



The Effect of Miller Cycle Strategy Early Intake Valve Closure on Thermal Efficiency of the Diesel Engine

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ABSTRACT

Diesel engines are very popular in automotive industry on account of its better thermal efficiency. Diesel uses higher compression ratio as compared to the gasoline engines which leads to the better thermal efficiency. But to meet the needs of current situation of speedily depleting fossil fuels, there is a requirement of more efficient working cycles. The over-expanding Miller cycle is a better alternative to conventional working cycles. In this paper, the one of the Miller cycle strategies, Early Intake Valve Closure (EIVC) is analyzed using simulation tool GT-Suite. Initially the base simulation model is validated with the experimental results of the test engine. Further a steady state non-transient model is prepared and filled with the calculated values of valve timing closure. A non-predictive combustion model is used for the analysis. The EIVC strategy of the Miller cycle is proven to be the best strategy for improvement in the thermal efficiency of the Diesel engine working on Miller cycle. In future the transient model with predictive combustion can be used for the analysis.

Keywords: Miller cycle, EIVC, Thermal efficiency, Valve timing.

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I. INTRODUCTION

In day to day life, transportation plays an important role. Diesel engines are the prime movers of the transportation industry. Diesel engines are the most promising prime movers on accounts of its thermal efficiency. Due to this advantage of diesel engines, they are very popular in transportation as well as in the agricultural industry. Diesel is a petroleum product and the sources of petroleum are found only in nature, which are limited. Due to fast growing transportation industry and heavy commercial and domestic use, the sources of petroleum are depleting at very faster rates. There is a great possibility that the sources of petroleum will exhaust in coming future. Therefore it is essential to utilize the available sources of petroleum products very cautiously and efficiently. Hence today there is a need of an engine which is working with higher efficiency compared to the today's scenario. Also now days, the emission norms are getting stringent because of the environmental aspects. Hence the emissions from the engines are to be maintained in a particular limit. By

analyzing these two situations, there is a need of more efficient engine which is more environmental friendly.

Any IC engine works on a particular working cycle. Petrol / gasoline engine works on Otto cycle. Diesel engine works on Diesel cycle. The working cycles are nothing but the series of various cyclic thermodynamic processes occurring inside the engine. Otto cycle and Diesel cycle are the traditional working cycles and in modern days these are facing many challenges of overall efficiency and emission control. Particularly diesel engines are facing the problems of emission. Though diesel engine produces less CO and HC emissions as compared to gasoline engine, but it produces more hazardous NO_x and soot. Emission norms are getting stringent and the sources of petroleum are depleting day-by-day. Hence there is necessity of advanced working cycles which is having high overall efficiency and giving out low emissions.

The over-expanding cycles are proven to be a promising method for the higher thermal efficiency but not at the cost of emissions. It uses higher effective expansion ratio as

compared to the compression ratio. As the expansion ratio is greater as compared to the compression ratio, the work to be supplied to the engine during the compression stroke gets reduced. Also, the potential of the exhaust gases is utilized completely while in the normal working conditions, where the expansion ratio is less as compared to the over-expanded cycles, the potential of the exhaust gases is not utilized completely.

The two popular over-expanding cycles are Atkinson cycle and Miller cycle [1]. Atkinson cycle uses intelligent but complicated mechanical linkage system for producing the effect of over-expansion. Different compression stroke length and expansion stroke length are achieved by using this mechanical linkage system. But this complicated mechanical linkage system makes the engine heavier and bulky. Miller cycle is an advanced implementation of Atkinson cycle. The Atkinson effect is achieved by using very advanced valve timing system. The inlet valve is closed either early or late than the normal closure timing. This enables to use the same size of engine to be used. But due to the early or late closing of the inlet valve, the inlet mass of the air gets reduced. Hence turbocharging is necessary for Miller cycle.

Many researchers have studied the over-expanding cycles and their effect on the performance parameters of the IC engine through experimentation as well as simulation. Martins et al. [2] gives the brief idea about the thermodynamic analysis of the over-expanding cycles. Researchers have developed the equations for Miller cycle working on part load and low load conditions. The theoretical efficiency at low load conditions was increased up to 15%. Millo et al. [3] focuses on the potential of dual stage turbocharging on the performance of diesel engine working on diesel cycle. The experimental analysis showed that there is 2% reduction in the bsfc and 6% improvement in the brake mean effective pressure with compression ratios of CR16 and CR 17.

The theoretical analysis of multiple linkage system to achieve the Atkinson effect for the improvement of thermal efficiency of a general purpose spark ignition engine was given by Watanabe et al. [4]. The advanced linkage system was provided in between the connecting rod and crank pin by which the Atkinson effect is achieved. The researchers also studied the Miller cycle with advanced valve timing system, through experimentation and simulation. For Atkinson cycle, using compression ratio of 8.5 and expansion ratio of 12.3 the improvement in the thermal efficiency observed was 4%. With advanced valve timing Miller cycle, the improvement in the thermal efficiency was 2.3% for EIVC. Edwards et al. [5] studied the effect of Miller cycle combined with internal EGR for cooling of iEGR. The cooling of iEGR is not possible with any cooler; the Miller cycle provides the cooling for iEGR. The EIVC strategy was selected for the analysis.

Kamo et al. [6] used the method of low heat rejection for studying the effect of Miller cycle on the performance and emission of the engine. Researchers added an additional rotary valve before the inlet valve for achieving the Miller

effect. At 100% loading condition, the percentage improvement in the indicated efficiency observed was 4.54%. Yang and Keller [7] studied the effect of Miller cycle combined with the variable geometry turbine on the performance of the diesel engine. Turbocharger assembly is necessary for maintain the flow of air in Miller cycle. Variable geometry turbine was used to change the blade angle and so the air compression. The observed reduction in the bsfc was 1%.

Sellnau and Rask [8] implemented the Variable Valve Actuation (VVA) system for achieving the Miller effect. Two strategies EIVC and Late Intake Valve Opening (LIVO) were used for the analysis. The valve lift and timing were continuously varied by using VVA system. The overall performance of the engine was improved by Miller cycle. Imperato et al. [9] focused on NO_x reduction by using Miller cycle. The engine used was a single cylinder diesel engine with separate air compression system. Researchers only considered EIVC strategy for the GT-Power simulation analysis. The percentage reduction in NO_x for low load condition observed was 45% and for full load it was 25%. Mattarelli [10] applied Miller cycle to HSDI engine for performance improvement. Researcher used VGT for turbocharging and the simulation was done by using GT-Power. The maximum power improvement was observed to be by 7.76%. The fuel efficiency was increased by 7.5% with positive displacement compressor.

Wang et al. [11] had given the comparative investigation of Atkinson cycle with different expansion ratios. The compression ratio was maintained at 10.4 while the expansion ratio was varied as 12, 13 and 14. The net indicated efficiency was increased by 5.7% compared to the base engine. Pertl et al.

[12] gives the theoretical overview of over-expanded Atkinson cycle with respect to the feasible piston movement. Authors give the piston motion for the Atkinson crank train concept. The thermodynamic losses between theoretical and indicated efficiency were analyzed. 15% increase in the net efficiency was observed for compression to expansion ratio (CER) of 0.5. Boretti and Scalzo

[13] explained the mechanism and advantages of Atkinson cycle. In the analysis, the efficiency improvement was observed to be 3% while the power output was improved by 11%. Schutting et al.

[14] gives the thermodynamic analysis of both EIVC and LIVO strategies for the Miller cycle. Authors compared the Miller cycle with EGR concept for reduction in the emissions. Authors concluded that though Miller cycle was proven to have increased efficiency and power output but when it comes to emission analysis, Miller cycle has no significant advantage over the conventional external EGR system.

In this paper, one-cylinder diesel engine working on conventional diesel cycle, with turbocharger is selected for the analysis. The experimental results for diesel cycle including the parameters brake efficiency, air flow, brake power are obtained. The validation of the work is done by obtaining the results of pilot simulation carried for the same diesel cycle engine in one-dimensional thermodynamic GT-

Power software and comparing the same with experimental results. After validation, the intake valve closure timing is varied for EIVC by giving the variation in the angle multiplier tab in inlet valve (IntVal) template. The simulation is done for different engine speeds and for each individual speed, for different loading conditions. The end-environmental conditions are specified by the environmental conditions at the time of experimentation. All simulations are carried out with an optimizer object included during the coding to optimize the efficiency to OptiMax and to optimize the NOx to OptiMin with a specified range.

2. METHODOLOGY

The methodology proposed for this dissertation work is divided in two parts. The first part includes the introduction to the simulation software GT-Power. The second part of methodology starts with building of steady state model which is further used for the simulation.

2.1 Introduction to GT-Power

GT-Power is based on one dimensional gas dynamics, representing the flow and heat transfer in piping and the related engine components. It reduces the time and cost involved and helps to predict the results very accurately and quickly. At the heart of GT-Power, there are two powerful software domains called GT-ISE (Integrated Simulation Environment) and GT-Post (Post Processor). The GT-ISE builds, executes and manages the simulation process. GT-Post is the post processing tool that provides access to all plot data generated by simulation. GT-Post is a powerful data analysis tool used to plot, view and manipulate data generated either by GT-Suite simulation or by any an external source. It offers a more efficient data analysis solution than standard spread-sheet software. By employing the data pointers, the result viewed in GT-Post is updated automatically and immediately when a model is changed and simulation is re-run.

GT-Power is used for wide range of applications relating to engine design, development and performance analysis.

Typical applications include:

Manifold design and tuning

Valve lift profile and timing optimization
Turbocharger matching, including
waste gates, VGTs and control
strategies EGR system performance

Manifold wall temperatures

Thermal analysis of cylinder components Combustion
analysis

Intake and exhaust noise analysis Transient turbocharger
response After treatment systems

2.2 Preparation of Actual Steady State Model

A typical four cylinder turbocharged diesel engine is modelled using 'EngCylinder' and 'EngineCrankTrain' component objects and 'ValveConn' and 'EngCylConn' connection objects as shown in Figure 8. The basic geometry and characteristics of the engine are defined by 'EngCylinder' and 'EngineCrankTrain' objects. Both objects refer to several reference objects for more detailed modeling information on aspects such as combustion and heat transfer. This model is steady state non-predictive combustion model and it is validated with the test data for different engine performance parameters. Percentage variation between simulated results and experimental results is calculated and graphs of simulated data are plotted against the experimental data.

Figure 1 shows the GT-Power model of the one-cylinder, turbocharged, test diesel engine. Cylinder is to be connected to the engine with 'EngCylConn' parts made from the predefined objects "ign", which is available in the template library. The 'EngCylConn' parts have no user-defined attributes. Hence the global cylinder number (used for firing order, etc.) for the cylinder is assigned by the port number where the 'EngCylConn' connection is attached to the engine. Cylinders are connected to intake and exhaust ports with 'ValveCamConn' connections. Many 'ValveCamConn' connection templates are available to define different types of valves and their characteristics [15].

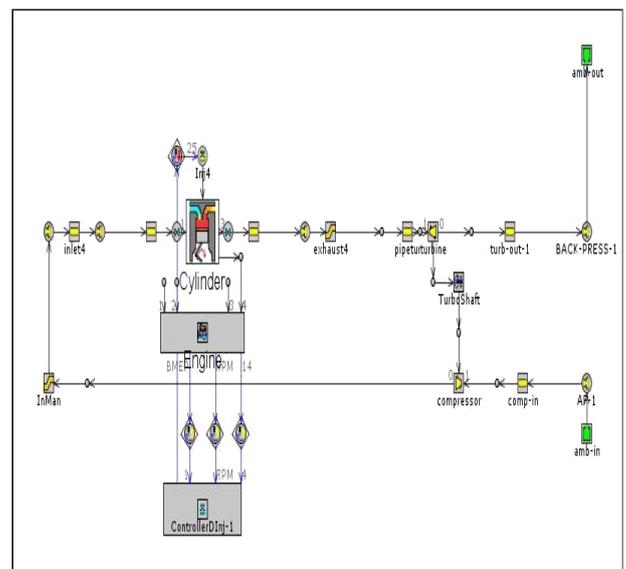


Figure 1: GT-Power Model for One-Cylinder Turbocharged Diesel Engine

The specified input values for different attributes are filled in the respective object places. After entry of all input values, the model is ready for the pilot simulation. Pilot simulation is done for the purpose of validation. After validation work, the model is then converted from diesel engine to Miller cycle engine, by changing the valve timing and shifting the inlet valve closure timing to early. The inlet valve closure timing is shifted from -151° of crank angle to -173° of crank angle in five equal intervals. For this, the

angle multiplier object of 'IntValve' template is varied from 1 to 0.9 by the difference of 0.02. The validation of the model and results for EIVC is analyzed in next chapter.

3. RESULTS AND DISCUSSIONS

3.1 Validation

The software always gives output for any random value of the input. Hence the validation of the same is very essential. All the validation data which includes the experimental data as well as the simulation data is normalized with respect to the maximum value of the particular parameter. The validation is carried out for three performance parameters bsfc, brake power and thermal efficiency. The RPM conditions are varied from 1000 RPM to 2000 RPM. Figure 2 shows the variation of bsfc with RPM conditions for experimental and simulated results. There is a good agreement between the experimental and simulated results. The average percentage deviation between the experimental and simulated results is 6.18%.

Figure 3 shows the variation of brake power with RPM conditions for experimental and simulated results. The experimental and simulated results are almost same for brake power. The average percentage deviation between experimental and simulated results for brake power is 0.0392%.

Figure 4 shows the variation of brake efficiency with RPM conditions for experimental and simulated results. Brake power is the important performance parameter to be analyzed. The maximum deviation in experimental and simulated data is 2.05% at 1500 RPM. The minimum percentage deviation is 0.29% which is seen at 2000 RPM. The average percentage deviation between the experimental and simulated results for brake efficiency is 1.17%.

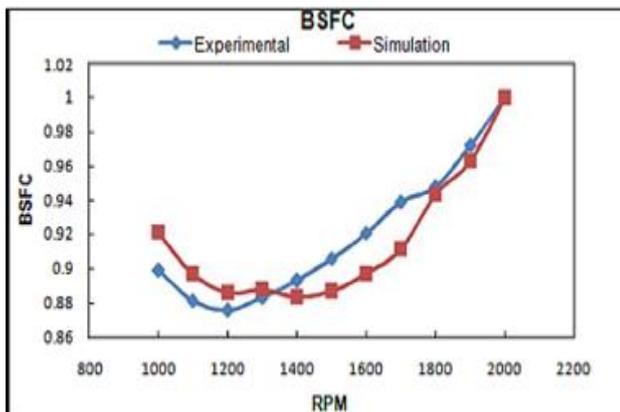


Figure 2: Validation of Experimental and Simulation Data for bsfc

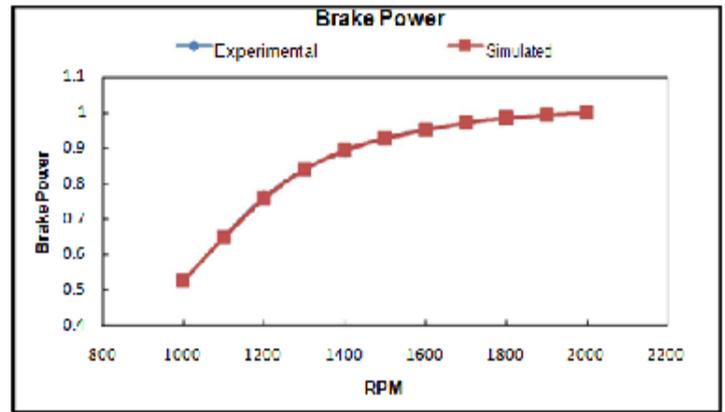


Figure 3: Validation of Experimental and Simulation Data for Break Power

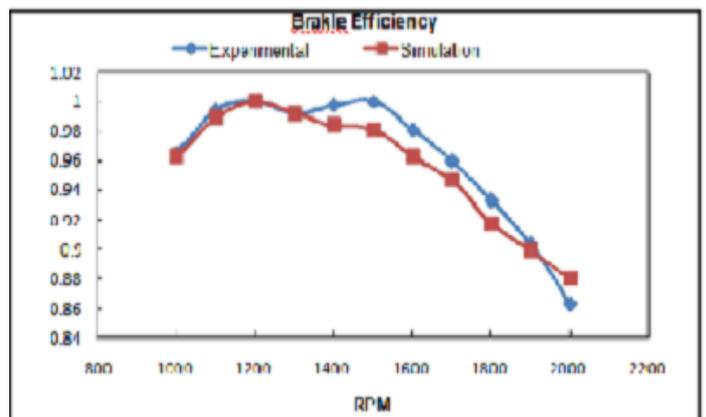


Figure 4: Validation of Experimental and Simulation Data for Brake Efficiency

For all the performance parameters, the average variation in experimental values and simulated values is less than 10% which is in the acceptable limit. This ensures the prepared model is valid and the results generated from the model are acceptable.

3.2 Simulation Results for EIVC

The break thermal efficiency of the engine for the different RPM and loading conditions are plotted against the angle multiplier of the inlet valve for EIVC strategy. The results are plotted for the RPM values corresponding to 2000 RPM, 1700 RPM, 1500 RPM, 1200 RPM and 1000 RPM. The simulation is done for the loading conditions of 100%, 75%, 50% and 25%. In this section, in all the graphs, all the values are normalized with respect to the maximum value of a particular parameter. The value of angle multiplier is varied from 1 to 0.9 with the difference of 0.02. The values of angle multiplier are 1, 0.98, 0.96, 0.94, 0.92 and 0.9. By varying the angle multiplier from 1 to 0.9, the intake valve closure timing shifts to early. The inlet valve closure timing is shifted from -151° to -173° of cam angle. Figures from 5 to 8, shows the graphs of brake efficiency versus angle multiplier for respective loading condition.

Figure 5 shows the graphs for EIVC at 100% loading for

different RPM conditions. The graph for EIVC is to be read in opposite direction from 1 to 0.9 that is from right to left. It is observed from the Figure 5 that, from right to left, for every RPM conditions except at 1500 RPM, there is a rise in the brake efficiency. The rise in the brake efficiency considerably increases with decrease in the angle multiplier. The highest percentage rise is observed in the case of 2000 RPM which is 2.4%. But for the case of 1500 RPM, no rise in brake thermal efficiency is observed. Due to early closure of the intake valve, the work of compression, which is to be supplied to engine for compressing the inlet air, gets reduced. Hence the rise in the brake thermal efficiency is observed.

Similarly, Figure 6 shows the graph for brake thermal efficiency versus the angle multiplier for EIVC at 75% loading. For this case also the maximum efficiency rise is observed for 2000 RPM which is 2.5%. For 1700 as well, a good efficiency rise of 2.3% is observed for 75% loading. But there are two cases in 75% loading in which the brake thermal efficiency is decreasing with the angle multiplier instead of increasing. For 1200 RPM and 1000 RPM there is a decrease in the thermal efficiency which is 0.27% and 0.28%. This decrease in the percentage for 1200 RPM and 1000 RPM is

comparatively less than the percentage rise in the brake thermal efficiency in the case of 2000 RPM and 1700 RPM. The probable reason behind this decrease in the brake thermal efficiency is the low RPM condition.

Figure 7 shows the EIVC strategy for 50% loading at various RPM conditions. Here the maximum percentage rise in the brake thermal efficiency is 3.2% which is observed at 2000 RPM. The percentage rise in brake thermal efficiency at 1700 RPM and 1500 RPM is 1.9% and 1.1% respectively. For 1200 RPM condition the brake thermal efficiency remains constant for all values of angle multiplier. Again at the lower RPM condition that is for 1000 RPM the brake thermal efficiency is reduced by 0.29%.

Figure 8 shows the variation of brake thermal efficiency with the EIVC angle multiplier values for 25% loading condition. As it is observed from Figure 8, the brake thermal efficiency for all RPM conditions is increasing with the change in the angle multiplier. The maximum percentage rise in the brake thermal efficiency in this case is 3.9% which is observed at 2000 RPM. For 1700 RPM, 1500RPM, 1200 RPM and 1000 RPM the rise in the percentage of brake thermal efficiency is 2.8%, 1.8%, 1.3% and 2% respectively.

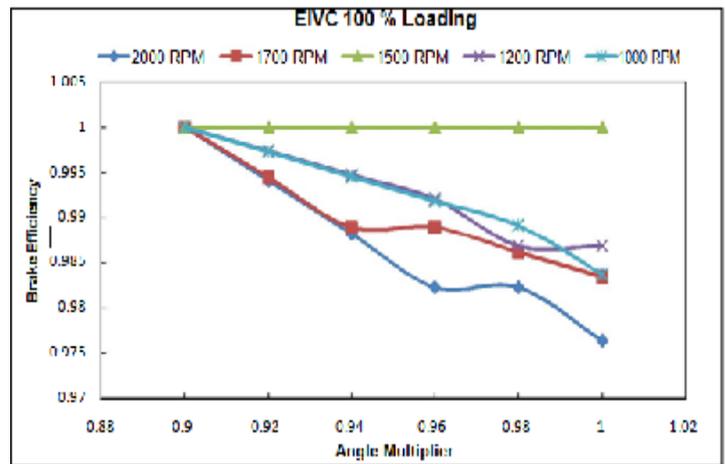


Figure 5: Variation of Brake Efficiency with Angle Multiplier for EIVC 100% Loading

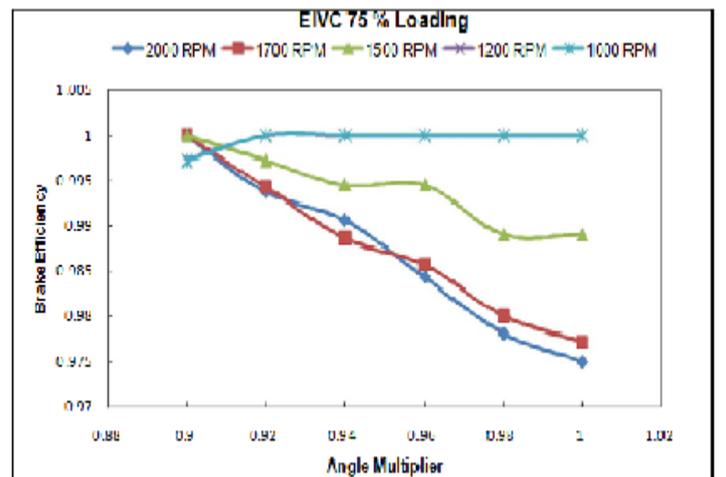


Figure 6: Variation of Brake Efficiency with Angle Multiplier for EIVC 75% Loading

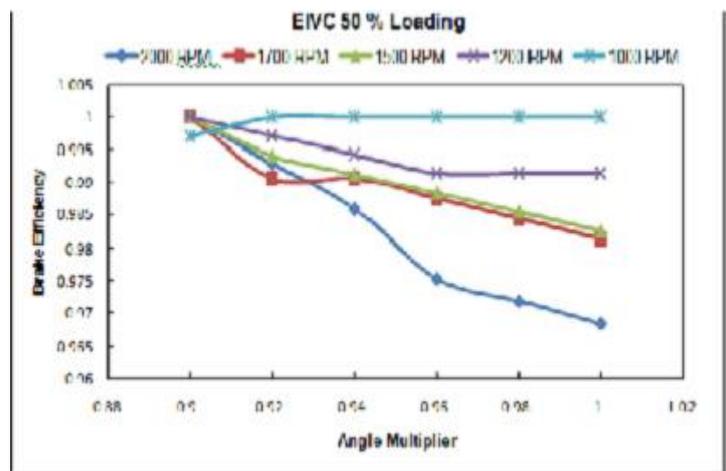


Figure 7: Variation of Brake Efficiency with Angle Multiplier for EIVC 50% Loading

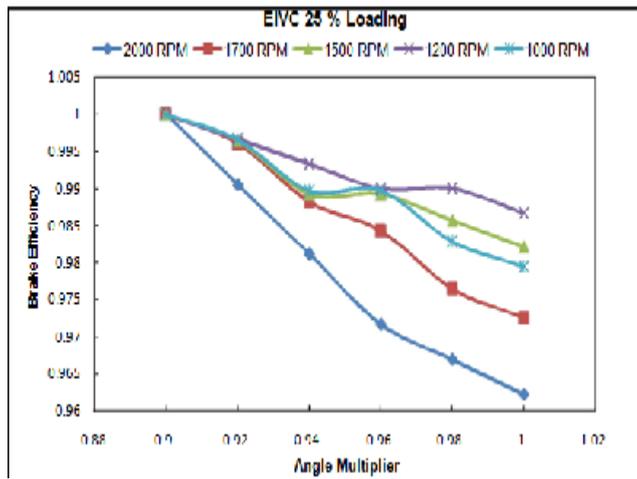


Figure 8: Variation of Brake Efficiency with Angle Multiplier for EIVC 25% Loading

It is observed from all the EIVC results that the highest raise in the percentage for the brake thermal efficiency is observed at 2000 RPM for all loading conditions. The highest percentage rise in the brake thermal efficiency is found to be at 25% loading and 2000 RPM, which is 3.9%. This means that the highest percentage rise is seen at the lowest loading condition. The conclusions of this paper are formulated in the next section.

4. CONCLUSIONS

In this study, the Miller cycle by varying the intake valve closure timing is analyzed. ONE of the Miller Cycle strategies, Early Intake Valve Closure (EIVC) is studied. The effect of EIVC on the important performance characteristic Brake Thermal Efficiency is studied. Followings are the important conclusions of this study -

1. A methodology is developed in GT-Power simulation tool for the analysis of effect of Miller Cycle on the brake efficiency of a diesel engine.
2. Very close validation is obtained when the simulated data is compared with the actual experimental data which is taken on the test engine. Some values of parameters in the simulated data exactly match with the experimental data over the range. The average difference between the experimental data and simulated data is less than or equal to 7%.
3. In case of EIVC, the brake thermal efficiency increases when the intake valve timing closure is shifted to early. This happen due the reduction in the work of compression due to early closure of intake valve. The maximum percentage rise in the brake thermal efficiency in case of EIVC is 3.9% when compared to the normal valve closure timing.

The maximum efficiency rise is observed in the case of high RPM condition and low load condition. Hence it is recommended for Miller cycle EIVC strategy to use high RPM and low load condition as it is most suitable for maximum efficiency rise.

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