observed that as the compression ratio increases, the energy to exhaust gases reduces; suggesting that it is better utilized in delivering higher engine outputs and is not wasted to the atmosphere.

It can also be seen that torque can increase by about 6% at low engine speed of 750 rpm for increase in compression ration from 10.5:1 to 18.5:1. Similar trend can be seen at other engine speeds as well, with different magnitude of gains. Better thermodynamic expansion and efficient utilization of fuel help engine to deliver higher torque. If these are extent of torque enhancement that one aims for, increasing the valve overlap or compression ratio can be options to be considered.

There are practical difficulties in getting the camshafts that would allow different valve overlaps, for engine that is under consideration. The engine does not have overhead and independent cams for inlet and exhaust valves. All the twelve cams are machined on same shaft and they actuate the valves with help of pushrods. This makes it difficult to use variable valve timings mechanism to effectively offset the cams for different overlaps, hence the limitations for conducting actual tests.

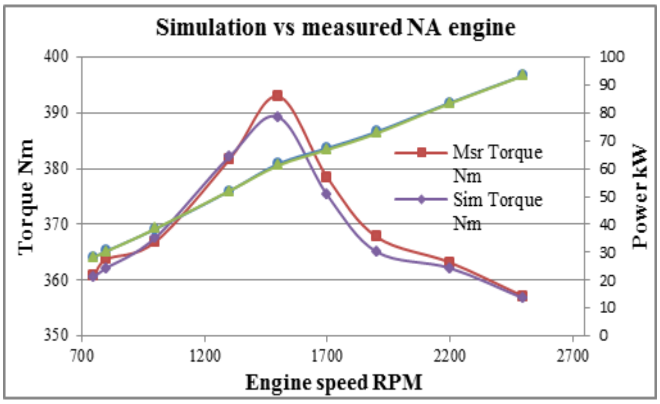

Figure 11 Simulated and measured engine output

The engine under consideration has a camshaft configured for valve overlap of 75°. Availability of various pistons with different compression ratio was constrain and actual engine assembly and tests were carried out with compression ratio of 12.5. Engine performance at full throttle was recorded at instrumented test bed. Comparison with simulated values can be observed in figure 11. As these match closely, the different simulations carried out for compression ratio and valve overlaps can be considered to be realistic representations of actual engine and thus applicable.

Table 4 Summarized results from different CR and valve overlaps

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Observations from different compression ratio			
Parameter	18.5 CR	10.5 CR	Gain
Torque (Nm)	383.45	341.16	12.40
Power (kW)	100.39	89.31	12.40
BSFC (gm/kWhr)	214.85	240.77	-10.77
IMEP (bar)	10.17	9.13	11.42
BMEP (bar)	8.49	7.55	12.40
FMEP (bar)	1.68	1.58	6.76
A/Flow (kG/hr)	348.92	347.93	0.29
Fuel (kg/hr)	21.57	21.51	0.30
Brake Eff (%)	33.76	30.13	12.06
Tot Exh Energy (%)	43.93	50.06	-12.25
Comb eff (%)	0.94	0.94	0.16
Exh Temp (°C)	777.77	875.29	-11.14
Pmax (bar)	63.14	41.85	50.87
Observations from different valve overlap			
Parameter	60° O/lap	90° O/lap	Gain
Indeff (%)	37.63	38.05	1.12
BSFC (gm/kWhr)	236.96	227.14	-4.14
Exh Temp (°C)	721.87	732.31	1.45
Power (kW)	82.77	100.87	21.86
Torque (Nm)	316.17	385.28	21.86
A/Flow (kG/hr)	317.35	370.68	16.81
Fuel (kg/hr)	19.62	22.91	16.80
Vol eff (%)	0.64	0.75	16.81
IMEP (bar)	8.59	10.15	18.16
BMEP (bar)	7.00	8.53	21.86
PMEP (bar)	-0.39	-0.43	10.34
Inc Com Work (mbar)	11.00	3.20	-72.05
Exh Val Op Loss (mbar)	63.01	24.72	-60.76
Pmax (bar)	44.39	50.33	13.38

V. CONCLUSIONS

It is thus to be noted that use of higher compression ratio may enhance the low speed torque of engine but only by a limited margin. As a limitation, there will always be tendency of engine to pre-ignite and knock, at higher engine speeds due to higher compression temperatures that cannot be avoided beyond a point.

From the simulations so far it can be observed that as the overlap increases, the engine is able to better breathe the incoming air and is able to effectively exchange it for by-products of combustion, thus enhancing the volumetric efficiency. It can also be seen that as a result of enhanced volumetric efficiency, the air flow increases as the valve overlap increases

This can be witnessed as higher indicated mean effective pressures, higher brake mean effective pressures, higher average maximum cylinder pressures, higher indicated efficiencies, leading to higher engine torque and high engine power. However, care is to be taken that there is a limit to which the overlaps can be pushed as the effect on emissions is still to be determined. The findings can be summarized as in table 4 below.

Considering stringent emission norms that are coming up, there will be a trade-off where engine output shall have to be sacrificed for better emissions.

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