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Measurement of dynamic lubricating oil film thickness between piston ring and liner in a motored engine

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ABSTRACT

The interface between the piston rings and cylinder liner plays an important role in total frictional losses and mechanical wear of internal combustion engines and is increasingly coming under scrutiny as legislated particulate emission standards are becoming more and more stringent. The capacitance method is used for measurement of minimum oil film thickness at the piston ring–liner interface in the present investigations. Measurement of capacitance formed between the piston ring and a probe mounted flush with the liner provides an accurate measurement of oil film thickness provided that the region between the probe and liner is flooded with lubricating oil whose dielectric constant is known. This paper presents detailed design of sensor, instrumentation and measurement of lubricating oil film thickness using capacitive micro-sensor. The present investigation is carried out in a motored engine in order to validate the sensor and instrumentation and it can be directly employed in a firing engine also.

The oil film thickness was measured at different speeds at three different locations, i.e. close to TDC, mid stroke position and close to BDC position and the results are accordingly presented in this paper. Lubricating oil film thickness is found to vary between 0.2 and 8 μm in the motored engine. At a particular position, lubricating oil film thickness varies significantly in upward and downward stroke of the engine due to reversal in direction of piston tilt.

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1. Introduction

Oil consumption is a major concern for all engines; however the causes are not clearly understood. In order to be able to design future engines to have low oil consumption levels, a more complete understanding of the mechanisms of oil consumption is required. The objective of this work was to utilize the capacitance probe technique to investigate oil transport and consumption in a motored diesel engine. Understanding the mechanism of lubrication between cylinder liner and piston ring is important for reducing the engine emissions as well as increasing the engine efficiency. Lubricating oil combustion contributes 2–25% (w/w) to the total particulate emission and 16–80% to the extractable organic fraction of the particulates and this can be significantly reduced by controlling the oil film thickness between the piston ring and the liner [1]. To understand transient oil transport, research in last two decades involved measurement of oil film thickness using various methods such as capacitance method, resistance method, inductance method, and optical methods [2–10]. The piston motion, ring profile, liner surface roughness and lubricating oil properties play a very important role in controlling the oil film thickness [11,12]. The oil film thickness is very critical even during lower engine loads since at lower loads, the film thickness is relatively higher and higher amount of lubricating oil gets thrown into the combustion chamber and thus lubricating oil contribution to the particulate formation becomes higher at lower loads. At high loads (near full load), the oil film thickness becomes critical because of very high cylinder pressures which may reach a critical level where a possibility of ring–liner metal-to-metal contact increases. This may have pronounced effect on engine durability.

The importance of the oil film thickness measurements in an engines is not only in the numerical values of the oil film thickness but also it is fundamental to increase the knowledge about the phenomena that occurs in the piston assembly and influences the piston ring and cylinder liner contact and thus the piston ring lubrication. Among the various measurement techniques used for measuring the minimum oil film thickness in engines, the capacitance-based measurement technique has been found to deliver the most reliable results [2].

For measurement of lubricating oil film thickness between piston ring and cylinder liner, a small electrode is installed in the liner

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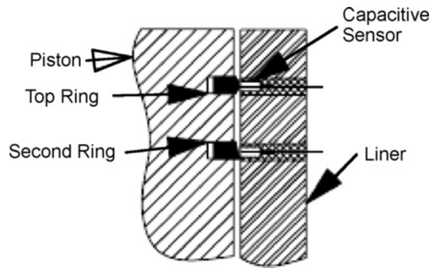

Fig. 1. Capacitive micro-sensors.

of the engine (Fig. 1). A parallel plate capacitor is formed between a small electrode installed in the liner and ring facing the electrode. The surface of this probe is honed flush with liner surface so that it does not cause any undesirable distinctively separate ring–liner interaction. This probe acts as a plate of capacitor. The facing area of the piston wall or ring surface in front of the probe acts as other plate of the capacitor. The separation distance between piston land and electrode varies as different parts of the piston ring assembly come in front of electrode with the reciprocating motion of the piston leading to change in capacitance thus formed. This change in capacitance is measured using an electronic circuit which converts the change in capacitance to change in voltage. This signal is recorded using a high-speed data acquisition system for data interrogation.

This method however has a limitation. The engine lubricating oil has a fixed dielectric constant and if the composition of the oil changes because of any reason (such as vapour trapping, air trapping, moisture trapping, etc. in the lubricating oil), its value will change and the sensors will over predict the oil film thickness. However since there is no other sensor, which can survive harsh environment as that of an internal combustion engine (>200 °C temp., 70–90 bar pressure, ≅10 m/s sliding speed), these errors can be ignored.

Further to these investigations, optical measurement techniques such as laser induced fluorescence technique need to be employed for more accurate measurement of oil film thickness at the ring–liner interface and the capacitance probes can be used to calibrate the LIF data under fully flooded conditions (at ring-reversal zone), where one can be reasonably sure that there is no air/vapour trapped in the lubricating oil.

2. Design of capacitance probe

The capacitance (C) of two infinite parallel conducting plates change as separation between them is varied as

$$C = K\varepsilon_0\, A/d$$

where K is the dielectric constant of medium between the parallel conducting plates, ε_0 is the permittivity of free space, A is the facing area of the two plates and d is the separation distance between the two plates of the capacitor formed. Piston of the engine is grounded and hence one plate of this parallel plate capacitor is grounded. This arrangement forms two parallel plate capacitors between ground and electrode. One capacitor forms between the electrode and the piston ring and another form between back-side of the piston ring and the piston [2]. These two capacitors appear in series to give the overall capacitance C_{total} which can be determined by the following equation:

$$\frac{1}{C_{\text{total}}} = \frac{1}{C_{\text{probe}-\text{ring}}} + \frac{1}{C_{\text{ring-piston}}}$$

However the plate area of the second capacitor ($C_{\text{ring-piston}}$) is very large (for present engine and sensor approximately 600 times) as compared to the first capacitor hence the second term in above equation becomes negligible, hence

$$C_{\text{total}} \approx C_{\text{probe}-\text{ring}} = \frac{K\varepsilon_0 A}{d_{\text{probe}-\text{ring}}}$$

2.1. Fringing of electric field

If the distance between the parallel plates is large enough then the fringing effect of electric field (converging of electric field lines at the edge of plates) can be neglected. In most of the region between the plates, the potential varies almost linearly from one plate to the other. Only near the edge of the plates, and in the regions near the outer surfaces of the plates, the electric field begins to bulge out into the universe at large so that the contours are spaced considerably further apart on the outsides of the plates than on the insides. Thus the total charge on each plate depends mostly on the field in the region between the plates. As the plates get closer and closer together, this effect becomes even more pronounced, and the charge on the outer surfaces becomes negligible compared to the charge on the inner surfaces. Furthermore, the fringing of the field at the edges of the large plates becomes a negligible part of the field structure, since it affects such a tiny part of the total plate area. The ideal formula is based on the assumptions that the charge on the outside of each plate is negligible, and that the effect of fringing can be neglected.

When plates move further apart, the contours of constant potential form ovoid around the plates; and the ovoid bulge out a bit more on the outsides of the plates than on the insides, suggesting that there is slightly more charge on the inner surface of each plate than on the outer surface. Under these conditions, the capacitance is much larger than what would be calculated from the ideal parallel plate formula.

As the distance between the plates increase even further, the ovoid become increasingly symmetrical, until they approach ellipsoids. At the limit, the plates cease to interact at all, and each plate holds a charge based only on its potential with respect to the surrounding space. Thus, as the equi-potentials approach ellipsoids, the capacitance approaches a constant value that is independent of further increases in plate distance. So from the above qualitative description of fringing effect, importance of this assumption is highlighted. It is concluded that measurement is accurate for smaller separation distances but not for larger separation distances between the ring and the liner.

Errors arising due to neglecting the fringing effect can be reduced by placing a shield around the probe electrode. This shield is put at same potential as the main electrode. Electrical insulation is maintained between the shield and the electrode. Now electric field lines start diverging after the shield hence parallel plate formula can be applied without significant error.

2.2. Composition of lubricating oil

For using parallel plate formula, it is assumed that region between ring and liner is fully flooded with oil, and oil is free from voids and bubbles. Presence of voids, bubbles and dissolved gases may change the value of dielectric constant. This assumption makes the magnitude of dielectric constant higher than actual value and hence over predicts the separation distance at certain locations. The actual value of K also depends upon the ratio of oil and air between rings and probe, since in most situations; the ring gap is not fully flooded with oil.

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