CHARACTERISING THE FRICTION AND WEAR BETWEEN THE PISTON RING AND CYLINDER LINER BASED ON ACOUSTIC EMISSION ANALYSIS

Nasha Wei，

Department of Economics and Management, Taiyuan University of Science and Technology, Shanxi Province, P.R. China 030024

Centre for Efficiency and Performance Engineering, University of Huddersfield, UK HD1 3DH

Fengshou Gu, Guoxing Li，

Centre for Efficiency and Performance Engineering, University of Huddersfield, UK HD1 3DH

Department of Vehicle Engineering, Taiyuan University of Technology Taiyuan, Shanxi Province, P.R. China 030024

Tie Wang，

Department of Vehicle Engineering, Taiyuan University of Technology Taiyuan, Shanxi Province, P.R. China 030024

Andrew Ball

Centre for Efficiency and Performance Engineering, University of Huddersfield, UK HD1 3DH

e-mail: F.Gu@hud.ac.uk

In this paper, an experimental investigation was carried out to evaluate the friction and wear between the cylinder liner and piston ring using acoustic emission (AE) technology. Based on a typical compression ignition (CI) diesel engine, four types of alternative fuels (Fischer-Tropsch fuel, methanol-diesel, emulsified diesel and standard diesel) were tested under different operating conditions. AE signals collected from the cylinder block of the testing engine. In the meantime, the AE signals in one engine cycle are further segregated into small segments to eliminate the effects of valve events on friction events of cylinder liner. In this way, the resulted AE signals are consistent with the prediction of hydrodynamic lubrication processes. Test results show that there are clear evidences of high AE deviations between different fuels. In particular, the methanol-diesel blended fuel produces higher AE energy, which indicates there are more wear between the piston ring and cylinder liner than using standard diesel. On the other hand, the other two alternative fuels have been found little differences in AE signal from the normal diesel. This paper has shown that AE analysis is an effective technique for on-line assessment of engine friction and wear, which provides a novel approach to support the development of new engine fuels and new lubricants.

Keywords Alternative fuels, Piston ring, Cylinder liner, Acoustic emission

---

- The project of this paper is supported by Natural and Scientific foundation named as "An investigation of the tribological behaviour diagnosis of alternative fuel engines based on acoustic emission analysis"(NO. 51375326).

1. Introduction

The limitation of petroleum resources and pressure of environmental protection have driven many researchers to investigate alternative fuels and technologies for better fuel economy and reduced emissions. Although published papers show that overwhelming researches are concerning finding potential resources which are more sustainable and cleaner as engine fuels, there are still several researchers investigating engine tribological characteristics for the reduction of frictional losses as a mean for fuel efficiency. Previous research has shown that the piston-cylinder system is a significant source of mechanical friction in internal combustion engines and the friction losses of this system account for approximately 20% of the total mechanical losses in modern internal combustion engines [1 2 3]. The piston skirt contribution to the total friction losses of the piston-cylinder system is substantial[2]. M Priest and the co-workers[4] investigated a new model to the piston ring pack of a diesel engine. The model is used to predict the lubrication performance of measured ring packs before and after periods of running at constant speed and load. The objective is to establish the change in tribological behaviour with observed wear in the engine. This research advanced the understanding of piston ring profile evolution with time and its dependence on complex interactions between lubrication and wear.This has been a revival of interest in boundary lubrication for rolling element bearings and more and more researchers began to monitor the lubricant condition using vibration and acoustic signals.

However, the tribological behaviour of the diesel engine using the alternative fuels has not yet been fully understood. Although the main characteristics of some new-type fuels are similar to diesel, alternative fuels still have different physical properties, such as density and viscosity. These differences of alternative fuels will influence the performance of engines mainly in the processes of piston lubrication, because the different properties of alternative fuels, new additives and excessive water generated in combustion compared to diesel will impact on quality of lubrication and the oil performance and increase friction and wear.

Acoustic emissions are the high frequency transient elastic waves that are spontaneously generated from a rapid release of strain energy caused by the deformation or fracture of materials [5] . One major advantage of using AE monitoring and diagnosis is that the signal has a very high signal-to-noise ratio and the frequency of AE signal, usually in the range from 100 kHz to 1 MHz, is significantly higher than vibration signals which the frequency range is generally from 20Hz to 20 kHz. consequently, AE technology have advantages over vibrating technology and offer the potential to monitor operating conditions such as fuel efficiency, combustion conditions, and lubrication and also to detect faults [6.7.8]. AE technology also can provide comprehensive information of continuous and repetitive stress waves which is generated by behaviour of interacting materials between stressed components of reciprocating mechanical movement. Therefore, the process of plastic strain, phase transformations and physical transformations of the surfaces may cause friction and wear failures that are sources of AE [9]. Moreover, a change in the tribological parameters, such as materials in contact, the efficiency of lubricants, the roughness of the contacting surfaces, relative velocity between the contacting materials and contact pressure can be monitored by AE technique [10].

Numerous studies [10.11.12] have been conducted to relate the AE contents to friction and wear, and these have shown that the potential of using AE in the investigation of friction and wear phenomena is very promising. Douglas, J.A. Steel et. al. [13] used non-intrusive acoustic emission (AE) measurements to provide information pertaining to the interaction between piston rings and cylinder liners in a range of diesel engines. The ring-liner interaction has been established as a source of continuous AE and a number of features were identified which suggested that activity was related to asperity contacts between the ring-pack and liner. Fengshou Gu, Andrew Ball et al. [14]investigated the AE characteristics associated with engine friction to predict the quality of engine oil under different operating conditions.

This paper explores the tribological characterises of alternative fuels with regards to the critical piston ring and cylinder liner system on diesel engines. An experimental investigation was carried out to evaluate the friction and wear between the cylinder liner and piston ring using acoustic emission (AE) technology. Based on a typical compression ignition (CI) diesel engine, three types of alternative fuels with different proportion of Fischer-Tropsch fuel, methanol-diesel and bio-diesel were tested under diffident operating conditions and their AE contents are compared to understand the potential influences of tribological characteristics.

2. Characteristics of piston assembly friction

Friction of the piston assembly accounts for a significant proportion of the total mechanical losses in internal combustion engines. To investigate the relationship of AE and friction of piston assembly, the source of engine friction can roughly be compartmentalized into two groups: coulomb friction(dry friction) which occurs when asperities come into contact between two surfaces moving relative to each other and fluid friction which develops between adjacent layers of fluid moving at different velocities [14]. 40-55% of the mechanical losses occur in the power cylinder and half of the power cylinder friction losses come from friction generated by the piston rings [2.15]. Frictional losses between the skirt and the cylinder wall are significant, estimating for about 30% of total piston assembly friction.

Grant Smedley and the co-workers[16] investigate that the most significant contributors to friction were identified as the top ring, the oil control ring, and the piston skirt. Piston design parameters such as skirt profile, piston-to-liner clearance, and piston surface characteristics were found to have significant potential for the reduction of piston skirt friction.

H. S. Benabdallah and D. A. Aguilar[9] investigate the relationships between friction and wear properties and the characteristics of acoustic emission was conducted in the case of dry and grease-lubricated sliding contact using a ball-on-cylinder testing apparatus. The results revealed a good correlation between the friction coefficient and acoustic emission (AE) RMS voltage for dry sliding. It was also determined that the friction work correlated well with the corresponding integrated AE voltage over time, intRMS. The detection of the sliding speed threshold beyond which accelerated wear would occur was possible from the intRMS variation. Proportionality between the theoretically determined grease film thickness and the intRMS was observed.

3. Experimental setup and methodology

A typical medium duty transportation compression ignition direct injection (CIDI) engine (Kunming Yunnei Power Co., Ltd., PR. China, Model: 4100QBZL) was used for conducting engine investigations. The specification of the engine is given in Table 1.

During the test, the schematic of experimental setup is shown in Fig 1. AE signals were measured by a D9202B AE sensor on the cylinder block as shown in Fig 2, which is a wideband differential sensor with a very high sensitivity and has a very good frequency response over the range of 400 - 800 kHz. In addition, the engine speed, cylinder pressure, crank angle position, vibration and acoustic were measured and recorded by the following measurements instrumentation.

The engine was coupled with an eddy current dynamometer and a controller (Chengbang, China, Model: DW 160). The suitable instrumentation was done for conducting various experiments. Engine speed and load were controlled by varying excitation current to the eddy current dynamometer; The in-cylinder pressure in cylinder #1 was measured by Kistler 6215B Model Thermo COMP® Quartz Pressure Sensor which was mounted on the cylinder head; The Crank Angle Encoder connects with the crankshaft to measure angular position within a single turn; The vibration of the engine body and cylinder head were measured using accelerometers with the axial sensitivity of 5mV/g.

Table 2 Specification of the test engine

Manufacturer/model	Kunming Yunnei Power Co., Ltd., PR. China
Engine type	4100QBZL

Number of cylinders	Four
Combustion system	Direct injection, toroidal combustion chamber
Bore/stroke	100/105 mm
Displacement volume	3.298 L
Compression ratio	17.5:1
Cylinder liners	Cast iron replaceable wet liner
Start of fuel injection	14±2° BTDC
Rated power	70/3200 kW/r/min
Max. torque	245/2200 Nm/r/min

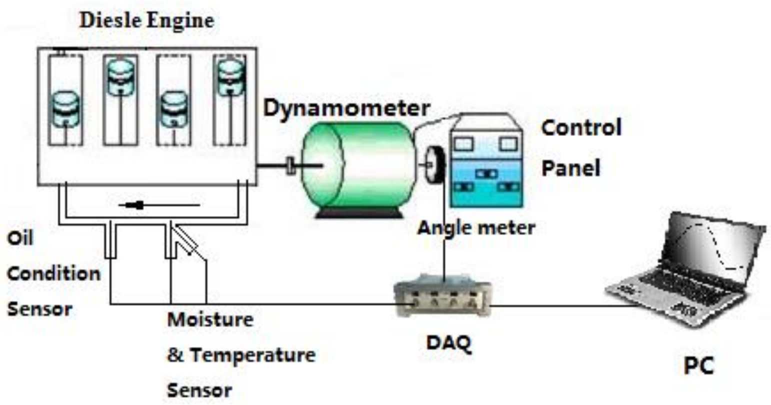

Figure 1. Schematic of experimental setup

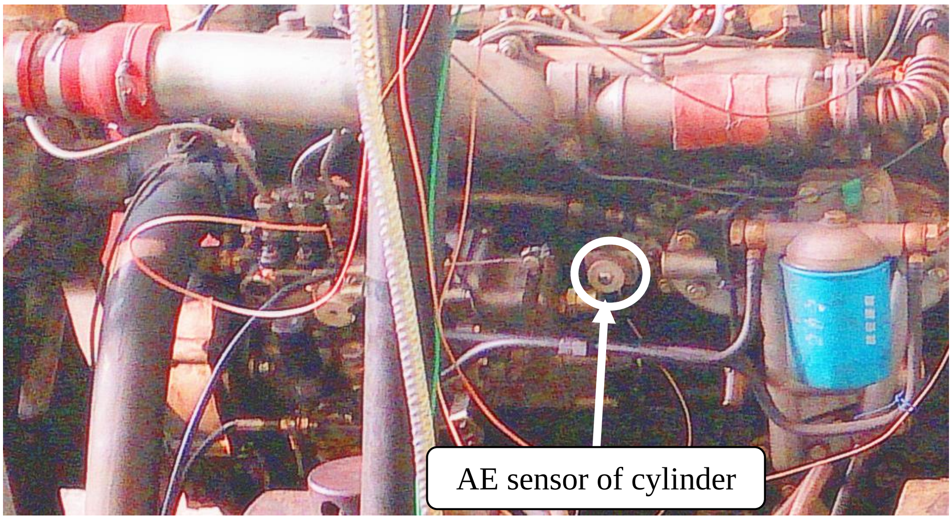

Figure 2. AE sensor of cylinder body Installation

In the test, the engine was fuelled with four types of fuels with different proportion (composed of Fischer-Tropsch fuel, methanol-diesel, and standard diesel) at the speeds of 1200rpm, 1600rpm, 2000rpm and 2400rpm. The loads were varied from 10 to 200Nm at each constant speed. In other words, the test engine was operated at different speeds and loads when different fuels were tested, allowing the examination of the friction behaviours under different lubrication conditions. To investigate the relationship between the resulting data and operating speed or load, we designed a variety of experimental operating conditions, as shown in Table 2.

The fuels used tested are standard diesel and three types of blended fuels which are blended by coal based F-T diesel (FT), methanol and standard diesel. The proportion of blends is detailed in Table 3 and the key properties of these fuels are shown in Table 4. The blends were designed to finding optimal fuels for better efficiency and lower emissions.

Table 2 Engine operating conditions

Engine speed (rpm)	Load (Nm)	Running time (min)
Warm-up running (1500)	30	20~30
Full-throttle test (1200~2800)	Cannot be set	15~20
1200	10/50/100/150	7/3/3/3/
1600	10/50/100/150/200	7/3/3/3/3
2000	10/50/100/150/200	9/3/3/3/3
2400	10/50/100/150/200	8/3/3/3/3

Table 3 Fuel proportion of alternative fuels

bulk factor	Methanol(M)	Bio-diesel(B)	Fischer-Tropsch fuel (FT)	Additives
M20	20	10	60	15(Isooctyl alcohol)
M10	10	10	75	8(N-octyl alcohol)
M05	5	10	80	4(N-octyl alcohol)

Table 4 Properties of methanol, F-T and conventional diesel fuels

	Methanol	F-T fuel	Standard Diesel
Density (20 ℃) (g/cm^3)	0.80	0.76	0.83
Viscosity (20 ℃) (mm^2/s)	0.75	2.14	4.65
Cetane number	5	74.8	45
Lower heating value (MJ/kg)	19.7	44.2	42.6
Aromatic content (Volume fraction) (%)	0	0.1	34.7
C /% (wt)	37.5	84.3	85.5
H /% (wt)	12.5	15.2	13.9

4. Results and discussion

4.1 Analysis of AE Signals under Different Speeds

Because engines has multiple acoustic emission sources of which combustion, fuel injection and piston slap present at around top and bottom dead centres [13] and are predominant AE signals with high amplitude burst. Recent study in[13] has shown that AE signal measured at cylinder blocks contains useful information of cylinder and piston friction process because of high velocity of piston motion. To extract the friction relating AE signals, the raw AE data is firstly converted into RMS values in the angular domain and then is weighted by a sinusoidal function with minima at TDCs. The weighting function suppress the AE content around TDC's which is less correlated with piston ring friction and highlight AE contents around the middle of the piston.

Fig. 3 shows the behaviour of AE RMS values under different speed and loads for the baseline diesel, which is obtained by an average of 80 engine cycles. It can be seen that AE RMS values in the middle of piston stroke are enhanced while the high bursts around TDC are suppressed significantly. Moreover, a clear increase of AE energy can be observed in the Fig. 3 with speed, indicating that speed cause more influence on AE, as it found in [13], which means that speed is the main factor that leads to engine friction. This also means that Oil-control ring boundary friction is the main AE excitation sources. It has narrow rails and does not generate hydrodynamic load carrying capacity and hence boundary lubrication conditions exist during the majority of the piston motion. Boundary lubrication implies that a proportion of the load is carried by asperity contacts, resulting in material deformation, which is the source of AE. On the other hand the lubrication between cylinder liner and compression ring because away from the dead centres the compression rings benefit from elastohydrodynamic lubrication with maximum effect at around mid-stroke, hence the possibility of asperity contact, and any resultant AE, is minimal.

In addition it has also observed that AE RMS has a smaller increase with loads. This may be because the large contact area between cylinder liner and rings. The degree of asperity contact is less influenced by loads compared with speed. This is apparently consistent with the fact that engine friction loss is more relating to engine speed.

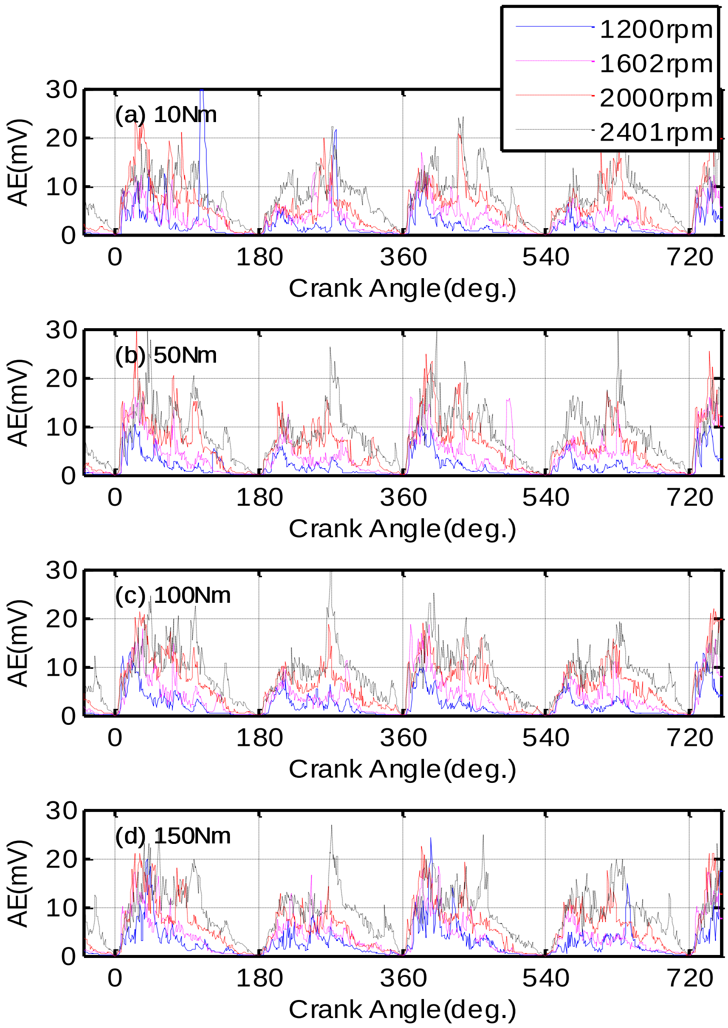

Figure 3. AE RMS value under different operating conditions for baseline diesel

4.2 Impacts of Alternative Fuels on Diesel Engine under different operating conditions

To examine the details of AE variation, the RMS values is averaged over one engine cycle and presented them in Fig. 4 over the tested loads and speeds. In the Fig. 4, Diesel-0 is standard diesel; cFT-100 is coal F-T fuel, M20 is the methanol-diesel (the proportion of methanol is 20%); HF-II is Emulsified diesel from Hong Feng Inc. As can be seen AE increases much more significantly with speed, owing that AE can be a good indicator for engine ring-liner friction and can be based for investigating the change of friction due to different alternative fuels.

The comparison of AE between different fuels under same operating conditions, also shown in Fig. 4, has found that methanol fuel produces a clearly higher AE energy for nearly all operating conditions. It shows that this fuel may leads to poorer lubrication condition and produces higher power loss and wearing. It may shorten engine server life time significantly as it was reported in [17] that wear metal in used oil were higher with methanol fuel compared with diesel.

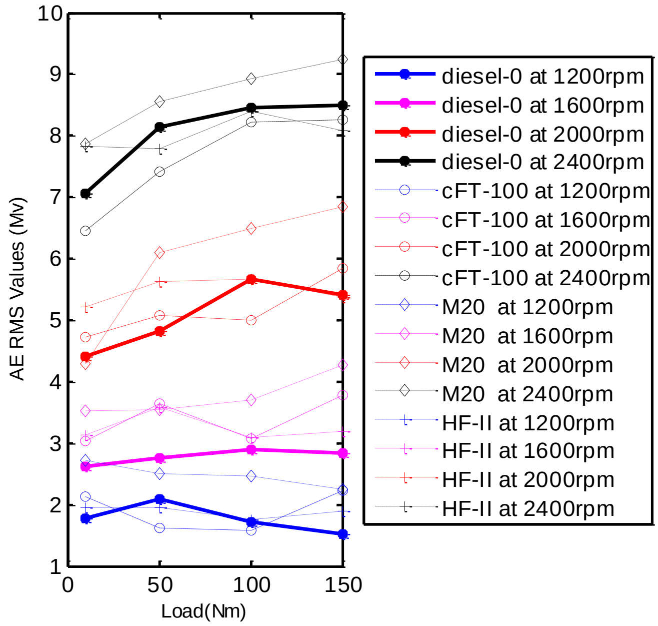

Figure 4. AE RMS values under different operating condition and fuel blends

5. Conclusions

This research has investigated the acoustic emission (AE) signals under different engine conditions for analysing the impacts of alternative fuels on CI engines. Based on the AE RMS amplitudes extracted in the middle stroke of the engine, it can be predicted that,

Speed is the main factor that leads to engine friction which is the main source of AE signals. Oil-control ring boundary friction is the main AE excitation source.

Emulsified diesel and F-T fuel have less impacts on the friction and wear of diesel engine cylinder parts and they are superior to the standard diesel to a certain extent. The methanol diesel oil has the worst impact on the engine running state.

AE RMS has a smaller increase with speed and loads, because the large contact area between cylinder liner and rings.

Angular domain analysis is effective for extract AE events relating to piston-liner friction.

REFERENCES

1. Tung, S. C. & McMillan, M. L. Automotive tribology overview of current advances and challenges for the future. *Tribol. Int.* **37,** 517–536 (2004).
2. Smedley, G. Piston ring design for reduced friction in modern internal combustion engines. (2004). at <http://dspace.mit.edu/handle/1721.1/27129>
3. N. G. Demas, R. A. E. Tribological studies of coated pistons sliding against cylinder liners under laboratory test conditions. *Lubr Sci* **24,** (2012).
4. Priest, M., Dowson, D. & Taylor, C. . Predictive wear modelling of lubricated piston rings in a diesel engine. *Wear* **231,** 89–101 (1999).
5. Mthis, K. & Chmelk, F. in *Acoust. Emiss.* (Sikorski, W.) (InTech, 2012). at <http://www.intechopen.com/books/acoustic-emission/exploring-plastic-deformation-of-metallic-materials-by-the-acoustic-emission-technique>
6. Sharkey, A. J. C., Chandroth, G. O. & Sharkey, N. E. Acoustic emission, cylinder pressure and vibration: a multisensor approach to robust fault diagnosis. in *IJCNN 2000 Proc. IEEE-INNS-ENNS Int. Jt. Conf. Neural Netw. 2000* **6,** 223–228 vol.6 (2000).

7. Antoni, J., Daniere, J. & Guillet, F. Effective Vibration Analysis of IC Engines Using Cyclostationarity. Part 1-A Methodology for Condition Monitoring. *J. Sound Vib.* **257,** 815–837 (2002).
8. Antoni, J., Bonnardot, F., Raad, A. & El Badaoui, M. Cyclostationary modelling of rotating machine vibration signals. *Mech. Syst. Signal Process.* **18,** 1285–1314 (2004).
9. Benabdallah, H. S. & Aguilar, D. A. Acoustic Emission and Its Relationship with Friction and Wear for Sliding Contact. *Tribol. Trans.* **51,** 738–747 (2008).
10. Skåre, T. & Krantz, F. Wear and frictional behaviour of high strength steel in stamping monitored by acoustic emission technique. *Wear* **255,** 1471–1479 (2003).
11. Jiaa, C. L. & Dornfeld, D. A. Experimental studies of sliding friction and wear via acoustic emission signal analysis. *Wear* **139,** 403–424 (1990).
12. Diniz, A. E., Liu, J. J. & Dornfeld, D. A. Correlating tool life, tool wear and surface roughness by monitoring acoustic emission in finish turning. *Wear* **152,** 395–407 (1992).
13. Douglas, R. M., Steel, J. A. & Reuben, R. L. A study of the tribological behaviour of piston ring/cylinder liner interaction in diesel engines using acoustic emission. *Tribol. Int.* **39,** 1634–1642 (2006).
14. Elamin, F., Gu, F. & Ball, A. Diesel engine lubricating oil condition and performance monitoring using acoustic emission measurements. (2011). at <http://www.comadem2011.org/>
15. Richardson, D. E. Review of Power Cylinder Friction for Diesel Engines. *J. Eng. Gas Turbines Power* **122,** 506–519 (2000).
16. Smedley, G., Mansouri, S. H., Tian, T. & Wong, V. W. Friction Reduction via Piston and Ring Design for an Advanced Natural-Gas Reciprocating Engine. 743–753 (2004). doi:10.1115/ICEF2004-0879
17. Shukla, D. S., Gondal, A. K. & Nautiyal, P. C. Effect of methanol fuel contaminants in crankcase oils on wear. *Wear* **157,** 371–380 (1992).