Effect of cylinder deactivation on tribological performance of piston compression ring and connecting rod bearing

N. Morris a, M. Mohammadpour a, R. Rahmani a,b,*, P.M. Johns-Rahnejat a, H. Rahnejat a, D. Dowson b

a Wolfson School of Mechanical, Electrical and Manufacturing Engineering, Loughborough University, Leicestershire, UK
b School of Mechanical Engineering, University of Leeds, Leeds, UK

ARTICLE INFO

Abstract

Thermo-mixed-hydrodynamics of compression rings and big-end bearings are presented. Frictional losses under normal engine operating conditions for a gasoline engine and those with cylinder deactivation (CDA) are predicted. With CDA, the combustion chamber pressure increases in the active cylinders, whilst some residual pressure remains in the deactivated ones. For the former, the increased in-cylinder temperatures reduce viscous friction, whilst reducing the load carrying capacity, promoting increased boundary interactions. In deactivated cylinders, lower contact temperatures yield increased viscous friction. Overall, a 5% improvement in expended fuel is expected with the application of CDA. However, 10% of these gains are expended due to increased friction. The study demonstrates the need to consider total system effects when introducing new technologies such as CDA.

Keywords:
- Cylinder deactivation
- Piston compression ring
- Big-end bearing
- Friction
- Power loss

1. Introduction

Recent years have witnessed the emergence of new technologies for improved fuel efficiency of internal combustion engines. These include, but are not confined to, variable valve actuation (VVA), cylinder deactivation (CDA) and stop-start in congested traffic. CDA is one of the most widely adopted of these energy saving technologies. It varies the number of active cylinders to match the required engine capacity for a desired output power. Therefore, it is most suited to congested traffic or those instances where full engine power is not required. For example, in steady state highway driving when most of the parasitic losses can be attributed to pumping typically only 30–40% of the peak engine power would suffice.

As a result, significant improvement in fuel economy can be achieved for a host of manoeuvres using CDA, primarily because of improved volumetric fuel efficiency [1,2]. Sandford et al. [1] have shown that 20% fuel saving is attainable through the use of CDA.

Overall engine efficiency, given as: $$\eta_{\text{eng}} = \frac{\eta_{\text{th}}}{\eta_{\text{th}} + \eta_{\text{v}}}$$, is typically a product of the indicated efficiencies; mechanical ($\eta_{\text{th}}$), volumetric ($\eta_{\text{v}}$) and fuel conversion (i.e. thermal) ($\eta_{\text{t}}$). It is commonly assumed that mechanical efficiency is independent of system-level changes which improve the volumetric and thermal efficiencies, such as the effect of CDA on frictional performance. As a result, the opportunity to harness the full potential of CDA is rather exaggerated as it disregards the performance of engine tribological conjunctions. Introduction of new technologies, such as CDA, affect the prevailing conditions in the load bearing conjunctions. In addition, the opportunity to refine the tribological conjunctions in order to mitigate any potential adverse effects is somewhat overlooked.

The main contributing factors determining the mechanical efficiency of an engine are pumping, windage and parasitic frictional losses; the last of which is the most significant. The investigation of frictional performance is the subject of the current paper.

Of the numerous bearing surfaces and seals within the internal combustion engine, the piston compression rings and the big-end bearings are the most susceptible to changes in the applied combustion process. During the traditional engine operating conditions (i.e. with all active cylinders; the standard operation mode), piston compression rings and big-end bearings have been shown to account for 5% of the expended input fuel energy [3].

The significant parasitic energy loss associated with the piston ring-cylinder liner conjunction has resulted in over 80 years of continuous research. The transient nature of piston operation with cyclic sliding velocity, loading and thermal conditions continues to pose significant challenges for time-efficient predictions and/or direct measurements of film thickness [4] and generated friction [5–7]. A comprehensive review

* Corresponding author.
E-mail address: R.Rahmani@lboro.ac.uk (R. Rahmani).

Received 26 October 2017; Received in revised form 26 December 2017; Accepted 28 December 2017
Available online 2 January 2018
0301-679X/© 2018 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).
of lubricant film measurement techniques for ring-bore conjunctions is provided by Sherrington [8].

Early analyses included the works of Castleman [9], and Eilon and Saunders [10] who employed Reynolds equation in one dimension to obtain the film thickness at various discrete piston stroke positions. The results were somewhat optimistic, predicting the formation of a full hydrodynamic film throughout the engine cycle. Later, Furuhama [11] advanced the previous analyses with the inclusion of squeeze film lubrication, which can contribute to the retention of a thin, finite lubricant film at piston reversals, where there is no lubricant entrainment. Furthermore, the inclusion of squeeze film motion enables a transient analysis of lubrication conditions to be undertaken. Hamilton and Moore [12] employed the Swift [13] – Stieber [14] boundary conditions to include the effect of lubricant film depletion and rupture. Ruddy et al. [15] considered the influence of direct contact of contiguous surfaces with any diminution of lubricant film. They also included the effect of inter-ringing gas pressures in their analysis. Dowson et al. [16] showed that a preceding ring would reduce the lubricant availability for those following behind in a ring-pack. It was shown that the resulting inlet starvation diminished the oil film thickness. It is now well-established that considerable boundary interactions occur at piston reversals between the compression and the power strokes [17,18]. In fact, Styles et al. [18] showed that frictional losses during this part of the piston cycle can account for more than 30% of the total losses. The prevailing conditions are also affected by the geometry of the ring contact face and its topography [19,20], as well as by the extent of ring-bore conformance during reversal [21,22].

Ring-bore conformance is also affected by elastodynamics of the ring, which is subjected to complex modal behaviour in its radial plane as well as in its out-of-plane motions. Analysis of these motions has been provided by Tian et al. [23,24] showing their effects on wear and oil loss, and by Baker et al. [25–27] who included their effects on loss of sealing, ring jump and blow-by. In practice, compression ring-bore conformance is also affected by a real out-of-round cylinder bore as shown by the analysis of Rahmani et al. [28]. Any non-conformance of the ring to the surface of the cylinder liner can lead to loss of sealing with ensuing power loss and blow-by.

Loss of sealing also causes reduced friction which can cause ring jump and power loss as shown by Namazian and Heywood [29] and Baker et al. [27,30]. This power loss is caused by the flow of gasses through the cylinder-compression ring crevices, rather than through any generated friction. In fact, there is reduced friction with the ring jump phenomenon. Therefore, a balance between sealing function and excess friction in transition between mid-cycle compression and power stroke should be sought.

With CDA, the valves of the deactivated cylinders are closed with residual decreased cylinder pressures. With reduced pressure loading on the piston rings, there would be less direct boundary interaction of contiguous rough surfaces. However, due to the lack of combustion, the instantaneous lubricant temperature would be reduced, and an increased viscous friction would be expected because of higher lubricant viscosity at liner temperatures. Recent investigations, experimental and numerical, have all shown that the lubricant temperature is primarily governed by the cylinder liner temperature [31–34]. Viscous shear is the dominant mode of generated friction for most of the piston cycle as amply demonstrated by many authors [16–19,35,36]. Therefore, in-cylinder frictional losses are not necessarily reduced in the deactivated cylinder; in fact, the only reported study to date points to a contrary conclusion [37] in line with the foregoing discussions. However, the study in Ref. [37] was isothermal. A thermo-mixed hydrodynamic analysis is required, which is the subject of the current paper.

The other load bearing junction of interest is the connecting rod (big-end) bearing, which undergoes severe variations in dynamic loading. Martin and Booker [38] showed that the inertial loading has an appreciable effect on the film thickness. Later, Booker [39] developed a tribo-dynamic method, referred to as the Mobility Method, in order to tackle the dynamic effects in big-end bearings. The approach is detailed by Bodeo [40], together with its practical implications for prediction of conditions in big-end bearings. Bates et al. [41] also presented a theoretical model for dynamic loading of big-end bearings and validated it against experimental measurements. The effect of bearing bushing deformation upon the lubricant film thickness was neglected. The effect of localised deformation of a soft overlay on the bearing bushing was included by Rahnejat [42], who took into account inertial dynamics and gas pressure loading in a multi-body dynamics approach. Temperature rise has a significant effect on the film thickness of big-end bearings. Balakrishnan et al. [43] extended the work of Rahnejat [42] by adding the effect of shear heating for overlay crankshaft bearings. Mishra and Rahnejat [44] reported a thermo-elastohydrodynamic model for big-end bearings, including multi-lobed out-of-roundness of bearing bushing with different roughness patterns such as longitudinal, transverse, isotropic and anisotropic configurations. Wang et al. [45] included the effect of surface waviness of bearing bushing as a multi-lobe geometry, simulating the micro-features of the bearing.

Lubricant cavitation is a major issue in big-end bearings. Aside from cavitation erosion, it also affects the load carrying capacity and frictional performance. Bonneau et al. [46] provided a mass-conserving solution for bearings, which included the effect of structural deformation of the bearing bushing. A comprehensive multi-phase solution for journal bearings was provided by Shahmohamadi et al. [47], including the combined solution of Navier-Stokes, energy and vapour transport equations with modified Raleigh-Plesset equation for finite thin film flow conjunctions. Their numerical analysis was validated by experimental results and then extended to the case of big-end bearings subjected to CDA for a 4-cylinder engine. The predictions showed reduced brake specific fuel efficiency because of the increased frictional losses. The findings agreed with an earlier work reported by Mohammadpour et al. [48], who used a solution for the same engine configuration using Reynolds equation with Swift-Stieber boundary conditions, as well as the energy equation.

This paper provides solutions for a typical cylinder of a 4-cylinder engine, including both the top compression ring-liner conjunction and the big-end bearing with CDA. This integrated approach has not hitherto been reported in the literature.

2. Analysis methodology for piston ring

2.1. Hydrodynamics

To accurately evaluate the frictional power loss from compression ring-liner conjunction a mixed thermo-hydrodynamic analysis is required. The methodology used here is based on the one-dimensional approach presented by Morris et al. [20], where the average flow Reynolds equation is given as [49]:

\[
\frac{\partial}{\partial x} \left( \frac{\rho_x h_x^3}{12 \sigma_x} \frac{\partial P}{\partial x} \right) = -U \rho_x \frac{\partial h_x}{\partial x} + \frac{\partial U}{\partial x} \frac{\partial h_x}{\partial x} + \frac{\partial}{\partial x} \left( \frac{\rho \hat{h}_x}{2} \right)
\]

(1)

where, \( \sigma \) is the composite root mean square (RMS) roughness of the contiguous contacting surfaces and \( \rho \), \( \phi_x \), \( \phi \), are the pressure, shear and contact flow factors respectively, as defined by Patir and Cheng [49] and Chengwei et al. [50] (Appendix 1). The use of a one-dimensional Reynolds equation is justified because the peripheral ring length-to-contact width ratio in this case exceeds 30, as demonstrated by Haddad and Tian [51]. An implication of this is that a fully conforming ring to the surface of an idealised right circular cylinder is assumed. The film thickness at any axial position along the ring contact face-width is given as:

\[
h(x, t) = h_0(t) + s(x)
\]

(2)

The contact frictional power loss and the elevated flash temperature of the surfaces require the inclusion of thermo-piez-viscous behaviour of
the lubricant. In most piston compression ring contacts, the generated pressures are found to be insufficient to cause significant piezoviscous behaviour of the lubricant, as well as any localised deformation of the contacting surfaces [17,19,22,35]. However, for the sake of completeness the piezo-viscous behaviour of the lubricant is included here, using Houppert’s viscosity-pressure relationship [52]:

\[ \eta_t = \eta_0 \exp \left( \left( \frac{\eta_0}{6} + 9.67 \right) \left( \frac{\eta_0}{6} - 138 \right)^{\frac{m}{6}} \left[ 1 + 5.1 \times 10^{-9} \left( p - p_{am} \right) \right]^2 \right) \]  

(3)

where:

\[ S_0 = \frac{\beta (\theta_b - 138)}{\ln \theta_b + 9.67}, \quad Z = \frac{a}{5.1 \times 10^{-9} (\ln \theta_b + 9.67)} \]  

(4)

Lubricant density variation with pressure and temperature is included, using the modified Dowson and Higginson equation [53] to take into account the variation of lubricant density with temperature:

\[ \rho = \rho_f \left( 1 + 0.6 \times 10^{-5} (p - p_{am}) \right) \left[ 1 - 0.65 \times 10^{-1} (\theta_r - \theta_b) \right] \]  

(5)

2.2. Boundary conditions

The current analysis assumes a drowned, fully flooded, inlet which extends to the edge of the ring contact face. However, in reality a starved inlet conjunction is likely due to restriction of oil flow through the ring pack.

The inlet pressure in the upstroke motion of the piston is considered to be the same as the combustion chamber pressure, whilst in the downstroke the inlet pressure is considered to be the crank case pressure.

In a more precise approach, the actual inlet pressure during downstroke should be set to the inter-ring pressure (i.e. the pressure in the area between the compression and the scraper ring). This requires the inclusion of a gas blow-by model such as that reported in Refs. [27,54,55].

At the exit of the conjunction, Swift [13]-Stieber [14] exit boundary conditions are implemented as:

\[ \rho = \rho_r, \quad \frac{dp}{dx} = 0 \text{ at } x = x_e \]  

(6)

where, \( \rho_r \) is the cavitation vapourisation pressure of the lubricant at the location of lubricant film rupture.

The hydrodynamic load carrying capacity is then obtained as:

\[ W_h = \int_{x_k}^{x_e} \frac{dp}{dx} \frac{h dx}{h} = \int_{x_k}^{x_e} \eta_t \Delta U (\varphi_r \pm \varphi_b) \]  

(7)

where the positive and negative signs represent the ring and the liner surfaces respectively. Therefore, viscous friction becomes:

\[ f_v = \int_{x_k}^{x_e} \tau h dx \]  

(8)

where \( A_t \) is the area attributed to hydrodynamic action only, thus subjected to viscous shear.

During parts of the piston cycle where mixed regime of lubrication occurs, a proportion of the load is carried by opposing asperity pairs on the counter face surfaces. The generated asperity load resulting from these interactions is calculated using [56]:

\[ W_a = \frac{8}{15} \sqrt{\pi} (\xi \varepsilon)^{\frac{3}{2}} \sqrt{\frac{\eta}{k}} E A F_{2/1}(\lambda) \]  

(9)

where, \( E \) is the reduced (effective) Young’s modulus of elasticity of the contacting pair, \( \xi \varepsilon \) is the roughness parameter, \( \sigma / k \) is a measure of averageasperity slope and \( F_{2/1} \) is a statistical function for a surface whose uppermost region conforms to a Gaussian distribution of asperity heights. Its value can be evaluated as a function of the gap between the two contiguous surfaces using a 3rd or 5th-order polynomial fit as described in Refs. [33,34].

The contact reaction is thus: \( W = W_h + W_a \). Therefore, the actual contact area of asperity tips can be written as [56]:

\[ A_a = \pi^{\frac{3}{2}} (\xi \varepsilon)^{\frac{3}{2}} A F_{2/1}(\lambda) \]  

(10)

2.3. Friction and power loss

The average lubricant film hydrodynamic shear stress is:

\[ \tau = \pm \frac{\varphi_r h}{2} \frac{dp}{dx} \frac{\eta_t \Delta U}{h} (\varphi_r \pm \varphi_b) \]  

(11)

2.4. Thermal model

A brief description of the thermal model, initially reported by Morris et al. [33], is provided here for the sake of completeness. The rate of frictional energy loss dissipated in the contact is obtained as:

\[ P_r = \dot{Q} = f \Delta U \]  

(13)

The contacting surfaces conduct the generated heat away. In addition, the generated heat can also be convected away by the lubricant film. A diagrammatic representation is provided in Fig. 1.

The model includes a set of defined thermal resistive barriers given as:

\[ R_t = \frac{S}{k r A}, \quad R_c = \frac{1}{h_n A}, \quad R_l = \frac{h_0}{2 k r A}, \quad R_e = \frac{1}{m c_p} \]  

(14)

Fig. 1. Heat partition with the piston ring cylinder liner contact (Morris et al. [33]).
The thermal resistive barriers require the characteristic length $S_f$. For the cylinder liner the characteristic length is a function of the average contact transit time: $2b/\Delta U$. The solution provided by Sharif et al. [60] gives:

$$S_f = \sqrt{\frac{2k_l h_l}{\rho_{l} \epsilon_{l} A \Delta U}}$$

(15)

Unlike the cylinder liner, the ring surface is always exposed to the heat source. When viewed as unwrapped, the rectangular surface characteristic length, $S_{r2}$ can be stated as [61] :

$$S_{r2} = \frac{1}{\pi A} \left( b^2 \sinh^{-1}\left(\frac{b}{R}\right) + b^2 \sinh^{-1}\left(\frac{b}{R}\right) + \frac{1}{3} \left[ R^2 + b^2 - (R^2 + b^2)^{1/2}\right] \right)$$

(16)

A thermal resistance method, portrayed in Fig. 2, can be produced to determine the heat transfer through the bounding surfaces or that carried away by the lubricant film.

Thus, the average lubricant film temperature rise, used to calculate the effective viscosity, is given as:

$$\theta_e = \frac{(\tilde{T}_R + \theta_l) \sum_{i,j=1}^{n} R_i R_j \theta_{e_{i,j}}}{\sum_{i,j=1}^{n} R_i R_j}, \quad i, j \in 1, 2 \text{ and } i \neq j$$

(17)

where, $i$ and $j$ are indices related to the liner and ring surfaces. The temperature rise for each contacting surface is found through an iterative procedure as:

$$\Delta \theta_i = \frac{R_i}{K_i} (\theta_e - \theta_{n_i})$$

(18)

2.5. Method of solution

The solution procedure is as follows:

Step 1: The combined gas pressure loading and the elastic force due to ring tension can be calculated at any crank angle, $\psi$ [28]:

$$F = F_g + F_e$$

(19)

where, $F_e$ is the ring elastic tension which can be calculated using the elastic ring pressure given by: $P_e = \frac{\partial F}{\partial \psi_{e_{min}}}$, and $F_g = 2\pi rb P_g$ is the force generated by combustion gas, $P_g$, applied to the inner rim face of the ring. A more accurate account of gas pressure loading can be obtained through a gas blow-by analysis [27,54,55].

Step 2: The procedure is initialised with a guess for the minimum lubricant film thickness with ambient values used for lubricant viscosity and density, enabling the determination of hydrodynamic pressure distribution using equation (1).

Step 3: The Stribeck oil film ratio and the load share for any asperity contact are determined using equation (9).

Step 4: The nominal clearance (initial minimum film thickness) is adjusted using: $h_{0i}^\prime = (1 + \epsilon^r) h_{0i}^{0.3}$ where the numerical damping factor $\epsilon \approx 0.075$ and $\chi$ is an adjusting parameter given as: $\chi = \frac{W(\psi)}{W(\psi_{max})} - \frac{W(\psi)}{W(\psi_{max})}$ [62], until the contact reaction balances the applied load calculated in Step 1.

Step 5: Friction and power loss are calculated through the use of equations (8), (11) and (12). The frictional power loss is then used to determine the contact temperature rise.

Step 6: The temperature rise in the contact allows the calculation of effective lubricant viscosity and density using equations (3) and (5), which are then used to restart the process at Step 2.

Step 7: The following convergence criteria should be satisfied for generated pressures, load, and effective temperature at any crank angle respectively [28,62]:

$$e_p = \frac{\sum_{i,j=1}^{n} \left| P_{e_{i,j}} - P_{e_{i,j}}^{0.3} \right|}{\sum_{i,j=1}^{n} P_{e_{i,j}}} \leq 1 \times 10^{-6}$$

(20)

$$e_p = \frac{\left| F(\psi) - W(\psi) \right|}{F(\psi)} \leq 1 \times 10^{-3}$$

(21)

$$e_p = \frac{\left| \left[ \frac{\partial F(\psi)}{\partial \psi} - \frac{\partial W(\psi)}{\partial \psi} \right] \right|}{\frac{\partial W(\psi)}{\partial \psi}} \leq 1 \times 10^{-4}$$

(22)

$$e_p = \frac{\left| h_0(\psi) - h_0(\psi - 720) \right|}{h_0(\psi - 720)} \leq 1 \times 10^{-3}$$

(23)

Step 9: When all the convergence criteria are met, the crank angle is updated and the procedure is repeated.

3. Analysis methodology for big-end bearing

Mohammadpour et al. [48] provided details of a big-end bearing analysis approach under CDA. The methodology used here is a condensed version of the same.

3.1. Elastohydrodynamic conjunction

For the case of a short-width big-end bearing with negligible side leakage, Reynolds equation in polar coordinates is:

$$\frac{\partial}{\partial \theta} \left( \frac{h^2 \partial p}{\partial \theta} \right) + 6 \left( \frac{\partial h}{\partial \theta} \right)^2 - \frac{\partial (h \partial p)}{\partial \theta} = 18 \omega \frac{\partial h}{\partial \theta}$$

(24)

The film thickness for an elliptic bore bearing at any circumferential position is given as [48] (see Fig. 3):
\[ h(\theta) = \frac{ab}{\sqrt{a^2 \sin^2 \theta + b^2 \cos^2 \theta}} - r - x \cos \theta - y \sin \theta + \delta \]  

(25)

where:

\[ a = r + e_m \text{ and } b = r + e_w \]  

(26)

\[ x = e_0 \sin \phi \text{ and } y = -e_0 \cos \phi \]  

are the geometric eccentricities of the bushing and the journal centres with an eccentricity of \( e_0 \) and an attitude angle \( \phi \). \( \delta \) is the elastic deformation of the soft bushing overlay such as a layer of Babbitt. The conformal nature of the contact and the relatively low elastic modulus of the overlay enable the determination of deflection using the column method [42]:

\[ \delta = \frac{(1 - 2\nu)(1 + \nu)d}{E(1 - \nu)} \]  

(27)

where \( E \) and \( \nu \) are Young’s modulus and Poisson’s ratio for the soft overlay and \( d \) is its thickness.

![Geometry of elliptic bore big-end bearing](image)

**Fig. 3.** Geometry of elliptic bore big-end bearing (Mohammadpour et al. [48]).

### 3.2. Frictional power loss

Viscous friction acting on the journal is obtained as:

\[ f_v = \int \left( \frac{dp}{d\psi} + \eta \frac{d\omega}{dt} \right) da, \]  

(28)

The asperity contact area can be obtained using the Greenwood and Tripp model [56] already described by equation (9)–(11). Therefore, the total power loss for the big-end bearing becomes:

\[ P_v = (f_a + f_v) \omega \]  

(29)

### 3.3. Thermal model

The bearing analysis employs a similar heat partitioning model to that described previously. The difference is that the bushing and journal are continually exposed to the heat source so the characteristic length for both surfaces can be written as [61]:

\[ S_y = \frac{1}{2A} \left\{ \left( 2\pi r \right) L^2 \sin^{-1} \left( \frac{2\pi r}{L} \right) + L (2\pi r)^2 \sin^{-1} \left( \frac{1}{2\pi r} \right) + \frac{1}{3} \left[ L^3 + (2\pi r)^3 \right] - \left[ L^2 + (2\pi r)^2 \right]^{3/2} \right\} \]  

(30)

### 3.4. Method of solution

The solution procedure is:

Step 1: At any crank angle, \( \psi \), the instantaneous connecting rod angle, \( \phi \) is obtained using equation (31) [63]. The applied bearing load is found using equation (32):

\[ \cos \phi = 1 - \frac{r^2}{2t_i^2} \sin^2 \omega t \]  

(31)

\[ F = \frac{F_x}{\cos \phi} + F_G \]  

(32)

where, \( F_x \) is the inertial loading generated by system dynamics [42]:

\[ F_x = r_c \omega^2 \left( \cos \omega t + \frac{r_c}{L} \cos 2\omega t \right) \]  

(33)

The bearing load in terms of connecting rod obliquity angle is [42]:

\[ F_G = \frac{p_i A_c}{\cos \phi} \]  

(34)

Step 2: An initial guess is made for eccentricity, \( e_0 \) and generated pressures are obtained from equation (24).

Step 3: Lubricant rheological functions are updated from equations (3) and (25).

Step 4: Generated pressures cause localized deflection (equation (27)), thus the thickness of film and the load balance using the convergence criterion:

\[ e_f = \frac{|F - W|}{F} \leq 1 \times 10^{-3} \]  

(35)

Step 5: The initial eccentricity is altered if the criterion is not met. Otherwise, the crank angle \( \psi \) is advanced. This procedure is repeated for the entire 4-strokes of the engine cycle until a cyclic convergence is achieved.

### 4. Engine specifications and input data

A typical 4-cylinder 4-stroke spark ignition c-class vehicle gasoline engine with a capacity of 1.4 L operating at 3000 rpm is considered in the current analysis. The combustion pressure for three possible in-cylinder operating conditions and the average cylinder liner temperature are measured and shown in Fig. 4. One condition refers to the engine operating under standard operating conditions, where all the four cylinders are active. Under CDA two redundant deactivated cylinders have reduced in-cylinder pressures and liner temperatures. The limited pressure variation is due to the compression and expansion of the residual combustion chamber content. The two active cylinders experience higher in-cylinder pressures in order to maintain the engine desired output power. This is accompanied by a rise in the cylinder liner temperature.

The engine geometric, material, lubricant and surface properties are listed in Tables 1–4. The cylinder liner is cross-hatch honed. Additional surface topographical parameters are provided in Table 4. The honing angle of 30° is used.

### 5. Results and discussion

#### 5.1. Results and discussion: piston compression ring conjunction

The minimum lubricant film thickness separating the piston compression ring and the cylinder liner is shown in Fig. 6 for a complete 4-stroke engine cycle. Two engine operating conditions are presented; (i)- standard operation (with all active cylinders) and (ii)- with cylinder deactivation. These results are for a typical cylinder condition. Therefore, with cylinder deactivation the results are presented for both an active
and a deactivated cylinder. The demarcation line between a full hydrodynamic film and that resulting under mixed regime of lubrication, based on the Stribeck oil film ratio \( \lambda = 3 \), is also shown.

For all cases the film thickness diminishes with reduced lubricant entrainment when approaching piston reversals. In the vicinity of piston reversals, the applied load is almost entirely carried by squeeze film lubrication and any direct interaction of the opposing rough surfaces. At mid-stroke the film thickness varies mainly in accord with lubricant dynamic viscosity which is largely dependent on the cylinder liner temperature. In the deactivated cylinder the reduced liner temperature leads to an increased film thickness. Likewise, the higher cylinder liner temperatures in the active cylinders reduce the viscous load carrying capacity.

Fig. 6 shows the predicted generated friction during a full 4-stroke engine cycle. Boundary and viscous friction are clearly observed. At mid-stroke the slope of friction follows the viscous service parameter: \( \Delta U/\eta \), whilst at the reversals, when the rough contiguous surfaces come into contact, there is a sharp rise in generated friction. Comparison of Figs. 5 and 6 is instructive in observing the influence of regime of lubrication on frictional performance. As well as the primary friction peak experienced in all operational conditions between the crank angles:

Table 3
Material properties.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Liner material</td>
<td>Grey cast iron</td>
<td>–</td>
</tr>
<tr>
<td>Young’s modulus of elasticity for liner material</td>
<td>92.30</td>
<td>GPa</td>
</tr>
<tr>
<td>Liner Poisson’s ratio</td>
<td>0.211</td>
<td>–</td>
</tr>
<tr>
<td>Density for liner material</td>
<td>7200</td>
<td>kg m (^{-3})</td>
</tr>
<tr>
<td>Thermal conductivity for liner material</td>
<td>55</td>
<td>W m (^{-1}) K (^{-1})</td>
</tr>
<tr>
<td>Specific heat capacity for liner material</td>
<td>460</td>
<td>J kg (^{-1}) K (^{-1})</td>
</tr>
<tr>
<td>Ring material</td>
<td>Steel SAE 9254</td>
<td>–</td>
</tr>
<tr>
<td>Modulus of elasticity for the ring material</td>
<td>203</td>
<td>GPa</td>
</tr>
<tr>
<td>Ring’s Poisson’s ratio</td>
<td>0.3</td>
<td>–</td>
</tr>
<tr>
<td>Ring coating</td>
<td>Chromium Nitride</td>
<td>–</td>
</tr>
<tr>
<td>Modulus of elasticity for CrN</td>
<td>400</td>
<td>GPa</td>
</tr>
<tr>
<td>Poisson’s ratio for CrN</td>
<td>0.2</td>
<td>–</td>
</tr>
<tr>
<td>Thermal conductivity of CrN</td>
<td>12.134</td>
<td>W m (^{-1}) K (^{-1})</td>
</tr>
<tr>
<td>Bearing overlay</td>
<td>Babbit</td>
<td>–</td>
</tr>
<tr>
<td>Journal material</td>
<td>SG cast iron</td>
<td>–</td>
</tr>
<tr>
<td>Babbit’s Poisson’s ratio</td>
<td>0.33</td>
<td>–</td>
</tr>
<tr>
<td>Babbit’s modulus of elasticity</td>
<td>60</td>
<td>GPa</td>
</tr>
<tr>
<td>Thermal conductivity for the bushing</td>
<td>46</td>
<td>W m (^{-1}) K (^{-1})</td>
</tr>
<tr>
<td>Thermal conductivity of journal</td>
<td>25.96</td>
<td>W m (^{-1}) K (^{-1})</td>
</tr>
</tbody>
</table>

Table 4
Surface roughness parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ra of liner surface plateau</td>
<td>0.26</td>
<td>μm</td>
</tr>
<tr>
<td>Rk of liner (plateau height)</td>
<td>0.75</td>
<td>μm</td>
</tr>
<tr>
<td>Rp of liner plateau</td>
<td>&lt;0.3</td>
<td>μm</td>
</tr>
<tr>
<td>Rvk (liner grooves)</td>
<td>&gt;0.3</td>
<td>μm</td>
</tr>
<tr>
<td>Ra of ring contact surface</td>
<td>0.235</td>
<td>μm</td>
</tr>
<tr>
<td>Roughness parameter ((\sigma/\zeta))</td>
<td>0.04</td>
<td>–</td>
</tr>
<tr>
<td>Measured asperity gradient ((\sigma/\zeta))</td>
<td>0.001</td>
<td>–</td>
</tr>
<tr>
<td>Big-end bearing composite surface roughness</td>
<td>1</td>
<td>μm</td>
</tr>
</tbody>
</table>

and a deactivated cylinder. The demarcation line between a full hydrodynamic film and that resulting under mixed regime of lubrication, based on the Strubeck oil film ratio \( \lambda = 3 \), is also shown.

For all cases the film thickness diminishes with reduced lubricant entrainment when approaching piston reversals. In the vicinity of piston reversals, the applied load is almost entirely carried by squeeze film lubrication and any direct interaction of the opposing rough surfaces. At mid-stroke the film thickness varies mainly in accord with lubricant dynamic viscosity which is largely dependent on the cylinder liner temperature. In the deactivated cylinder the reduced liner temperature leads to an increased film thickness. Likewise, the higher cylinder liner temperatures in the active cylinders reduce the viscous load carrying capacity.

Fig. 6 shows the predicted generated friction during a full 4-stroke engine cycle. Boundary and viscous friction are clearly observed. At mid-stroke the slope of friction follows the viscous service parameter: \( \Delta U/\eta \), whilst at the reversals, when the rough contiguous surfaces come into contact, there is a sharp rise in generated friction. Comparison of Figs. 5 and 6 is instructive in observing the influence of regime of lubrication on frictional performance. As well as the primary friction peak experienced in all operational conditions between the crank angles:
$-10^\circ < \psi < 90^\circ$, corresponding to compression to mid power strokes, a second friction peak is observed in the deactivated cylinder in the region: $350^\circ < \psi < 370^\circ$. The significant boundary friction observed in this region is as the result of increased in-cylinder pressures (Fig. 4a) and the contact load due to the compression of the residual combustion chamber content.

The corresponding frictional power losses for each of the cases studied are shown in Fig. 7. The most significant power losses are concentrated at mid-stroke, where the sliding velocity attains its maximum value. The deactivated cylinder experiences significant power loss at mid-stroke as the result of a lower cylinder liner temperature, corresponding to a higher lubricant viscosity. The highest power losses occur during the power stroke as the high contact loads promote a mixed regime of lubrication for a longer duration. It is noteworthy that the power loss in the deactivated cylinder is very similar to the standard engine operating conditions. This, together with the fact that active cylinders of a CDA arrangement are subjected to higher combustion pressures, shows that CDA promotes deteriorating in-cylinder frictional power loss. To a certain extent this offset the envisaged gains through fuel saving made by deactivation of some of the cylinders.

5.2. Results and discussion: big-end bearing conjunction

Fig. 8 shows the predicted minimum film thickness variation of the big-end bearing through a full engine cycle. The results show that the film thickness reduces critically in the case of active cylinders with CDA. The dashed-line in the figure shows the onset of mixed regime of lubrication after which some boundary friction contribution ensues. The bearing of a deactivated cylinder carries lighter loads, allowing for significantly higher film thickness during the power stroke. However, the deactivated cylinder experiences increased loading in the exhaust and intake strokes, causing a reduced bearing lubricant film thickness.

The frictional power loss in the various big-end bearing conjunctions is shown in Fig. 9. A significant rise in boundary friction is observed during the power stroke as would be expected. Under standard operating conditions a small rise in friction can be observed because a reduction in film thickness increases the lubricant film shear rate. During the other strokes there is little difference between the various operating conditions.

6. Concluding remarks

The average power loss across the whole engine cycle for both the compression ring and big-end bearing conjunctions are presented in Fig. 10. It can be observed that for both contacts a significant increase in power loss occurs as a result of cylinder deactivation. This has been
shown to be due to the changes in the cylinder liner temperature and an increase in loading for the cylinders which remain active. Most significantly, during cylinder deactivation the big-end bearing of an active cylinder is shown to operate in a mixed regime of lubrication. This can be remedied through appropriate bearing design. A second key observation is that the lower cylinder liner temperatures in deactivated cylinders promote higher losses due to shear in the piston ring conjunction. Increased loading of the piston ring-cylinder liner contact in the active cylinder with CDA dramatically increases the frictional power loss. Palliative measures such as surface texturing of the piston ring [64–66] or the cylinder liner at the top dead centre reversal [67] can reduce this problem to a certain extent.

It is instructive to represent the effect of frictional power losses in the form of approximate mass of fuel expended for each operational scenario; (a)- full engine operation and (b)- the alternative CDA configuration. The calculations are included in Appendix 2. The results are presented in Fig. 11. A 0.5% increase in input fuel expended due to friction at the two investigated conjunctions is predicted. Under standard operating conditions the piston compression ring and the big-end bearing frictional losses are shown to account for 1.37% and 2.35% of the input fuel mass respectively. With cylinder deactivation, the piston compression ring and the big-end bearing frictional losses account for 1.65% and 2.61% of the input fuel mass respectively. The analysis presented here is confined to the case of cylinder compression rings and big-end bearings. These are directly affected by the changes in the in-cylinder conditions. However, this is also true for piston skirt-cylinder liner conjunction, which with modern partially-skirted pistons undergoes significant thermo-elastic distortion, affecting the conjunctural gap [70,71]. Therefore, any changes in cylinder pressure as the result of CDA and the ensuing cylinder temperature also alter the engine fuel efficiency, which should be studied, but is outside the scope of the current paper. The only other contact conjunction of note is the cam-follower, which owing to the prevalent elastohydrodynamic regime of lubrication (EHL) only accounts for 6% of the frictional losses (a fraction of the expended fuel). As the output power is maintained with CDA, the contact sliding speed, the dominant parameter for the EHL, would remain almost unchanged.

There are some practical implications of the analysis results, indicating that selection of suitable ring and/or liner coating material and bearing overlay can improve upon heat conduction from these contacts, thus improving upon lubrication conditions and reducing the frictional power losses.

Acknowledgments

The authors would like to express their gratitude to the UK Engineering and Physical Sciences Research Council (EPSRC) (EP/G012334/1) for the financial support of the Encyclopaedic Program Grant (www.Encyclopaedic.org), under which the majority of this research was carried out.

Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Apparent contact area</td>
</tr>
<tr>
<td>A_a</td>
<td>Asperity contact area</td>
</tr>
<tr>
<td>A_v</td>
<td>Area subjected to viscous shear</td>
</tr>
<tr>
<td>A_p</td>
<td>Area of piston head</td>
</tr>
<tr>
<td>a</td>
<td>Ring radial thickness</td>
</tr>
<tr>
<td>b</td>
<td>Ring axial-width (contact face-width)</td>
</tr>
<tr>
<td>c_maj</td>
<td>Contact clearance along the semi-major axis</td>
</tr>
<tr>
<td>c_min</td>
<td>Contact clearance along the semi-minor axis</td>
</tr>
<tr>
<td>c_p</td>
<td>Specific heat capacity of the lubricant</td>
</tr>
<tr>
<td>c_s</td>
<td>Specific heat capacity of solid surfaces</td>
</tr>
<tr>
<td>d</td>
<td>Thickness of bushing shell or overlay</td>
</tr>
<tr>
<td>e_0</td>
<td>Journal/Bushing eccentricity</td>
</tr>
<tr>
<td>e_F</td>
<td>Error tolerance for load convergence</td>
</tr>
<tr>
<td>e_p</td>
<td>Error tolerance for pressure convergence</td>
</tr>
<tr>
<td>e_t</td>
<td>Error tolerance for temperature convergence</td>
</tr>
<tr>
<td>e_ψ</td>
<td>Error tolerance for crank angle periodicity</td>
</tr>
<tr>
<td>E</td>
<td>Young's modulus of elasticity</td>
</tr>
<tr>
<td>E</td>
<td>Reduced (effective) elastic modulus of the contacting pair</td>
</tr>
<tr>
<td>F</td>
<td>Total contact applied load</td>
</tr>
<tr>
<td>F_5/2, F_2</td>
<td>Statistical functions</td>
</tr>
<tr>
<td>F_A</td>
<td>Air-fuel mass ratio</td>
</tr>
<tr>
<td>F_c</td>
<td>Ring tension force</td>
</tr>
<tr>
<td>F_0</td>
<td>Inertial imbalance force</td>
</tr>
<tr>
<td>F_G</td>
<td>In-cylinder gas force</td>
</tr>
<tr>
<td>F_g</td>
<td>Combustion gas force applied to the ring</td>
</tr>
<tr>
<td>f</td>
<td>Friction</td>
</tr>
<tr>
<td>f_b</td>
<td>Boundary friction</td>
</tr>
</tbody>
</table>
$f_{vl}$  Viscous friction
$G$  Ring end-gap in its free state
$h$  Film thickness
$h_0$  Minimum film thickness
$I$  Second area moment of inertial of ring cross-section
$h_t$  Heat transfer coefficient of boundary layer
$k_s$  Thermal conductivity of solid surfaces
$L$  Big-end bearing width
$l$  Ring outer circumference
$l_c$  Connecting rod length
$m$  Effective mass of piston and proportion of connecting rod in pure translation
$m_a$  Mass of air
$m_{fda}$  Mass of expended fuel with cylinder deactivation
$m_{fo}$  Mass of expended Fuel under standard operation
$m_{loss}$  Mass of expended fuel
$N$  Engine speed in RPM
$n$  Step of iteration
$p$  Pressure
$p$  Average Pressure
$p_a$  Asperity contact pressure
$p_{am}$  Atmospheric pressure
$p_c$  Cavitation vaporisation pressure
$P_b$  Power loss of big-end bearing
$P_e$  Ring elastic pressure due to tension
$P_e$  Combustion gas pressure
$P_{out}$  Engine output power
$P_{f}$  Power loss from of piston ring-cylinder liner conjunction
$Q$  Calorific value of fuel
$Q_{cv}$  Heat flow rate due to convection
$Q_{in}$  Heat flow rate at the contact inlet
$r$  Journal radius
$r_0$  Nominal radius of the bore
$r_c$  Crank radius
$R_t$  Convective thermal resistance in lubricant flow
$R_f$  Conductive thermal resistance of solid boundaries (flash temperature rise)
$R_l$  Conductive thermal resistance for the lubricant film
$R_v$  Convective thermal resistance of the boundary layer
$s$  Ring face profile
$S_f$  Characteristic length
$t$  Time
$U$  Speed of entraining motion
$V$  Variance ratio
$V_c$  Piston swept volume
$W_a$  Load carried by the asperities
$W_h$  Load carrying capacity of hydrodynamic film
$W$  Total contact reaction
$x$  Direction along the ring face-width (direction of entraining motion)
$x_e$  Position of lubricant film rupture
$Z$  Pressure-viscosity index
$z$  Direction along the bearing-width

Greek Symbols
$\alpha$  Piezo-viscous coefficient
$\beta$  Thermo-viscous coefficient
$\gamma$  Correlation length ratio
$\Delta U$  Sliding speed
$\delta$  Localised elastic deflection
$\epsilon$  Numerical damping factor
$\phi$  Connecting rod obliquity angle
$\varphi$  Bearing reaction attitude angle
$\psi_c$  Contact flow factor
$\psi_s$  Shear flow factor
$\phi_x$  Pressure flow factor
$\phi_{p}, \phi_{fs}, \phi_f$  Friction flow factors
Appendix 2. Fuel energy calculation


\[\eta_0\]  Lubricant dynamic viscosity at ambient pressure and temperature
\[\eta_e\]  Effective lubricant dynamic viscosity
\[\theta_0\]  Initial/ambient temperature
\[\theta_c\]  Effective lubricant contact temperature
\[\theta_{i1}, \theta_{i2}\]  Initial surface temperatures of liner and ring
\[\beta\]  Circumferential position in bearing
\[\kappa\]  Average asperity tip radius
\[\lambda\]  Striebeck oil film parameter
\[\rho_d\]  Density of air at the inlet manifold
\[\sigma\]  Root mean square roughness of contiguous surfaces
\[\zeta\]  Boundary shear strength of surfaces
\[\tau\]  Average shear stress
\[\tau_0\]  Eyring shear stress
\[\zeta\]  Asperity density per unit contact area
\[\nu\]  Poisson's ratio
\[\omega\]  Crankshaft angular velocity
\[\psi\]  Crank angle
\[\chi\]  Load adjusting parameter

**Appendix 1. Flow factors**

The flow factors used in the current study are based on those provided in Refs. [49,50]. The pressure flow factor \(\varphi_p\) is given as:

\[\varphi_p = 1 - 0.9e^{-0.5\lambda}, \lambda > 0.5 \text{ and } \gamma = 1\]  \(\text{(A1-1)}\)

where \(\gamma\) is the ratio of the roughness correlation lengths in the x and y directions, which equates to unity for an isotropic roughness.

The shear flow factor \(\varphi_s\) is calculated using:

\[\varphi_s = \begin{cases} 1.899e^{0.99}(V_1 - V_2)e^{-0.92\lambda + 0.05\zeta^2}, & \lambda \leq 5, \gamma = 1 \\ 1.126(V_1 - V_2)e^{-0.23\lambda}, & \lambda > 5, \gamma = 1 \end{cases}\]  \(\text{(A1-2)}\)

where, the parameters \(V_1\) and \(V_2\) are the variance ratios: \(V_i = \sigma_i^2/\sigma^2, i \in 1, 2\).

The contact factor \(\varphi_c\) is calculated using:

\[\varphi_c = \frac{1}{2}(1 + erf(\lambda))\]  \(\text{(A1-3)}\)

The shear stress factors \(\varphi_{sp}, \varphi_{sh}\) and \(\varphi_f\) are given by the following relationships:

\[\varphi_{sp} = 1 - 1.4e^{-0.66\lambda}, \lambda > 0.75, \gamma = 1\]  \(\text{(A1-4)}\)

\[\varphi_{sh} = \begin{cases} 11.12\lambda^{2.31}(V_1 - V_2)e^{0.38\lambda + 0.11\zeta^2}, & 0.5 < \lambda < 7, \gamma = 1 \\ 0, & \lambda > 7 \end{cases}\]  \(\text{(A1-5)}\)

\[\varphi_f = \begin{cases} \frac{35}{32}\xi \left\{ (1 - \xi^3) \ln[300(1 + \xi)] + \frac{1}{60}N \right\}, & \lambda \leq 3 \\ \frac{35}{32}\xi \left\{ (1 - \xi^3) \ln \left( \frac{\xi + 1}{\xi - 1} \right) + \frac{\xi}{15} [66 + \xi \ln(30\xi^2 - 80)] \right\}, & \lambda > 3 \end{cases}\]  \(\text{(A1-6)}\)

where \(\xi = \lambda/3, N = \xi^2(132 + \xi(M + 345)) - 55M, M = \xi^2(60 + 147\xi) - 405 - 160\)

**Appendix 2. Fuel energy calculation**

According to Heywood and Welling [68], a typical 1.4 L engine has a peak output power \(P_{out} = 80\ kW\). For steady state highway driving, approximately 30% of this power is required. The following equation is used to characterise the fuel mass required with and without cylinder deactivation at the engine speed of 3000 rpm:
\[ m_{\text{lb}} = \frac{2P_{\text{e}} \eta_{m} N}{Q \rho_{a} V \eta \text{i} \eta_{r} \eta_{f}} \]  

(A2-1)

where, \( Q, V, \) and \( \rho_{a} \) are the calorific value of fuel, engine swept volume and density of air at the inlet manifold respectively. The values for \( \eta_{r}, \eta_{f}, \) and \( \eta_{m} \) are found for similar engine configurations through tabulated data in Taylor [69]. Sandford et al. [1] show that under the currently prescribed operating conditions (BMEP = .38 MPa), a fuel economy improvement of 5% can be attained through cylinder deactivation. The fuel mass consumed in the deactivated case for the current condition can reasonably be considered to be:

\[ m_{\text{lb}} = 0.95 m_{\text{lb}} \]  

(A2-2)

The percentage fuel expended through the big-end bearing and piston ring conjunctions can then be written as:

\[ m_{\text{loss}} = \frac{P_{f} + P_{r}}{Q m_{\text{lb}}} \]  

(A2-3)

where, \( m_{\text{lb}} \) is the \( m_{\text{lb}} \) or \( m_{\text{lb}}' \), as appropriate, and \( m_{\text{loss}} \) is the expended fuel mass due to friction in the studied contacts.

### Table A2

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \eta_r )</td>
<td>0.8</td>
<td>-</td>
</tr>
<tr>
<td>( \eta_m )</td>
<td>0.6</td>
<td>-</td>
</tr>
<tr>
<td>( \eta_f )</td>
<td>0.25</td>
<td>-</td>
</tr>
<tr>
<td>( \rho_a )</td>
<td>1.225</td>
<td>( \text{kgm}^{-3} )</td>
</tr>
<tr>
<td>( Q )</td>
<td>45</td>
<td></td>
</tr>
</tbody>
</table>