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The influence of lubricant degradation on measured piston ring film thickness in a fired gasoline reciprocating engine☆

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ABSTRACT

A laser induced fluorescence system has been developed to visualise the oil film thickness between the piston ring and cylinder wall of a fired gasoline engine via a small optical window mounted in the cylinder wall. A fluorescent dye was added to the lubricant in the sump to allow the lubricant to fluoresce when absorbing laser radiation. The concentration of the dye did not disturb the lubricant chemistry or its performance. Degraded engine oil samples were used to investigate the influence of lubricant quality on ring pack lubricant film thickness measurements. The results show significant differences in the lubricant film thickness profiles for the ring pack when the lubricant degrades which will affect ring pack friction and ultimately fuel economy.

1. Introduction

With the drive towards better energy resource utilisation and an improved environment, current automotive engine tribology research is geared towards reduced pollutant emissions and improved efficiency. A large proportion of the internal friction of an engine is due to the piston assembly, comprising the piston ring pack and the piston skirt, and the lubricant in the ring pack also plays a vital role in exhaust emissions control [1,2]. Demands on the engine lubricant to help improve engine efficiency are becoming more intense and recent engine technology, such as engine downsizing and stop start functions, are increasing the stress on modern engine lubricants. Consequently, there is a growing need to investigate the influence of lubricant degradation on the tribological behaviour of the engine. The trend to use less viscous lubricants to reduce engine frictional power loss, whilst still maintaining engine wear protection over long oil drain intervals, is further exacerbating this need.

Typically, 12% of the available fuel energy is wasted as engine friction, with 25% of this total attributed to the piston ring pack [1]. Lubricant has been observed to be most degraded in the piston ring pack, especially around the top compression ring, due to the higher pressures, interaction with the combustion gases and higher temperatures in this region compared to the sump and elsewhere in the engine [3,4]. As the lubricant degrades, a change in the chemistry, in terms of additive depletion, oxidation and nitration [5,6] and the viscosity [7,8] results and these parameters can alter the lubricant film thickness experienced by the piston ring and thereby the piston ring friction. Oil film thickness (OFT) measurements of the lubricant between the piston ring and cylinder wall have been of great importance in the past to help validate mathematical models and provide information on the ring pack tribological performance.

There is little detailed knowledge of how the degradation of the engine lubricant with time, primarily by oxidation, affects the tribological behaviour within the piston ring pack and thereby impacts upon fuel economy and durability. A better understanding of this evolution in performance could be used to optimise lubricant oil drain intervals and thereby reduce lubricant waste and maintenance costs. The lubricant film thickness between the piston rings and the cylinder wall is fundamental to these crucial parameters.

Laser induced fluorescence (LIF) has been applied to measure lubricant film thickness between a piston ring pack and cylinder wall in a fired gasoline engine with lubricant ageing as a key factor alongside global engine operating conditions such as load, speed and temperature. The LIF measurement technique has been used in the past to measure films for fresh lubricant [9–12] but rarely for degraded lubricant because of poor optical response. To date, there have been three main methods used experimentally to quantify the piston ring OFT; electrical methods, LIF or the more recent ultrasound techniques, the latter being the only technique which is truly non-intrusive.

Electrical film thickness methods can either be conducting using

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☆ This research study was done independently at the University of Leeds when Rai Singh Notay was completing his PhD studies and now works for Lubrizol Corporation. This research study is in no way associated with Lubrizol Corporation.

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electrical resistance and inductance transducers or capacitive. For resistance methods, by electrically insulating the piston ring from the rest of the piston and allowing an electric current to flow between the piston ring and the cylinder wall and measuring the resistivity, it is possible to obtain information on the lubricant film thickness [13–15]. The electrical resistance measured is proportional to the film thickness and a thicker film consequently produces a greater resistance. However, with such an examination of the films, a smooth plot of resistance against crank rotation is not easily observed. When the ring contacts the cylinder wall a short circuit is experienced and a complete breakdown of the films is observed at top dead centre (TDC) and bottom dead centre (BDC) where boundary lubrication results [16]. Alternatively, the distance between the piston ring and the cylinder wall can be measured with inductive transducers to give a measurement for the lubricant film thickness present. These transducers work on the principle of induction of a magnetic material where the separation between a wire coil and a magnetic material is dependent on the inductance [16]. One of the first reported lubricant film thickness measurements by the capacitance transducer method was achieved by Hamilton and Moore in 1974 [17,18]. Lubricant film thicknesses between 0.4 μm and 2.5 μm were measured in a Petter AV1 diesel engine speeds from 900-1500 rpm with capacitance transducers mounted in the liner. It was found that lubricant cavitation provided an exaggeration of the film thickness. Moore later continued this research [19–22] with the lubricant film thickness between the piston ring and wall determined by measuring the electrical capacitance of the interface [19], using a similar technique of parallel plate capacitance as done earlier by Hamilton and Moore [17,18]. Moore stated that for thin films between 0.1 μm and 1.0 μm the capacitance method could be accurately calibrated using the simple parallel plate formula. Greater than 1.0 μm and it was necessary to calibrate the system through other means, since the fringing field of electrons diverges the signal from theory [19]. Measuring lubricant film thickness with a capacitance transducer requires the dielectric constant of the lubricant to be known for correct calibration. As the lubricant degrades, the dielectric constant of the lubricant changes and as a result any existing calibration would not be valid. Also, the small transducer, and consequently small electric wires, did not survive for long periods due to the harsh environment of extreme temperature and pressure. Thermal expansion of the transducer wires and the glue used to hold the wires, to either the liner or the piston, caused reliability issues with transducers failing after short periods. During engine run-in, Moore [19] found that the signal was very random and erratic, which was found to be caused by short circuiting between the cylinder wall and the ring, as the lubricant films became thin enough to cause contact between the combined surface asperity heights. Shin et al. [23], struggled to get any signals and it was found that coating the transducers with aluminium oxide improved signal to noise ratio and reliability. Even though the technique can have its problems, there has been some success in the use of capacitance transducers. In a recent paper, Söchting and Sherrington [24] investigated the effect of engine load and lubricant viscosity on the minimum oil film thickness experienced at the piston ring to cylinder wall interface. It was found that the use of thinner lubricants generally provided a reduced minimum film thickness at the piston rings and the change in load had less of an effect than the change in viscosity. Similar results of the impact of engine load on oil film thickness were also observed by Tamminen et al. [25] and Takiguchi et al. [26]. Advances in capacitance transducer technology has led to responsive, accurate and low noise sensors that are insensitive to temperature changes being used in a fired engine and has simultaneously allowed the mapping of oil film thickness changes with ring twist to be measured [27].

Laser induced fluorescence (LIF) measurement of lubricant film thicknesses between the cylinder wall and the piston ring was first conducted by Ting in 1980 [28] and many subsequent followed [9,10,12,29–37]. The principle uses laser light which absorbs in oil that has been doped with a fluorescent dye. The oil fluoresces at a different wavelength to the carrier signal and this return beam is converted into a voltage signal by using photomultiplier tubes. The intensity of the signal is related to the film thickness [29,34] for a given lubricant and dye. The natural florescence of the lubricant has been examined for film thickness measurements without the use of a dye by Brown et al. [37], but the signal intensity would be too weak with degraded lubricants. The success of LIF lies in the calibration. In the past, researchers have etched grooves of known depths in the piston skirt as a means of calibration in situ, as Seki et al. [33], but Dearlove suggested that this method is ineffective since the grooves will wear [30]. Other researchers [29,34,38] have used lubricant samples of known film thicknesses statically and ex situ to calibrate the system. Initially, LIF was used as a means to achieve film thickness measurements [10,28,29] but it was clearly seen that the system had the potential to investigate lubricant transport within the ring pack. The common system of shining a laser beam through the liner was criticised [26,36,39] for only providing information at one point and not valuable information about the oil film variation for the entire piston ring – cylinder wall interface, as the capacitance method was capable of doing when transducers were mounted in the ring [23,26]. This led to the introduction of multipoint LIF investigations, whereby multiple LIF probes were used at various positions on the cylinder liner to improve the understanding of the oil film profiles axially and radially around the piston [9,34,40]. The benefit of this outweighs the additional cost in extra probes and photomultiplier tubes, as Takiguchi et al. [34] found that a considerable amount of oil is supplied to the oil control ring at TDC for completion of the compression and exhaust strokes on the thrust side of the cylinder liner, and only at the end of the exhaust stroke on the anti-thrust side. Further improvements in multipoint LIF have seen a two dimensional LIF system being developed at Massachusetts Institute of Technology, USA by Thirouard et al. [39,41].

LIF as well as capacitance film thickness measurements do have their limitations. They both cannot cope with lubricant cavitation, as both techniques require a lubricant film to be present so that a measurement can be made, and as a result anomalies are recorded.

Recently, a novel method of using ultrasound to measure the lubricant film thicknesses has been developed [42–47]. The method involves transmitting and measuring reflecting ultrasonic pulses between different densities of materials. The more different the densities of the materials, the more ultrasound signal will be reflected from their interface. So, if there is a film present between two solids, an ultrasonic pulse, directed at the film, will reflect from it. This offers a sensitive method of lubricant film thickness measurement, without the invasive approach of electrical transducers and LIF systems. The nature of the reflected pulse is proportional to the stiffness of the film and the film thickness can be determined from the stiffness, provided the acoustic characteristics of the film medium are known [46,47]. When investigating lubricant films between the piston ring and cylinder wall, this method uses an ultrasonic transducer attached to the outside of the liner. The transducer continuously pulses and any reflected pulses, from the piston as it passes, are recorded and analysed using Fast Fourier Transform analysis to determine the film thickness. This technique is capable of measuring thin films from 2 to 21 μm [42] which is respectable when compared to capacitance and LIF techniques. Through strict calibration even thinner films between 0.5 and 1.3 μm have been reported [47].

The ultrasonic method relies on the stiffness of the lubricant being known, similar to the dielectric constant that is need for capacitance transducers. These both rely on the lubricant being isotropic, as they are bulk parameters. There is some argument that the stiffness of the lubricant, and hence the bulk modulus and the dielectric, changes during operation when ring dynamics are considered and at the dead centres where ring reversal takes place and piston frictional forces are greater. The ultrasound technique can however detect some cavitation of the lubricant, since the method can detect lubricant and air (cavitation). The reflection can only take place off either the piston ring, for