Design and development of Piston & Piston ring pack to predict the Engine Blow-by using AVL Excite

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Abstract*-Piston ring pack performance is very important to evaluate diesel engine blow-by. Structural analysis tools can be used to ensure the piston structural integrity. For the performance analysis in dynamic condition & to predict Engine blow-by; AVL GLIDE software is used. In this study, detailed model of Piston Ring, Cylinder liner is prepared in AVL GLIDE. The results after simulation will be compared with the tested results. Comparisons of engine test measurements and model predictions operating conditions will be presented. This study is very important for designing the optimized piston rings. It also helps to optimize the ring tension which is helpful for improving the mechanical efficiency of engine. The blow-by prediction also helps to evaluate the oil replacement period. Optimizing the blow will direct affect the oil change interval period. Also main cause of the oil contamination is the mixing the unburned combustion gases to the oil, which reduces the life of oil also reduces the oil change interval. This study and will help to optimize the piston and ring pack design. The results will be matched with selected cycle to evaluate the co-relation between the simulation and practical results.

***Key words*-TDC: Top Dead Center, BDC: Bottom Dead Center, LOC: Lub-Oil Consumption.**

I. INTRODUCTION

Dynamic seals support the cleanliness of a lubricant from external contamination, and thus contributes to suppressing wear caused by pollutant particles. A common base of all dynamic seals for linear motion or inline motion is that they operate against a moving counter surface, for which reason they have to be optimized in terms of sealing capability, low friction and engine wear. Wear for counter surface, caused by reciprocating contact with the piston leads to changes in the surface quality of the contact surface, which in turn change the qualifications for the dynamic seal.

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Piston rings in present internal combustion engines have to meet all the requirements of thermal and chemical conditions. In short, following basic needs for piston rings can be identified:

- Less friction, for assisting a high power efficiency rate
- Less wear of the ring, for ensuring a long functioning lifetime
- Low wear of the cylinder liner, for maintaining the desired surface texture of the liner
- Emission suppression, by limiting the flow of engine lubricants
- Good sealing ability and less blow-by
- Good resistance against chemical attacks and hot erosion
- Reliable operation and cost efficient for a significantly long time

The tribological considerations in the interactions formed by the piston skirt, rings & cylinder liner; attracted much attention, not least highlighted by the large number of articles published on this topic in latest editions.

The main work of the piston is to convert thermal energy into mechanical energy. Furthermore, the piston rings seal the combustion zone from the crankcase and transfers heat to the engine coolant. The piston skirt acts as a load-carrying face, which keeps the piston appropriately aligned within the cylinder bore.

LITERATURE REVIEW

Kevin L Hoag, explained the basic principle of the engine design process. The detailed explanation of the each subsystem and the individual components give the right approach for the dealing the design issues. [1]

Understanding the Fundamentals of Piston Ring Axial Motion, Twist and Effects on Blow-By; Richard Mittler and Albin Mierbach: This paper defines the ring movement under dynamic load and gives the overview of the results. It also was important to validate the model with actual engine measurements results to understand the fundamentals of ring design parameters as a function of the described mathematics. [2]

Peter Andersson, Piston Ring and tribology, explained the basics of the piston and ring pack. The evaluation techniques of the complete piston and ring pack is explained and carried out the fundamental study of the same. [4]

S Suresh Bagavathy, N Balasubramanian, D Premnath and S Krishnan Ashok Leyland, discussed the experimental study aimed to understand empirical relationship between the gravitational forces w. r. t. to engine tilt angle for evaluating the optimum blow-by measurement and various circuit possibilities for approximate oil throw from the engine. [5]

In recent trends of the engine design and optimization phase, due to stringent norms and requirement of maximum BSFC, need has been developed to reduce the frictional power of engine. There are number of components responsible in frictional power of the engine. Out of which maximum involvement is from piston and rings, as they are in continuous contact with liner. To reduce frictional power, the ring tensions need to reduce and it will allow more blow-by into the crank case. So it is very much important that to optimize the piston rings for minimum blow-by and optimum frictional power.

This study and will help to optimize the piston and ring pack design. The results will be matched at the max torque speed of engine & cylinder pressure to evaluate the good co-relation between the simulation and practical performance results. In this paper, the scope is limited to develop the methodology for simulation of the Piston ring pack and comparing the results with tested results.

II. Methodology

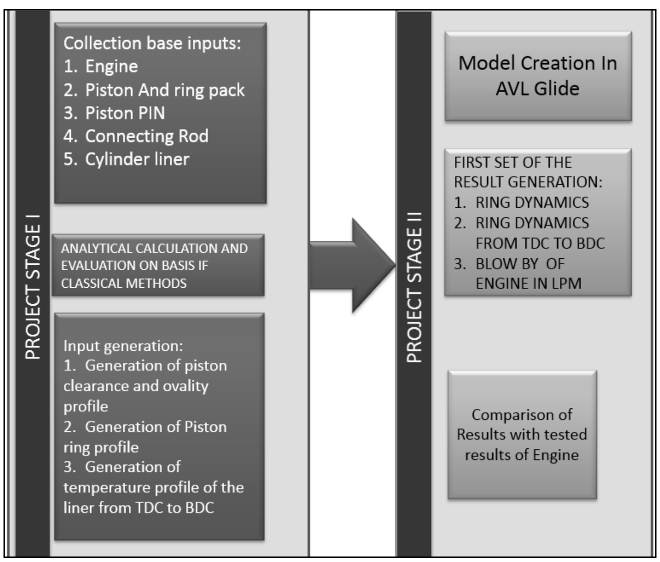

Fig 1: Methdology of of Ring Simulation

As per the specifications provided, the blow of engine is need to evaluate as per the application. The Off road engines are always run in the maximum torque point as per the usage. So, the prediction of the blow by at Max torque need to be done.

III. Piston Ring Pack And Details

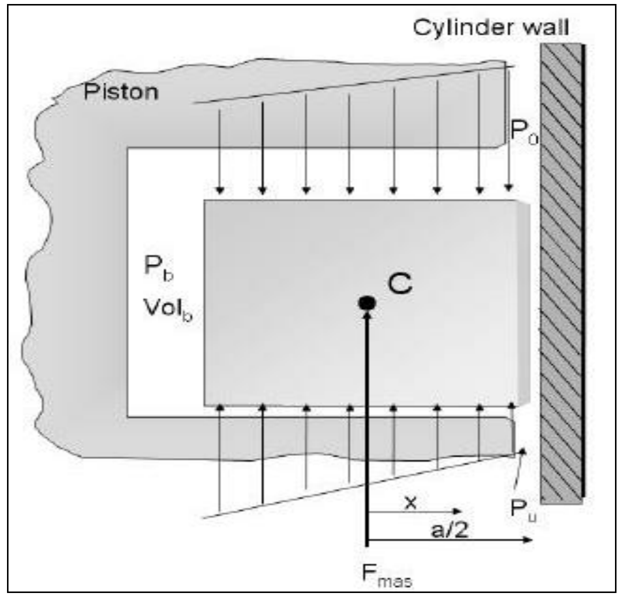

Fig 2: Force Acting on the Ring

Po = Cylinder Pressure on the top face of ring

Pb = Pressure Acting on the rear face of the ring

C is the center of gravity of piston Ring

Above figure shows the forces acting the piston ring. The rings are always in dynamic condition and there dynamic behavior makes the complex model for the evaluation of accurate blow by.

In present application following rings are used:

- Top Ring: Keystone Ring
- Middle Ring: Taper Compression Ring
- Oil Ring: Conformable Oil Ring

A. Piston Nomenclature

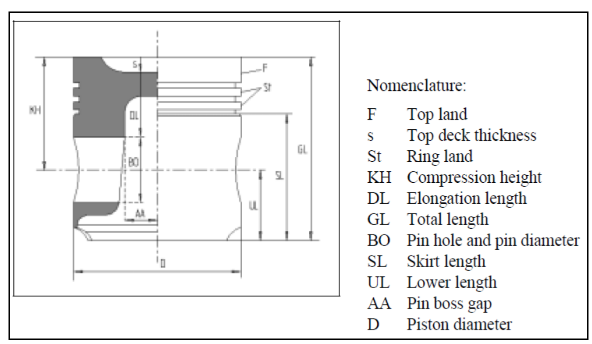

Fig 3. Nomenclature of Piston

Above fig shows the architecture of the piston. The various nomenclature and the notifications is provided for better understanding of the piston architecture. Table 2 shows the design consideration and the proportion of piston for diesel engine and the range of the different proportions as design inputs.

Table 1. Proportions of Piston w.r.t. Nominal Diameter

	Diesel engines	
	Four-stroke	
Diameter D [mm]	75–180	> 180
Total length GL/D	0.9–1.3	1.1–1.6
Compression height KH/D	0.50–0.80	0.70–1.00
Pin bore diameter BO/D	0.30*–0.40	0.36–0.44
Top land width F/D	0.10–0.20	0.14–0.22
1^{st} ring land St/D**	0.07–0.09	0.07–0.09
Top ring width [mm]	1.5–4.0	3.5–8.0
Skirt length SL/D	0.50–0.90	0.70–1.10
Pin boss spacing AA/D	0.30–0.42	0.28–0.46
Crown thickness s/D	0.10–0.15***	0.13–0.20
Characteristic weight G_N/D [g/cm^3]	0.9–1.4	1.1–1.6

*Minimum value for passenger car diesel engines
**Figures given for diesel engines apply to ring insert pistons
***For direct injection engines approx. 0.2 × the combustion cavity diameter

III. PISTON RING SIMULATION IN AVL-EXCITE

A. GUI of AVL EXCITE

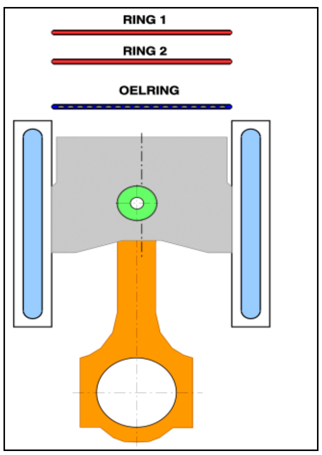

Fig 4. GUI of Excite Piston & Rings

The Piston Movement Module of EXCITE Piston & Rings serves to determine characteristics of the movement of pistons in reciprocating engines. Typical applications are mono-pistons and articulated pistons of all size of engines.

An overview of typical steps for the application of the Piston Movement Module can be given as follows:

- Determination of piston stiffness matrix
- Determination of piston and liner contour due to assembly and thermal loads
- Input of geometry, mass and cylinder gas pressure
- Calculation with EXCITE Piston & Rings - Piston Movement Module
- Result plots over engine cycle and animation of piston slap motion

Thus, results of the Piston Movement Module help for optimization targets in piston and liner design, such as minimization of piston slap induced noise, cavitation and wear at the liners and oil consumption. For this purpose, information can be derived from the software in order to reduce piston impacts. Furthermore, the Piston Movement Module results serve as input for post processing in order to calculate piston ring dynamics (EXCITE Piston & Rings - Piston Ring Dynamics Module), oil consumption (EXCITE Piston & Rings - Lube Oil Consumption Module) and forced vibration of engine structures.

The simulation model of the piston rings is created and the following input details are provided for the evaluation of the blow by quantity considering the cylinder pressure data at max torque condition.

The piston rings finalised for the analysis are as follow. To evaluate the specifications GOETZE RING MANUAL is used and the specifications are finalised on the basis of benchmarking values.

Table No. 2 Piston Ring Details

Sr No	Ring Type	Final Specifications
1	Top/1^{st} Ring	Kystone Ring
		Width = 3mm
		Ring Tension= 20N
		Graphited
2	Middle/2^{nd} Ring	Taper Compression Ring
		Width= 2 mm
		Ring Tension= 17N
		Phospated
3	Last/3^{rd} Ring	Conformable Oil Ring
		Width = 3 mm
		Ring Tension = 60 N
		Chrom Plated

The detial model is made to evaluate the ring performance and blow by for the above specified engine details.

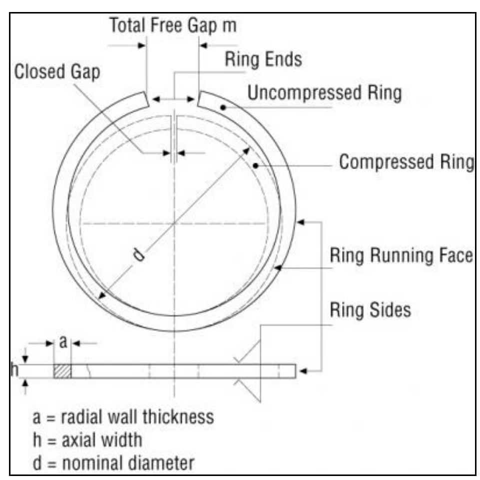

Fig 5. Piston Ring Nomenclature

Fig 5 shows that the architecture of the ring. The overlap of the piston ring in free and assembled condition is shown for better understanding.

B. Cylinder Liner & Bore Deformation

One of the most important parameter is to control the cylinder bore deformation in full torque condition. The cylinder bore distortion is measured from TDC to BDC and the nominal design value is 30 to 40 micron for these kind of application engine.

Factors affecting the Cylinder bore distortion:

- Stiffness of block
- Bolt layout of the cylinder head
- Tightening sequence

Considering all above aspect we have measured the cylinder bore deformation for the present case and generated the profile in cold condition.

In general, we observe the more distortion in top deck of the block. In many cases the excessive deformation is measure cause of the more blow-by. The reason behind it is that if bore is deformation is not within acceptable range, the ring pressure distribution will not be uniform along the periphery. This will cause the provision of passage for the combustion chamber gases. Thus huge blow by will be observed. To avoid this condition the bore deformation must be controlled within design limits.

Following figure shows the exaggerated view of the cylinder bore distortion.

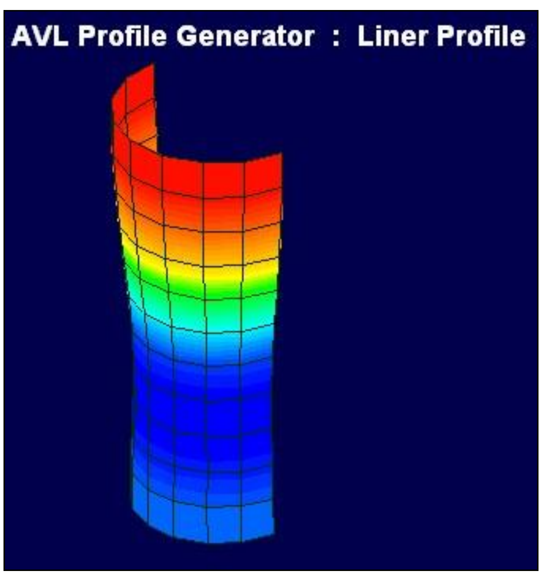

Fig 6: Cylinder Bore distortion

In the present case, the range of bore deformation observed is 32 to 48 micron along the length of the liner. By using the bore gauge all the data is recorded and above profile is generated.

IV. RESULTS & DISCUSSION

A. Ring Dynamics

The operating behaviour of an engine is significantly affected by the dynamics of the piston rings. Ring dynamics influence on blow-by, lube oil consumption (LOC) and friction losses of the piston liner group.

The main characteristics of the Piston Ring Dynamics Module can be listed as follows:

- Each ring is modelled as a single mass. The interaction between the thrust and antithrust sides is given by a beam model and a model for pressure compensation. Twisting, (including pre-twist angle) is considered.
- For the calculation of the gas flow through the rings, inter-ring areas are considered as volumes, which are given by the piston and ring geometry's and the actual clearances between piston and liner. The volumes are connected due to the actual clearances of ring end gaps and actual position of the rings in the grooves. The possible gas flow behind the rings and between ring and groove flanks is considered.
- The oil film is taken into account between the ring running surface and liner by calculating the pressure distribution in the clearance according to the liner and ring contours.

Following points are very much important from Ring dynamics point of view:

1. End Gap Variation of Each Ring
2. Inter Ring Pressure Variation w. r. t. cylinder pressure
3. Ring Twisting

A detailed analysis is carried out for the same and following results are estimated

1. End Gap Variation:

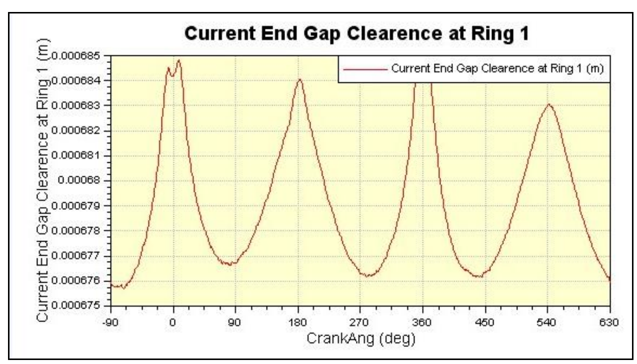

Fig.7 Ring cap variation for second Ring 1

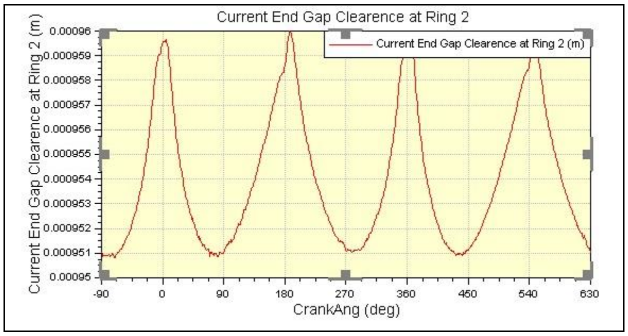

Fig.8 Ring cap variation for second Ring

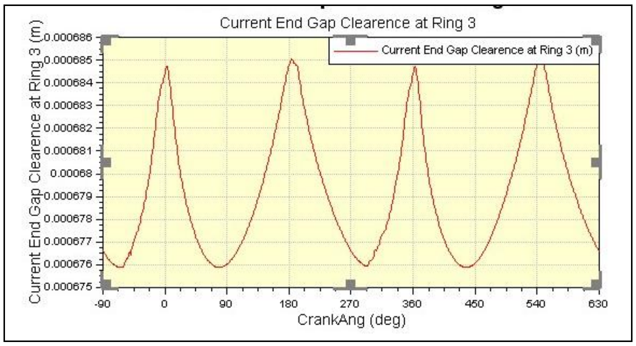

Fig.9 Ring cap variation for 3rd Ring

From above figures it is observed that the variation of the ring gap is uniform throughout the cycle and there is no abnormal gap variation during the transition of piston from TDC to BDC.

All these only happens only if:

- Improper Ring Seating
- Non Uniform cylinder pressure on the ring surface
- Distortion of bore is not acceptable

As the all ring gap variation is uniform, all above problems are not related to this case. The ring pack optimized for this engine is suitable for the final simulation.

2. Inter Ring Pressure:

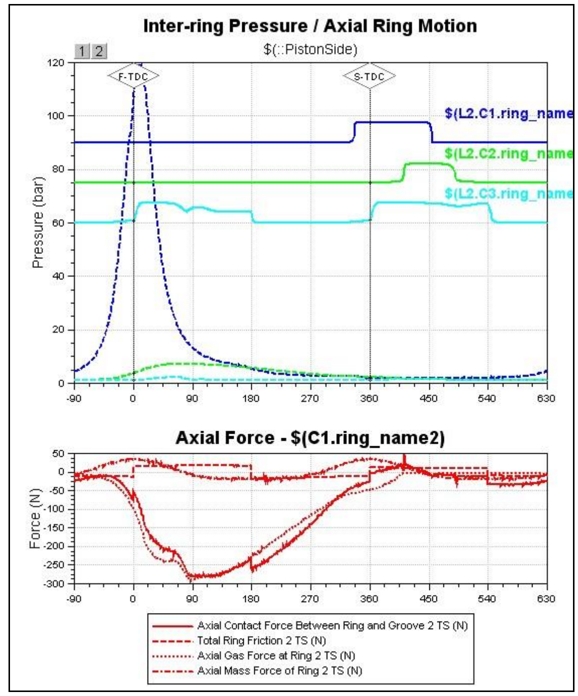

Fig10. Inter-Ring Pressure

The inter ring pressure is nothing but the cylinder pressure acting of the surface of the ring and the behavior of the ring during the engine operating condition. From above figure it shown that there is no any abnormal ring lift or the breakage of the ring is possible. The interring change in the pressure is observed in last ring, but as the profile is uniform, so this is in acceptable range.

3. Ring Twisting Angle

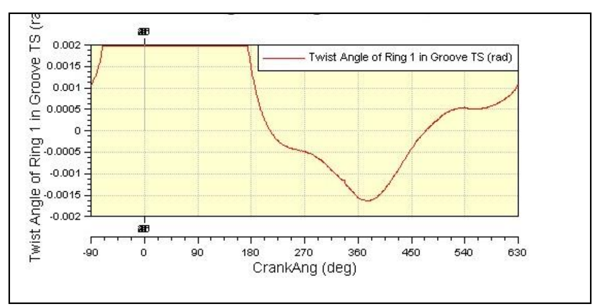

Fig.11. Ring Twist for 1st Ring

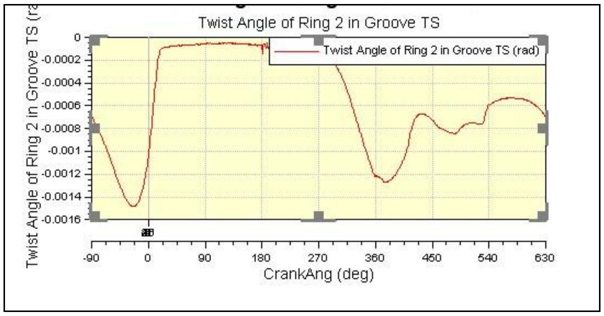

Fig12. Ring Twist for 2nd Ring

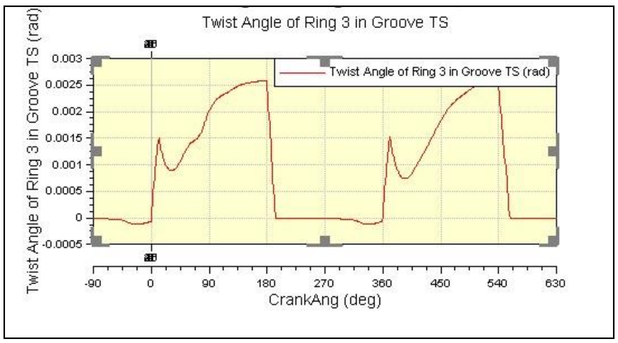

Fig13. Ring Twist for 3rd Ring

The ring twisting phenomena shows the performance of the ring inside the grove. In general the ring twisting is very much important from the fatigue life point of view. The variation into the twisting of the ring brings failure. If we observe the variation in the twist angle is very much uniform and this is well within acceptable limit.

The non-uniform twisting of the ring decreases the uniform contact of the ring with liner; this causes the increase in the blow-by. Fig 12 and Fig 13 shows the twisting angle of the ring in dynamic condition with respect to crank angle. The cumulative value of the twisting is 0.002 to -0.0015 rad. This is very small and is acceptable range.

B. BLOW-BY Results

Blow-by is nothing but the unburnt gases leaked through piston rings during the engine operation. The estimation of blow by is very much difficult due to its dependency on the various parameters. Some of the parameters are listed below:

- Cylinder Bore distortion
- Ring Dynamics
- Dynamic behaviour of engine
- Piston and Ring Design

As the cylinder pressure value depends on the torque condion of the engine. The engine which is selected for this study is off-road application. The off-road application engines runs amximum time for peak torque condition. So the simulation is carried out for the measured cylinder pressure at 1400 RPM.

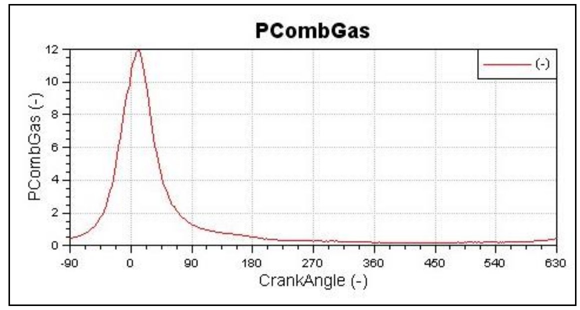

Fig.14 Cylinder Pressure Vs Crank Angle Data at 1400 RPM (Scale for Y Axis is P x 10 bar)

The maximum cylinder pressure observed was 120 bar. Following are the measured values of Engine-blowy in LPM

Table 3: Measured values of BLOW-BY

Speed of Engine	**Measured Blow-by in LPM**
2000	57.47
1800	62.36
1600	58.7
1500	55.6
1400	52.4
1300	53.7
1200	45.4
1100	40
1000	45

Below graph shows the variation of blow-by with respect to crank angle:

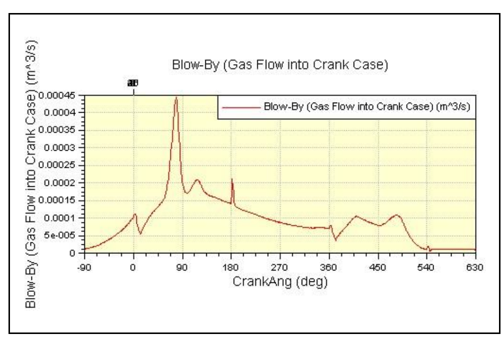

Fig 15 Simulated Results of BLOW-BY @1400 RPM

The average value of the Blow-by throughout the crank angle and the respective cylinder pressure is 0.0002 m^3/s, i.e. 12 LPM/cylinder. So for 4-cylinder engine the cumulative value of the blow-by is 48LPM @1400RPM.

Table 4: Simulated Results of BLOW-BY

Sr. No	Speed of Engine	Simulated Value	Measured Blow-by in LPM	% Variation
1	1400	48	52.4	8.4

The estiamated value of the blow by is matching with the measured values of the blow-by within 10%.

V. CONCLUSION

A description of the ring and gas forces, as well as the effects of the moments during the engine cycle, is introduced to predict ring dynamics. It is clearly apparent that the effects of ring dynamics are much more helpful by theoretical inspection than by detailed engine measurements.

Ring design optimization will drastically improve the mechanical efficiency, Lub-oil consumption and ENIGNE BLOW-BY. As the poor design rings will drastically increase the engine blow by and will also cause the contamination of the oil in minimum time. This will reduce the oil change interval. This is the additional cost to the end user and will also hamper the life of product. To improve the oil change interval and to reduce the engine BLOW-BY it is very much important to optimize the ring design of the piston pack.

To optimize the ring designs it is necessary to know the fundamentals of ring behavior under the different engine conditions. The simulations offer a clear idea for the improvement.

The AVL EXCITE-PR model is prepared depending upon input data available. The evaluation of the simulated results are done with actual tested results of the engine. As the combustion pressure varies with respect to speed, depending on the application we have focused our analysis on two speed, i.e. Max torque and Rated. (1400 RPM & 2000 RPM respectively)

In the simulation of the piston ring to predict the BLOW-BY, we have considered the effect of ring dynamics, ring cylinder bore distortion etc.

The comparison is done between the simulated and measured values of the BLOW-BY. Maximum 10 percentage variation is observed which is well within acceptable limit.

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