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Influence on friction from piston ring design, cylinder liner roughness and lubricant properties

Markus Söderfjäll [a,*], Hubert M. Herbst [b], Roland Larsson [a], Andreas Almqvist [a]

[a] Division of Machine Elements, Luleå University of Technology, SE-971 87, Luleå, Sweden
[b] Scania CV AB, Södertälje, Sweden

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ABSTRACT

The piston rings are responsible for a large portion of the fuel consumption in heavy duty diesel engines. In this work a high speed component test rig for evaluation of piston ring friction is used. A number of different piston rings and cylinder liners are evaluated based on their friction performance. Shear thinning of typical multi grade oil is investigated by comparing it to single grade oil. Experimental simulation of higher speeds by decreasing the viscosity is evaluated. A method for indication of effects on oil consumption, without combustion, for different oil control rings is presented. Finally, a numerical simulation model for the oil control ring is validated by comparing the friction predicted with the model to the experimental results.

1. Introduction

Increasing demand for reduced fuel consumption is driving the vehicle manufacturers towards more optimisation of their components and systems. Frictional losses in a heavy duty diesel engine (HDDE) significantly contribute to the fuel consumption of a truck. According to Holmberg et al. [1] 180 billion litres of fuel are used to overcome friction in heavy duty vehicles every year. Friction losses in the engine are responsible for 4–15% of the fuel consumption [2,3]. The losses from the power cylinder unit (PCU) are responsible for approximately half of those frictional losses. Included in the PCU are the piston with rings in contact with the cylinder liner and also the connecting rod. The piston with rings is responsible for approximately 75% of the losses, where the piston rings are responsible for more than half of those losses. Therefore there is great potential for reduction of fuel consumption by improvement in the piston ring to cylinder liner interface. In order to reduce these losses the interaction between piston ring and cylinder liner needs to be well understood. Tools for evaluating different friction reduction concepts need to be developed and used properly in order to achieve understanding of the system. Simulation models can be a fast and inexpensive way to do the investigations but accuracy of such need to be experimentally evaluated [4]. A great number of experimental studies on friction reduction possibilities have been made previously. However, many of them have been performed in low speed test rigs. These are best used for investigation of operation close to reversal zones where the influence on friction power loss is negligible, such as the work by Obert [5]. Rejowski [6] showed that by replacing the conventional cast iron liner with a DLC coated cylinder liner, one can reduce friction by 2.5% at low engine speeds. This claimed to be because of reduced amount of mechanical, metal - metal, friction. Sato [7] also showed friction reduction by DLC coated cylinder liners. It was claimed to be because of less axial scratches created in the harder DLC compared to a cast iron liner thus providing better state of lubrication. Sato also showed that a rough surfaces can be beneficial for friction in the mid stroke region under some specific conditions. Spencer et al. [8] investigated a top compression ring in contact with different liner variants in a Plint reciprocating tribometer. They found that smoother cylinder liner surface could provide lower friction. The test conditions were numerically simulated and good correlation was found at some operating conditions. Liao et al. [9] investigated the friction of a twin land oil control ring (TLOCR) with various tangential loads at different temperatures in a floating liner test engine. In Refs. [10] and [11] the same floating liner test engine was used and the results were compared with a simulation model. It was found that by selecting the surfaces used in the simulation model carefully, decent correlation could be found. Difficulties regarding measurement of piston ring friction in the floating liner engine were discussed. The lateral stops and friction from the piston makes it difficult to extract friction from the piston ring only. This is not an issue with the test rig used in this work since the piston ring holder is linearly guided and thus only the piston ring is contacting the cylinder liner. In the work by Akalin and Newaz [12] a model for top

* Corresponding author.
E-mail address: markus.soderfjall@ltu.se (M. Söderfjäll).

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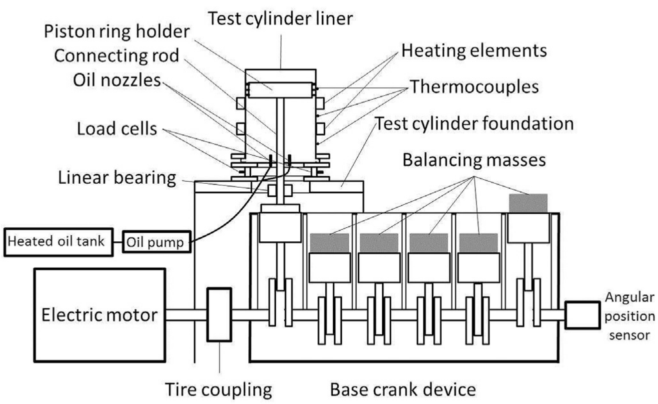

Fig. 1. Schematic view of test rig.

Table 1
Piston rings used in the investigation.

ID	Piston ring	Type	Ring tension (N)
TCR1	Standard Euro 6	TCR	33.2
TCR2	DLC coated	TCR	30.2
SCR	Standard Euro 6	2nd CR	25
OCR1	Standard Euro 6	2 piece OCR	56
OCR2	Stepped land	2 piece OCR	28.3
OCR3	DLC coated	2 piece OCR	27
OCR4	Loose rails	3 piece OCR	65.2

compression ring friction developed in Ref. [13] was validated. The correlation between simulation and experiments showed the same trends for roughness and load variation. However, the predicted friction force differed some from the measured value. Gore et al. [14] also validated a simulation model of top ring friction with a floating liner motorcycle engine. The results showed that the model needed further development. The simulation model used by Gore et al., Akalin and Newaz and Liao and Chen uses the same contact model, the well-known Greenwood - Tripp model, which uses statistical parameters of a surface to estimate asperity contact pressure as a function of separation, called stiffness curve. The contact model used in this work calculates the stiffness curve for the actual surface measurement. In addition it includes elastic deformation of the ring cross section and motion of the ring inside the piston ring groove caused by inertia and friction forces. In the work by Hoshi et al. [15] a numerical tool was used, small differences in friction power loss were found when comparing motored pressure less conditions to fired conditions. Deuss et al. [16] used the FMEP method for comparison of fired operation and externally pressurised combustion chamber tests. It was concluded that the top compression ring is subjected to the vast majority of effects by combustion pressure. They also showed that external combustion pressure in the form of compressed air shows the same difference in friction when varying the height of the top compression ring. Effectively this means varying ring load which is well represented by external pressure. However, when evaluating the engine fully this was said to be the only type of test where external pressure testing is applicable since heat from the combustion will influence the result. It was shown that FMEP was mostly dependent on speed and almost no dependence on load was found when running the engine with combustion. In the tests with external pressure a high dependence for FMEP on load and speed was found. The same relation was found in the work by Allmaier et al. [17] who also used the FMEP method to measure friction on a 13 L heavy duty diesel engine and compare fired operation to motored operation with externally pressurised combustion chamber. When running fired tests and varying the load from approximately 30%–80% almost no influence on FMEP was found. Interestingly, in general FMEP is a function of load and was found to be close to symmetric at around 50% load. This means that similar FMEP was found at low load (<30%) increasing with decreased load and at high load (>80%) increasing with increased load. This was concluded to be an effect of increased oil temperature in the contact due to combustion. Also Allmaier et al. showed that when running with externally pressurised combustion chamber FMEP was significantly affected by the load which again suggests that external pressure is good for isolating the effect from top compression ring loading but not for representation of combustion effects. Kunkel et al. [18] run motored tests with a passenger car engine modified for floating liner measurements to investigate run in of twin land oil control rings. It was also here shown that in general, combustion has a secondary role in friction losses for the oil control ring; its friction power loss is mainly dependent on oil viscosity, tangential load and speed. Kunkel stated that when focusing on oil control ring friction tests are usually made in motored conditions because of the difficulty in repeatability otherwise. This is the approach used in this work, as the test equipment does not include any combustion or other external pressures for loading of the compression rings. Because of conclusions from previous work mentioned in this section, the method used in this work could be seen as an appropriate way of evaluating friction for the entire ring pack. However care must be taken when analysing the friction force from the compression rings. Previously mentioned work has shown that operation at low pressure without combustion will result in friction power similar to fired highly loaded conditions. However, the lack of heat and high pressure from combustion will result in different conditions. For evaluation of oil control ring friction, the pressure less condition is, as earlier mentioned, an appropriate approach.

There are few previous studies where effect on TLOCR friction by different ring geometry and tangential load were investigated. To the authors knowledge no studies exists where the friction of piston rings were measured without influence from the piston at engine like speeds. In this paper, this is investigated by utilising experimental equipment developed by the authors in Ref. [19]. An extensive primarily experimental study was performed for several investigations:

- Friction measurement for a number of different piston rings and cylinder liners at different speeds,
- Effect on oil supplied to the top compression rings by changing the tangential load of the oil control rings,
- Accuracy of simulating different speeds in the experiment from varying the lubricant viscosity with temperature,
- Shear thinning effect of multi grade oil by comparing its frictional performance to single grade oil at similar Hersey parameters, and
- Validation of a numerical simulation model developed by the authors [20].

2. Method

This section describes the test method and it also lists the components which were investigated and the operating conditions used. A number of different piston rings and cylinder liners were investigated at a few operating points. Then, two selected component combinations and two different oils were tested at several operating conditions in order to produce Stribeck like curves.

2.1. Test equipment

In this work the test equipment developed and described by the authors in Ref. [19] was used. A schematic view of the test rig can be seen in Fig. 1. The rig consists of an inline six cylinder engine block acting as a base crank device. On one of the pistons in the base crank device, a rod