Improvement of IC Engine Performance by Piston Ring Design having Temperature Controlled Clearance

Jobin George[1], Gurmeet Singh Gahir[2]

[1]Masters Scholar (Machine Design), Department of Mechanical Engg, Shri Shankaracharya Technical Campus, Bhilai, Chhattisgarh, India
[2]Assistant Professor, Department of Mechanical Engg, Shri Shankaracharya Technical Campus, Bhilai, Chhattisgarh, India

Abstract: ***Piston rings and cylinder wall has a snug fit in modern passenger/commercial vehicles to provide an efficient seal but in Formula One Race cars, they have more precise machined pistons and almost an interference type fit which helps to produce more power than the same swept volume capacity passenger/commercial vehicles but it does have a detrimental effect which is to start an F1 engine it has to overcome the friction between the cylinder wall and piston rings to do that one needs to preheat the engines and run hot engine oil throughout and F1 also requires a heavy-duty starter motor to start the engine. Because of such costly precision machining and unjustifiable engine ignition method, these are not recommended for passenger vehicles. So, the objective is to design such a piston ring assembly that could have the advantages of F1 car engines but does not have to undergo such a long-time-taking procedure to start the engine. It is done by cleverly designing temperature-controlled piston rings which expand radially when the engine achieves optimum engine temperature so during the cold start stage of the engine, piston rings offer a snug fit hence low cylinder wall friction and as engine temperature goes up, the radial clearance decreases simultaneously thereby creating a more efficient seal.***

Keywords: Temperature-controlled radial clearance, piston ring, Piston-Cylinder Wall Friction, Internal Combustion Engine

1. Introduction

A piston is a cylindrical engine component that slides back and forth in the cylinder bore by forces produced during the combustion process. The piston acts as a movable end of the combustion chamber. The stationary end of the combustion chamber is the cylinder head. Pistons are commonly made of cast aluminum alloy for excellent and lightweight thermal conductivity. Thermal conductivity is the ability of a material to conduct and transfer heat. Aluminum expands when heated and proper clearance must be provided to maintain free piston movement in the cylinder bore. Insufficient clearance can cause the piston to seize in the cylinder. Excessive clearance can cause a loss of compression and an increase in piston noise.

Piston features include the piston head, piston pin bore, piston pin, skirt, ring grooves, ring lands, and piston rings. The piston head is the top surface (closest to the cylinder head) of the piston which is subjected to tremendous forces and heat during normal engine operation.

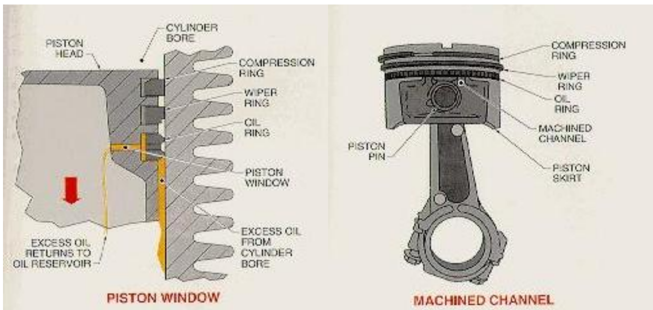

Figure 1: Piston-ring assembly cross-section and component

1.1 Compression ring

The compression ring is the top or closest ring to combustion gases and is exposed to the greatest amount of chemical corrosion and the highest operating temperature. The compression ring transfers 70% of the combustion chamber heat from the piston to the cylinder wall. Most Briggs & Stratton engines use either taper-faced or barrel-faced compression rings. A taper-faced compression ring is a piston ring that has approximately a 1° taper angle on the running surface. This taper provides a mild wiping action to prevent any excess oil from reaching the combustion chamber.

1.2 Wiper ring

The wiper ring, sometimes called the scraper ring, Napier ring, or back-up compression ring is the next ring away from the cylinder head on the piston. The wiper ring provides a consistent thickness of oil film to lubricate the running surface of the compression ring. Most wiper rings have a taper angle face. The tapered angle is positioned toward the oil reservoir and provides a wiping action as the piston moves toward the crankshaft. The taper angle provides contact that routes excess oil on the cylinder wall to the oil ring for return to the oil reservoir. A wiper ring incorrectly installed with the tapered angle closest to the compression ring results in excessive oil consumption. This is caused by the wiper ring wiping excess oil toward the combustion chamber.

1.3 Oil ring

An oil ring includes two thin rails or running surfaces. Holes or slots cut into the radial center of the ring allow the flow of excess oil back to the oil reservoir. Oil rings are commonly one piece, incorporating all of these features. Some on-piece oil rings utilize a spring expander to apply additional radial pressure to the piston ring. This increases the unit (measured amount of force and running surface size) pressure applied at the cylinder wall.

The piston acts as the movable end of the combustion chamber and must withstand pressure fluctuations, thermal stress, and mechanical load. Piston material and design contribute to the overall durability and performance of an engine. Most pistons are made from die- or gravity-cast aluminum alloy. Cast aluminum alloy is lightweight and has good structural integrity and low manufacturing costs. The light weight of aluminum reduces the overall mass and force necessary to initiate and maintain acceleration of the piston. This allows the piston to utilize more of the force produced by combustion to power the application. Piston designs are based on benefits and compromises for optimum overall engine performance

2. Problem Identification

Despite the maturity of modern technologies, we still cannot achieve the efficiency of F1 car's engine for regular passengers due to two key technical issues.

2.1 Tight tolerances

F1 cars engine have very tight tolerances which can't be achieved due to the high cost which will make them not feasible.

2.2 Cold Start

Passenger cars' engines should be able to ignite at the push of a button which is not possible in the case of F1 car's engine as they need a long starting process to run the engine which is not appreciable. It is majorly because the piston and cylinder walls are tight shut and have too much friction between them.

3. Design methodology

The design methodology is to improve the performance of the engine to do that we have designed to control the radial tolerance between piston rings and cylinder. While designing, some of the conditions which need to be met are:

3.1 Cold start

At the time of cold start engine temperature would be close to room temperature so, at that moment, it is required that radial clearance should be more since the engine is trying to bring its temperature to optimum and starting to get to its no-load running condition at that time it is preferred that engine should be able to run with as much ease as possible.

3.2 Running at full load

At full load condition piston temperature may reach up to 200°C so at that time the radial clearance should be kept as low as possible to capture all the rapid expansion of gases.

3.3 Degree of tapered angle

The degree of tapered angle on the piston against which the piston ring slides up defines the relation between thermal expansion and radial clearance. So lesser the degree, the higher will be the change in radial clearance for every µm expansion of the thermal expander

3.4 Material of thermal expander

Material plays a crucial role as the thermal expansion coefficient of material defines the rate at which radial clearance varies as it is directly dependent on the rate of expansion with respect to temperature

4. Working Principle

To reduce the clearance between the compression ring and cylinder wall, some clever design is done. Variable clearance with respect to temperature is achieved by using thermal expansion which expands when there is a rise in temperature which in turn slides the ring against the tapered piston groove.

We know that metals expand when they are introduced to heat, or they may shrink when there is a temperature drop. This property of metal is known as Thermal Expansion and is mathematically expressed as:

Change in length due to thermal expansion = $a * L * \Delta T$….(1)

Whereas

α = Thermal expansion coefficient of the material
L = Length of Material
ΔT = Change in Temperature

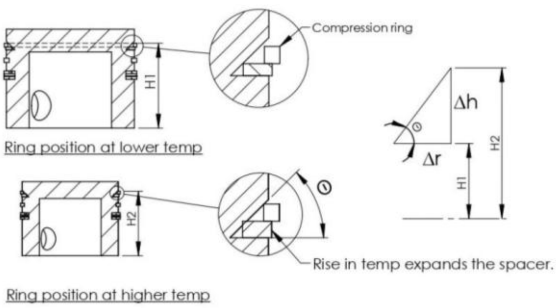

Figure 2: Piston-ring assembly cross section at High and Low temperature

From figure 2, We can say that change in position of compression rings with respect to piston, which is denoted by H1 & H2 can change the diameter of Compression ring. So,

Change in Height, $\Delta H = H1 - H2 = \Delta h$ ...(2)

Let the initial height of the thermal expansion spacer be "h" and degree of tapered grove be "θ"

Now calculating the change in height due to the thermal expansion spacer using equation of thermal expansion:

Change in height i.e. $\Delta h = a * h * \Delta T$ …….(3)

From the figure, it is clear that position of the compression ring will change due to the thermal expansion of the spacer which leads to move the ring and it will slide against the tapered surface of the piston which ultimately leads to the change of diameter of the ring.

The change in diameter of the compression ring is proportional to the change in height, Δh. The diameter of compression rings increases as the ring moves up due to a change in height of the spacer. Considering trigonometrically relation between change in height and change in radius of the ring, we can say:

$$\tan\theta = \frac{\Delta h}{\Delta R} \quad ……….. (4)$$

It can also be written as, $\Delta R = \Delta h / \tan\theta$ ……….(5)

And ΔR can also be considered as a change in radial clearance

So, the new outer diameter of the compression ring will be:-

Día, $Dnew = Doriginal \pm 2 * \Delta R$ …….(6)

Putting the value of ΔR in equation 6

Dia, $Dnew = Doriginal \pm 2 * \frac{\alpha * h * \Delta T}{\tan\theta}$ ... (7)

Note: + or - purely depends on the direction of ring movement i.e., if the temperature rises the expansion spacer expands which moves the ring upwards hence increasing the diameter of the compression ring and if temperature drops; it moves downwards & diameter decreases.

Putting the value of Δh from equation-3 in equation-7 & equation-5

Dia, $Dnew = Doriginal \pm 2 * \frac{\alpha * h * \Delta T}{\tan\theta}$ ... (8)

So the change in Clearance, $\Delta R = \pm \frac{\alpha * h * \Delta T}{\tan\theta}$ … (9)

For making the equation simple we can take out $\frac{\alpha * h}{\tan\theta}$ as constant A. so equation-8 and equation-9 will be:

$Dia, Dnew = Doriginal \pm 2 * const.A * \Delta T$ … (10)

Change in Radial Clearance, $\Delta R = const.A * \Delta T$ … (11)

Const. A = $\frac{\alpha * h}{\tan\theta}$ … (12)

So, we get the following theoretical relation between change in diameter of compression ring, change in radial clearance from equation-10, 11 & 12

From the above equation, we can say that change in clearance can be controlled by the thermal expansion coefficient, and while considering "*h*" as constant.

Below charts show relations between different parameters with changes in radial clearance by taking the rest of the parameters as constant.

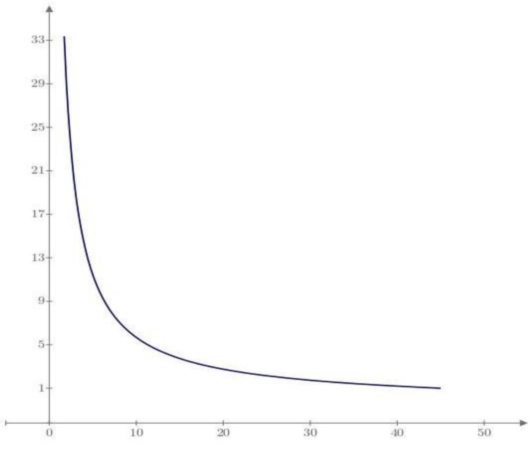

Chart 1: Relation between Changes in radial clearance vs tanθ

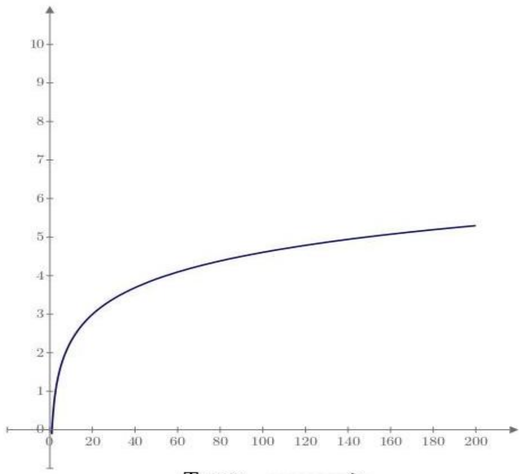

Chart 2: Relation between Changes in radial clearance vs temperature of piston ring assembly

For an example theoretical calculation of piston ring clearance is shown in the below table. The relation between the radial clearance and temperature is formularized before which is $\Delta R = \pm \frac{\alpha * h * \Delta T}{\tan\theta}$

Where,

Thermal coefficient, α = 25.5x10-6 /°C for aluminum

Height of thermal Expander, h = 2mm or 2000µm

Slope Angle, θ = 30°

Table 1: Theoretical Calculation of piston clearance

Piston Temperature	Piston Clearance (μm)	Change in Temp (ΔT)	Change in Clearance (μm)
Cold Start / Room Temp (30°C)	80	0	0
At Transition Temp (110°C)	72.93	80	7.07
At optimum Temp (190°C)	27.93	80	7.07

5. Design of components

Modelling of piston and ring assembly is done in Solidworks 2018, Other than addition of a single part rest of the piston and ring assembly is same. Assembly mainly consists of four components:

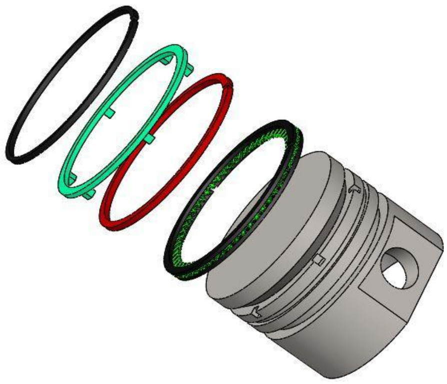

Figure 3: Piston-ring assembly

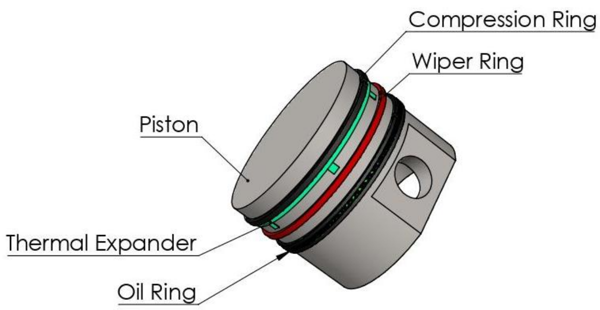

Figure 4: Piston-ring assembly

5.1 Piston

Piston is made of aluminium alloys as done in today's industry, the only change in piston other than the regular is that a precise tapered angle cut is introduced. It is an engine component that slides back and forth in the cylinder due to the rapid expansion and compression of gases.

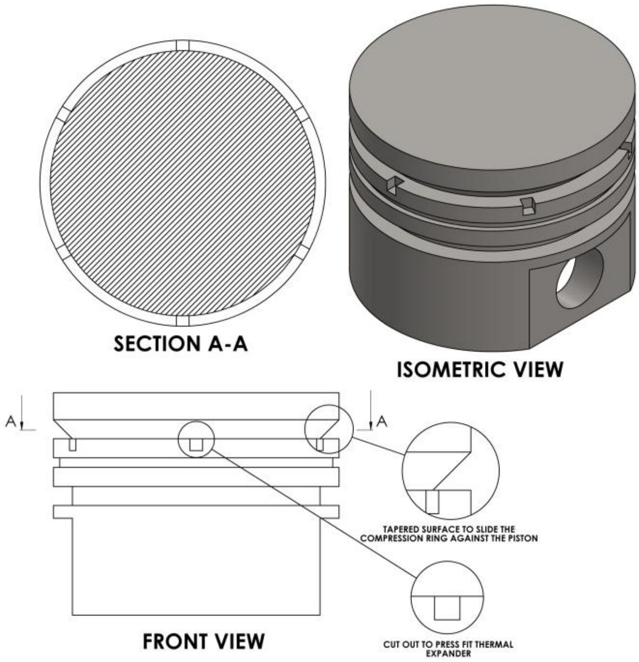

Figure 5: Piston

5.2 Compression ring

The primary role of the top compression ring is to seal off most of the combustion gases to ensure you get the maximum power output from your engine. Any failure or weakening of the piston ring in this area means your engine is working less efficiently than it should. And clearance is required to prevent from engine seize. When the engine temperature rises up, thermal expander rises up it forces compression ring against piston tapered surface.

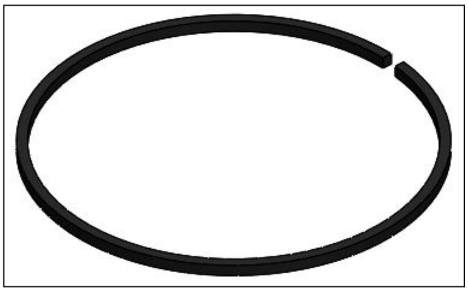

Figure 6: Compression ring

5.3 Wiper ring

The wiper ring used to further seal the combustion chamber and to wipe the cylinder wall clean of excess oil. Combustion gases that pass by the compression ring are stopped by the wiper ring.

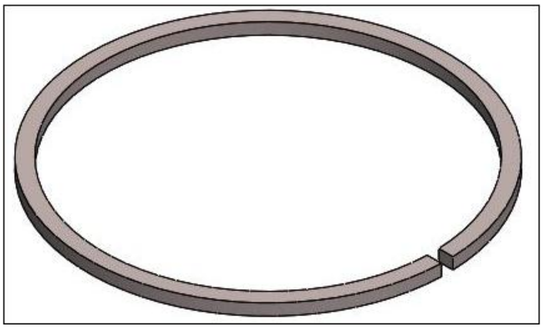

Figure 7: Wiper ring

5.4 Oil ring

Oil ring is a combination of three or more component its primary role is to lubricate the cylinder surface and provide adequate amount of oil to cool piston and cylinder.

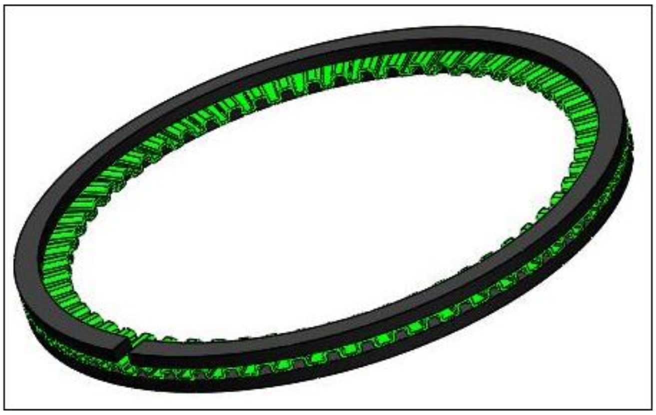

Figure 5: Oil ring

5.5 Thermal Expander

This is the only extra component that was introduced other than that rest of the piston and rings are same as traditional. Its job role is to expand according to change in temperature and in turn move the compression ring upwards which forces the ring to open and that will reduce the clearance between piston and cylinder. The main thing that needs to be consider while designing is the requirement i.e., the material properties such as thermal expansion coefficient plays a vital role. Thermal expander can be press fitted into piston via studs those projects out

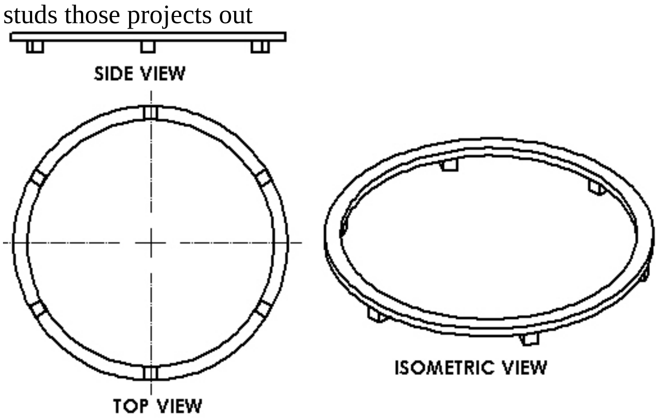

Figure 9: Thermal Expander

6. Conclusion

As of now passenger cars engine are optimized up to its limit but to increase the efficiency of the engine furthermore, we can create seals which could vary with temperature, which will prevent the high friction between the cylinder walls and piston during cold start and taking reference from already existing F1 engines we can say that engines work with these kinds of tight seals.

Taking reference from the graph and conclusion in the journal paper (Mayer 2021.). From this, we can clearly conclude that as the temperature goes up the piston clearance decreases which leads to a decrease in torque hence power-loss

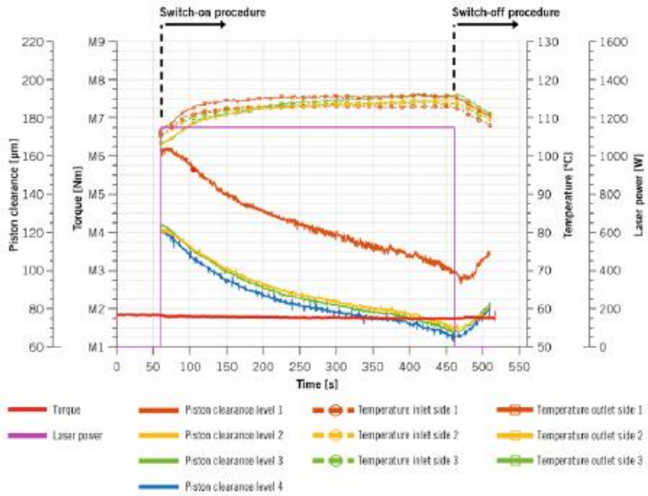

Chart 3: Simulated load steps during OP 1 at hot engine (105^0C) – transient progression of the motored torque, the piston clearances, and the liner temperatures at the respective measuring levels (© Mercedes-Benz AG) (Mayer 2021).

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