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Optimising the design of a piston-ring pack using DoE methods

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►Use of DoE methods to optimise a ring-pack in an ic engine. ►Significant power loss reductions can be obtained. ► Interactions between design variables observed suggesting that DoE methods should be used when conducting experiments on real engines

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Optimising the design of a piston-ring pack using DoE methods

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A R T I C L E I N F O

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A B S T R A C T

This paper shows how design of experiments can be used with a ring-pack simulation program to optimise the design of a piston-ring assembly. Ten factors are varied—six describing the ring profile, three ring tensions, and the lubricant viscosity. Statistical analysis shows that there are some significant interactions between some of the factors—an issue that should be considered when performing test-bed measurements on engines. It is shown that an improved design can be achieved that reduces ring losses by 57% whilst reducing upward oil flow by 39%. This could lead to a 7% improvement in fuel economy provided there are no deleterious effects in other parts of the engine.

1. Introduction

According to the US Energy Information Administration, the world consumed 31,017 million barrels of oil in 2006 [1], and this produced 11,219 Mt of CO_2. King [2] suggests that about half of this oil was used by road transport contributing some 5610 Mt of CO_2 to the atmosphere. Furuhama [3] argued that friction in the engines of road transport vehicles consumes about 7% of the energy in the fuel at full load, and around 14% at half load. The contacts generating these losses are well known, but the sizes of the individual contributions are still not clear. Taylor [4] believes that about 40% of the total friction power loss can be attributed to ring friction. Using this value, and assuming that 10% of the fuel's energy is lost in friction, it can be estimated that piston-ring friction generated 22.4 Mt of CO_2 in 2006. This is about the same as the emissions from Europe's largest conventional power station, Drax, which generates at a rate of 3.96 GW and supplies the UK with around 7% of its electricity needs.

Unless mitigating actions are taken, it is estimated that there will be an 81% increase in global CO_2 emissions from road transport by 2030 [5]. Using the IEA's projections on oil prices ($130/barrel at 2007 prices), this implies that the global cost of piston-ring friction will be $4.41 billion dollars in 2030.

The automotive industry, therefore, is under enormous pressure to reduce carbon emissions and increase fuel efficiency [5]. This is leading to smaller ic engines with increased power densities [6], smaller sump volumes, and lower viscosity lubricants. The hybrid market is growing, leading to engines running at sub-optimum temperatures with large numbers of stop–starts per kilometer and varying load conditions [7]. These trends are placing increasing demands on engine designers and lubricant manufacturers to maintain reliability and reduce friction. Not surprisingly, there is considerable interest in reducing ring-pack friction whilst maintaining durability [5].

The function of the ring-pack is to provide a seal between the combustion chamber and the crankcase. In order to reduce friction, the designer aims to maintain a fluid film between each ring and the cylinder wall, whilst ensuring that the oil transported into the combustion chamber is minimised. Lowering oil consumption will generally increase friction, and vice versa.

There are many design factors which can be changed in a ring-pack, ranging from the number, shape, axial height, depth, and tension of the rings, through geometrical features of the piston grooves, to the viscosity of the lubricant. To evaluate the influence and inter-dependence of these factors would require hundreds, if not thousands, of individual experiments in a real engine, or a similar number of runs of a simulation program.

This paper shows how design of experiments (DoE) can be used to reduce the runs of a simulation program to a much more manageable number in the search for an optimal design. The ring-pack simulation program was developed at UCLAN in the 1990s [8] and was the first to apply the so-called Jacobssen–Floberg–Ollson (JFO) boundary conditions to this geometry, using a modified version of the Elrod–Adams [9] mass conservation algorithm proposed by Paydas and Smith [10]. The program is discussed in detail in Ref. [8], where it is demonstrated that the program's minimum film thickness predictions agree reasonably well with experimental measurements. The DoE approach entails making large adjustments to the factors, and then using multiple linear regression (MLR) to produce equations for multidimensional response surfaces of power loss and oil transport. These can

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Nomenclature

δ_n	offset ratio of ring n ($=e_n/w_n$; see Fig. 1)
n	ring number (1 = compression, 2 = scraper, 3 = oil-control)
R_n	radius of curvature of ring n (m)
R_a	ring/liner composite surface roughness (μm)

then be searched for an optimum combination of the factors. In addition, the paper shows how interactions between the factors can be studied and how the equations of the response surfaces can be reduced in complexity with little loss of accuracy. The DoE package used was MODDE from Umetrics.

The engine used in the study is a Mercedes M111 petrol engine as employed by Ma et al. [8], which is widely used in lubricant testing (e.g. CEC L-53-T-95 black-sludge and CEC L-53-T-96 fuel-economy tests). This paper concentrates on 10 features of the ring-pack of this engine—the tensions, curvatures and offset-ratios of the 3 rings, and the viscosity of the lubricant. These 10 characteristics are known as 'factors', and the power loss and oil consumption are called 'response variables'. The approach is to

(a) use the DoE software to choose sets of values for the factors,
(b) run the ring-pack program to generate a set of responses, and then
(c) employ the DoE package to produce response surfaces, from which an optimal set of factors can be determined.

2. Results

The main features of the engine are presented in Table 1. The details of the ring pack are illustrated in Fig. 1, along with the definition of offset ratio of the ring face. The combustion and inter-ring pressures employed in all the 'experiments' were the same and are plotted in Fig. 2.

The ten factors are listed in Table 2. It is convenient when designing experiments to use scaled factors and these are assigned the values −1, 0, or +1. The interpretation of this coding is outlined in Table 2, with the shaded cells indicating the values pertaining in the actual engine.

The work described in the paper is divided into following 3 parts:

1. Design 1: Factors 1–4 were varied, with factors 5–10 fixed at their values in the real engine. Engine speed was 2500 rpm.
2. Design 2: As Design 1, with an engine speed of 3500 rpm.
3. Design 3: Factors 1–10 were varied. Engine speed was 2500 rpm.

These two engine speeds cover the range pertaining when a car is cruising on a motorway. The maximum recommended engine speed is about 6000 rpm.

2.1. Design 1: N = 2500 rpm

The design table for the experiments is presented in Table 3. Since there are four factors, and three values for each, a full-

Table 1
Details of the Mercedes M111 engine.

Bore radius (mm)	44.8
Crank radius (mm)	39.7
Connecting-rod length (mm)	132.2
Separation distance between top and second rings (mm)	4
Separation distance between second third rings (mm)	2.7
Top-ring offset ratio, δ_1	0.0
Second-ring offset ratio, δ_2	−0.5
Oil-control ring offset ratio, δ_3	1.0
Top-ring radius of curvature, R_1 (m)	0.1
Second-ring radius of curvature, R_2 (m)	0.1
Oil-control ring radius of curvature, R_3 (m)	0.15
Top-ring tension (MPa)	0.20
Second-ring tension (MPa)	0.20
Oil-control ring tension (MPa)	0.98
Ring/liner composite surface roughness, R_a (μm)	0.4
Friction coefficient for boundary lubrication	0.1
Liner temperature at TDC for ring 1 (C)	150
Liner temperature at BDC for ring 3 (C)	80
Liner temperature mid-way between these locations (C)	100

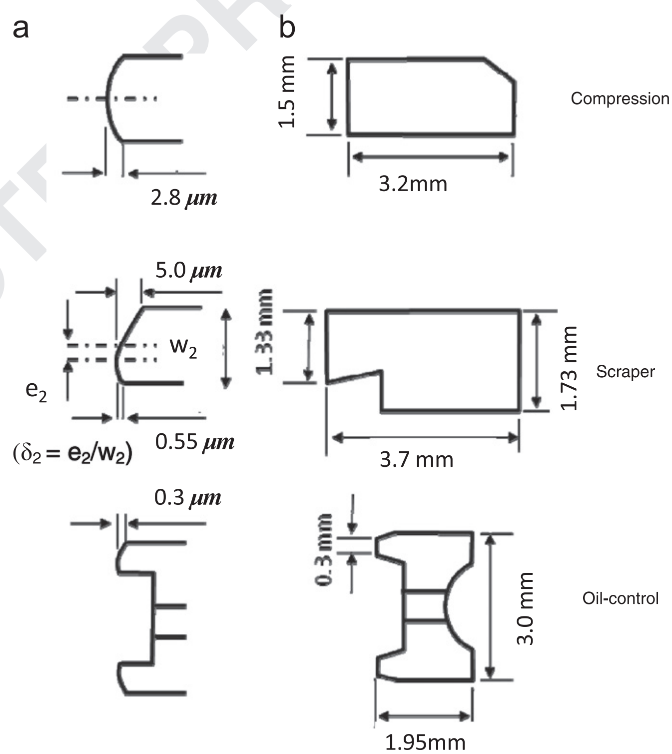

Fig. 1. Geometry of the rings: (a) contact features and (b) overall shape.

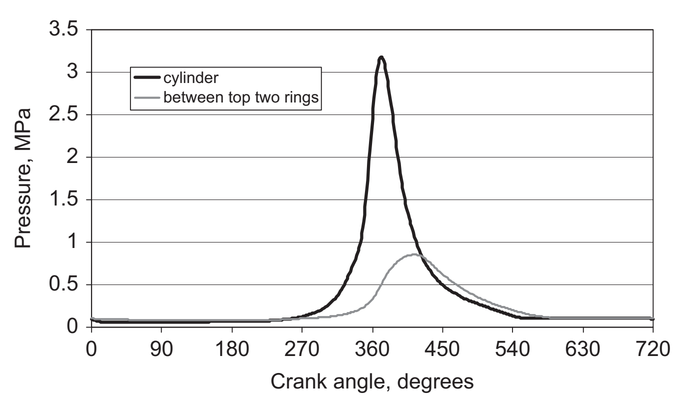

Fig. 2. Pressures in the cylinder and the ring-pack.

Table 2
Factors values and DoE coding (actual engine values shown shaded).

Interpretation of design coding				
Factor		**−1**	**0**	**1**
	Description	Values used in ring-pack program		
1	Top ring tension (MPa)	0.10	0.20	0.30
2	Second ring tension (MPa)	0.10	0.20	0.30
3	Oil control ring tension (MPa)	0.49	0.98	1.47
4 (a)	Oil viscosity at 40 C (Pa s)	53.5	107.0	160.5
4 (b)	Oil viscosity at 100 C (Pa s)	8.35	16.70	25.05
5	Top-ring offset ratio	−0.2	0.0	0.2
6	Second-ring offset ratio	−0.7	-0.5	-0.3
7	Control-ring offset ratio	0.6	0.8	1.0
8	Top-ring radius of curvature (m)	0.050	0.100	0.150
9	Second-ring radius of curvature (m)	0.050	0.100	0.150
10	Control-ring radius of curvature (m)	0.075	0.150	0.225

The coding is linear. For example, for factor 1, 0.5 represents 0.25 MPa.

Table 3
Experimental conditions of the four factors for the two designs.

Experiment	Top ring	2nd ring	3rd ring	Viscosity	Experiment	Top ring	2nd ring	3rd ring	Viscosity
1	−1	−1	−1	−1	15	−1	1	1	1
2	+1	−1	−1	−1	16	1	1	1	1
3	−1	+1	−1	−1	17	−1	0	0	0
4	+1	+1	−1	−1	18	1	0	0	0
5	−1	−1	+1	−1	19	0	−1	0	0
6	+1	−1	+1	−1	20	0	1	0	0
7	−1	+1	+1	−1	21	0	0	−1	0
8	+1	+1	+1	−1	22	0	0	1	0
9	−1	−1	−1	+1	23	0	0	0	−1
10	+1	−1	−1	+1	24	0	0	0	1
11	−1	+1	−1	1	25	0	0	0	0
12	1	1	−1	1	26	0	0	0	0
13	−1	−1	1	1	27	0	0	0	0
14	1	−1	1	1					

Table 4
Ring-pack program predictions. N=2500 rpm. Design 1. Not optimised (experiments 25, 26, and 27 represent the actual engine).

Experiment	Power loss/cylinder (kW)	Net upward oil flow/cylinder (l/h)	Experiment	Power loss/cylinder (kW)	Net upward oil flow/cylinder (l/h)
1	0.1549	0.0713	15	0.4273	0.0725
2	0.164	0.0691	16	0.4429	0.0719
3	0.1626	0.0611	17	0.2945	0.0727
4	0.171	0.06	18	0.3076	0.0711
5	0.2129	0.0397	19	0.2948	0.0718
6	0.2284	0.0383	20	0.3057	0.0723
7	0.2235	0.0401	21	0.2534	0.1018
8	0.239	0.0384	22	0.3335	0.0585
9	0.3198	0.1234	23	0.202	0.0493
10	0.3323	0.1243	24	0.3892	0.0869
11	0.3355	0.118	25	0.3011	0.0723
12	0.3481	0.1176	26	0.3011	0.0723
13	0.4135	0.0718	27	0.3011	0.0723
14	0.4293	0.072			

factorial design would entail the completion of 4^3 (=64) runs of the ring-pack program. This has been reduced to twenty-seven by using a central composite factorial (CCF) design with a quadratic model, with two replicated runs (twenty-six and twenty-seven). (A quadratic model implies that a factor may appear on its own, as its square, or as a product with another factor—all multiplied by appropriate coefficients.) Using these conditions, the ring-pack program was run twenty-seven times. The values of power loss and oil consumption predicted by the ring-pack program are presented in Table 4. These were input to the DoE package as responses, so that prediction plots and response surfaces could be determined. Whilst fitting equations to the data, the analysis showed that the compression-ring tension, when varied between the upper and lower limits of Table 3, had an insignificant influence on both power loss and oil flow. In addition, the interaction effects between the four factors were negligible. This was a surprising result since it was thought that the rings' behaviours would be linked via the oil flow through the pack. The effect of this was to greatly simplify the equations which described the 2 response surfaces.

Prediction plots are illustrated in Fig. 3. The top row of charts shows how the DoE software predicts the way in which power

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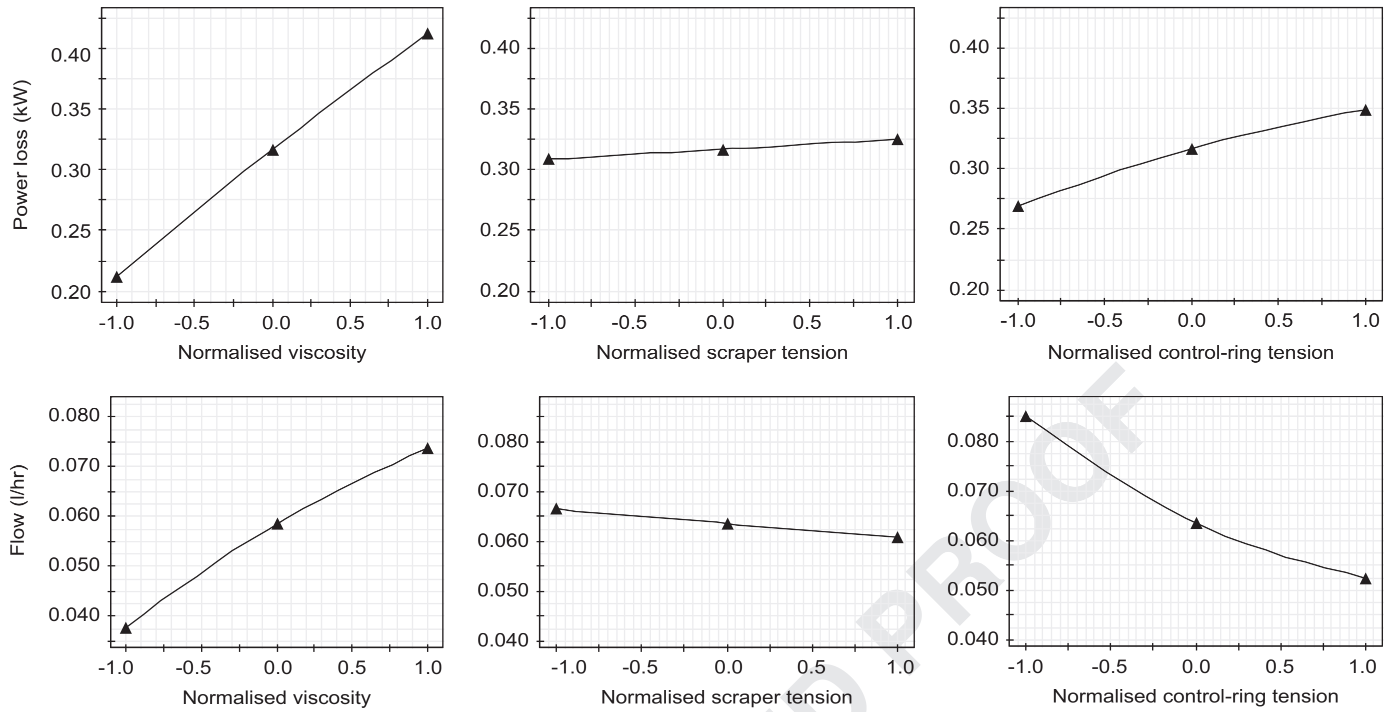

Fig. 3. DoE predictions of power loss and oil flow and their dependence on viscosity, scraper-ring tension and control-ring tension. Design 1. (In each plot, all other factors are set at their nominal values. Triangles are values at the experimental points, and lines are the predictions between them.)

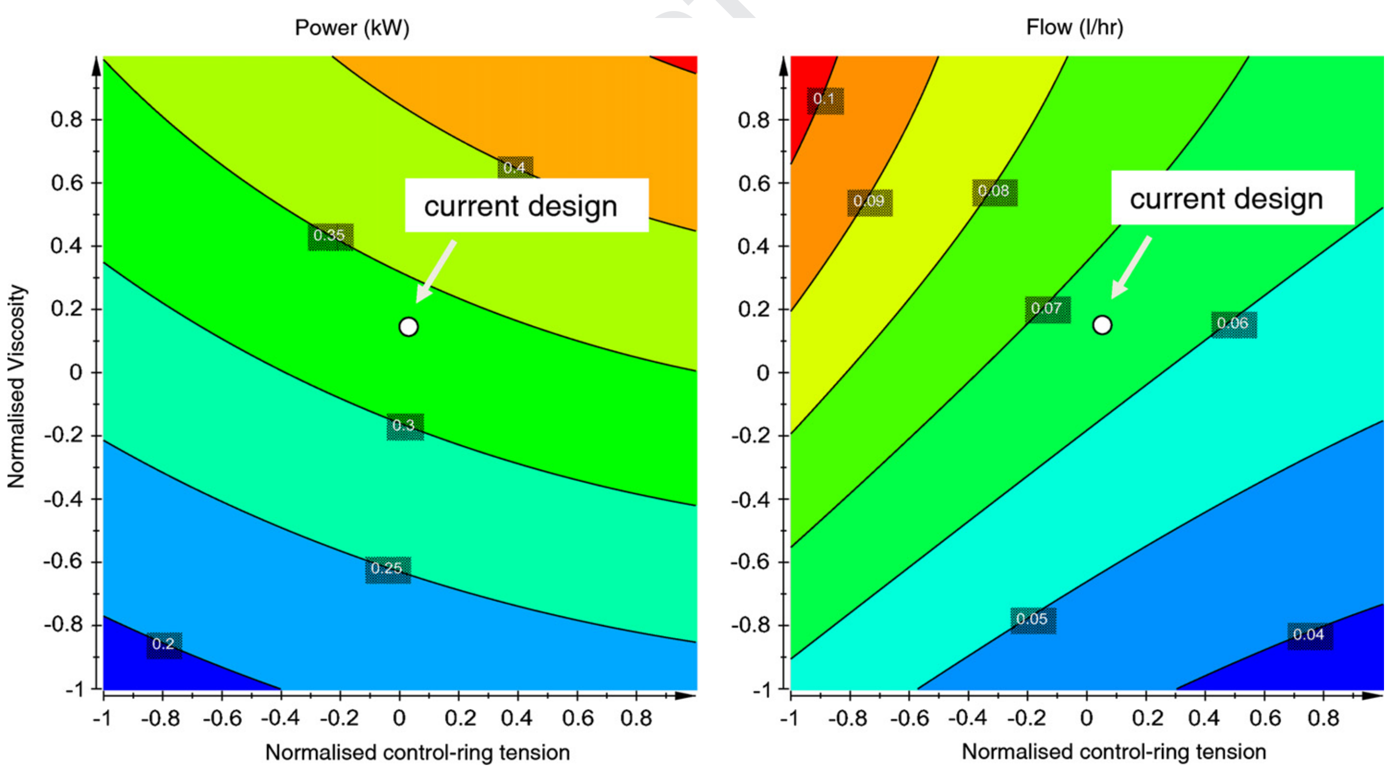

Fig. 4. Contour plots. Design 1. Not optimised.

Table 5
Optimal values of power and oil from response surfaces. Design 1.

Power loss (kW)	0.173	(i.e. 43% less than nominal)
Oil consumption (l/h)	0.063	(i.e. 13% less than nominal)

loss varies with changes in the oil-control ring tension, viscosity, and scraper-ring tension. The second row presents the dependency of the oil flow on these factors. The markers are the values predicted at the experimental points. The plots reveal that power loss is most affected by viscosity, with the tension of the oil-control ring having a less powerful, yet significant, influence. The

Table 6
Optimal values of the normalised factors. Design 1.

Top ring tension	−1 to +1	No impact on power or flow
Second ring tension	+1	Little impact on power or flow
Control ring tension	−1	(i.e. 50% less than nominal)
Viscosity	−1	(i.e. 50% less than nominal)

Table 7
Comparison of response surface and ring-pack program predictions for Design 1 (optimal conditions of Table 6).

	Power loss (kW)	Oil consumption (l/h)
Predicted from response surface	0.173	0.063
Predicted from ring-pack program	0.167	0.058

scraper-ring tension has very little effect, and the compression ring, as noted earlier, has an insignificant impact. Turning to oil flow, viscosity and oil-control ring tensions are equally influential; with scraper-ring tension only have a small effect.

Contour plots of the response variables (power loss and oil flow) versus oil-control ring tension and lubricant viscosity are presented in Fig. 4, with the scraper ring tension set at its nominal value. The small circles represent the DoE predictions when all four factors are set at their normal values, this representing the predicted behaviour in the actual engine. It is clear that changes in viscosity and oil-control ring tension could reduce considerably the power loss and oil consumption, as long as this does not induce blow-by. (Of course, a reduction in viscosity can only be considered if this does not adversely affect other engine components.)

The two response surfaces can be searched for an optimal set of values for the 2 significant factors (oil-control ring tension and viscosity). For the purposes of this study, the software searched

Table 8
Power loss and oil flow. Design 2. Not optimised.

Experiment	Power loss/cylinder (kW)	Net upward oil flow/cylinder (l/h)	Experiment	Power loss/cylinder (kW)	Net upward oil flow/cylinder (l/h)
1	0.2663	0.1149	15	0.7476	0.1189
2	0.2792	0.1148	16	0.7748	0.1176
3	0.2798	0.1071	17	0.5088	0.1180
4	0.2921	0.1063	18	0.5287	0.1178
5	0.3586	0.0677	19	0.5104	0.1180
6	0.3793	0.0665	20	0.5273	0.1183
7	0.3741	0.0683	21	0.4462	0.1681
8	0.3954	0.0675	22	0.5776	0.0915
9	0.5654	0.2050	23	0.3337	0.0828
10	0.5883	0.2055	24	0.6880	0.1446
11	0.5925	0.1953	25	0.5201	0.1182
12	0.6155	0.1957	26	0.5201	0.1182
13	0.7253	0.1190	27	0.5201	0.1182
14	0.7527	0.1172			

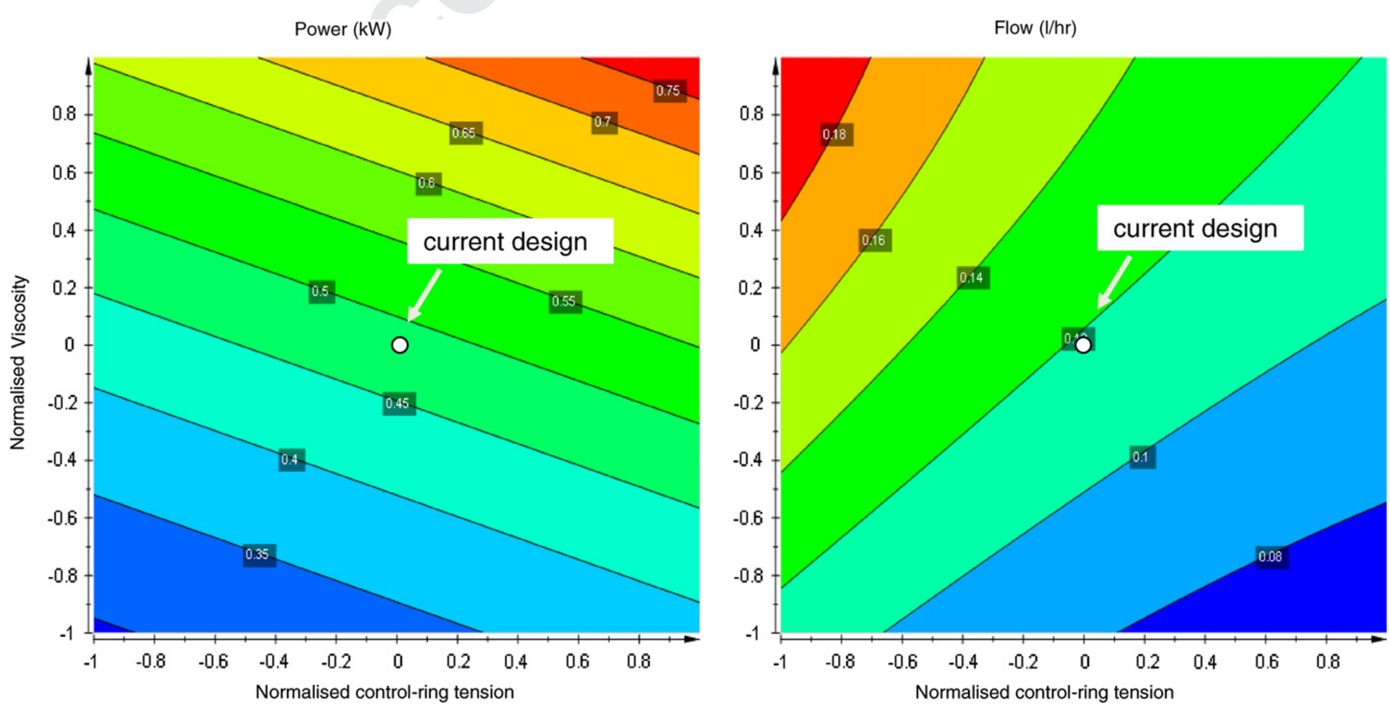

Fig. 5. Contour plots. Design 2. Not optimised.

for a minimum value of power loss whilst not increasing the oil consumption above the value predicted in the actual engine. The optimum is presented in Table 5, with the optimal set of factors listed in Table 6. The latter shows that the compression-ring tension can be increased or decreased by 50% with little or no effect; moreover, reducing the oil-control ring tension and oil viscosity by 50% will yield a significant power loss reduction and a small fall in oil consumption.

It should be remembered that the values listed in these two tables are those determined from a response surface produced by the DoE software, not values calculated by the ring-pack program. It was necessary, therefore, to check that the ring-pack program would actually predict these improved values. The ring-pack program's power and oil consumption predictions are shown in Table 7, where it is evident that they agree, within a few percent, with the predicted value from the DoE program. This suggests that the response surfaces calculated by the DoE program did adequately reflect the ring-pack programs' predictions of behaviour.

2.2. Design 2: $N=3500$ rpm

Since the only difference between this design and the previous one was the operating speed, the number of factors remained the same. Hence the design table (Table 2) was still applicable, and twenty-seven runs of the ring-pack program were completed, the results being listed in Table 8. The contour plots are presented in Fig. 5. In this case, the scraper and oil-control ring tensions had insignificant influences on power loss and oil flow. Again, interactions were negligible. The small circles have the same meaning as before.

Using the same criteria as before, the optimum values for the factors were obtained, and they are shown in Table 9. The resulting effects on power loss and oil flow are listed in Table 10, and again it is apparent that significant improvements in power loss can be obtained without a deleterious effect on oil flow, simply by reducing the oil-control tension and oil viscosity by 50% as in Design 1. Of course, the absolute values of power loss and oil flow are higher in this design because the speed is higher, but the percentage reductions achievable are similar to those in Design 1.

Table 9
Optimal values of power and oil consumption from response surfaces. Design 2.

Power loss (kW)	0.294	(i.e. 43% less than nominal)
Oil consumption (l/h)	0.112	(i.e. 5% less than nominal)

Table 10
Optimal values of the factors. Design 2.

Top ring tension	−1 to +1	No impact on power or flow
Second ring tension	−1 to +1	Little impact on power or flow
Control ring tension	−1	(i.e. 50% less than nominal)
Viscosity	−1	(i.e. 50% less than nominal)

2.3. Design 3: $N=2500$ rpm. All factors varied

The final design included all 10 factors—the three ring tensions, the curvatures and offset ratios of the three rings, and the oil viscosity. The design table for the 10 factors and the power and oil consumption predictions from the ring-pack program are presented in Tables A1 and A2 in the Appendix. Optimisation was again undertaken using the same criteria as before, and the optimised values of the factors, along with the predicted response values, are listed in Tables 11 and 12, respectively. (For ease of reference, the optimum values from Design 1 are also included since the engine speeds are the same in the two designs.) Interactions were more noticeable in this design, and these are discussed later. A contour plot with factors at their optimum values is illustrated in Fig. 6, and the optimum operating condition is marked by the small circles in the bottom left-hand corners of the plots.

3. Discussion

In Design 1 (2500 rpm), varying the compression and scraper ring tensions by ±50% has little effect on power loss and oil flow. As expected from the work of many other researchers, the major influencing factors are control ring tension and viscosity, with a 43% power reduction being achieved whilst simultaneously reducing oil consumption by 13%. This is achieved by reducing the oil-control ring tension by 50%, and reducing the oil's viscosity by a similar amount. The tensions of the other two rings can be varied by ±50% without any significant effect on these results.

It is interesting to examine in more detail how the power loss reduction is achieved. To do this, the power loss is broken down first into the contributions from each ring, and then into the contributions from hydrodynamic and boundary lubrication. This data is presented in Table 13, where the original (non-optimised) and optimised values are compared.

In both cases, boundary friction is the minor component of the total power loss—13% in the original, and 15% in the optimised case. The major savings come from reduced hydrodynamic losses arising from lower viscosity and reduced film thickness.

The minimum film thicknesses of each ring are plotted against crank angle in Fig. 7, for both original and optimised conditions (TDC firing is at 360°). The following observations can be made:

(1) The compression ring (ring 1) in the optimised design operates with slightly thinner films between mid-stroke expansion and mid-stroke exhaust, otherwise film thicknesses in both situations are virtually the same.

Table 12
Optimal values of power and oil consumption from response surfaces. Designs 3 and 1 compared.

Design	Power loss (kW)	Oil consumption (l/hr)
3	0.129 (i.e. 57% less than nominal)	0.044 (i.e. 39% less than nominal)
1	0.173 (i.e. 43% less than nominal)	0.063 (i.e. 13% less than nominal)

Table 11
Optimal values of the factors. Designs 3 and 1 compared.

Design	Ring 1 tension	Ring 2 tension	Ring 3 tension	Viscosity	Offset ring1	Offset ring2	Offset ring3	Curv ring1	Curv ring2	Curv ring3
3	−0.80	−1	−0.99	−1	−0.98	−1.00	−0.78	−1.00	−0.96	−1.00
1	−1 to +1	+1	−1	−1						

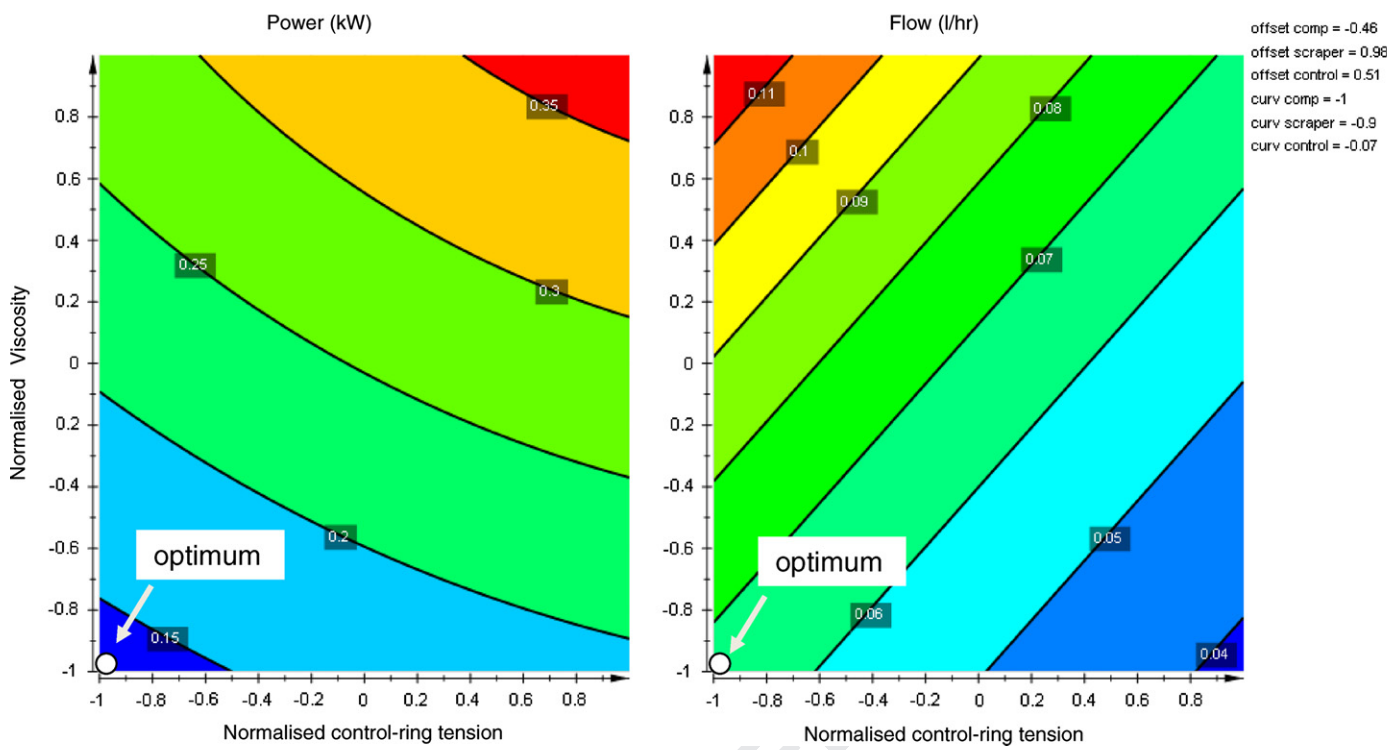

Fig. 6. Contour plots. Design 3. Optimised.

Table 13
Power-loss predictions from the ring-pack program: Design 1. Original and optimised compared.

	Top ring loss (kW)		2nd ring loss (kW)		3rd ring loss (kW)		Sub-totals (kW)		Totals (kW)
	hydro	boundary	hydro	boundary	hydro	boundary	hydro	boundary	Totals (kW)
Original	0.0876	0.0260	0.0869	0.0077	0.0880	0.0049	0.2625	0.0386	0.3011
Optimised	0.0484	0.0162	0.0503	0.0056	0.0437	0.0029	0.1425	0.0247	0.1672
Reduction (% of total)	13.0	3.3	12.2	0.7	14.7	0.7	39.9	4.6	45.3

(2) The optimised scraper ring (ring 2) runs with films 0.5 μm smaller than the nominal case around the BDC positions, and also thinner films at the mid-stroke regions.
(3) The optimised oil-control ring (ring 3) behaves in a similar way to its original counterpart, but exhibits slightly thinner films during the latter half of the exhaust stroke.

The effect on blow-by can be assessed by examining the plots in Fig. 8. Here the percentage of the conjunction occupied by a full film is plotted against crank angle for the three rings, under the original and optimised conditions. It can be seen that blowby is not predicted at any point.

In Design 2 (3500 rpm), the compression and scraper effects were again minimal. By running with a 50% reduction in control ring tension and viscosity – as in Design 1 – power loss can be reduced by 43% whilst also reducing oil flow by 5%.

The final design, Design 3, studied the influence of ring offset ratio and ring curvature in addition to the other factors. There were more interactions between factors in this model, and these interactions are indicated in Fig. 9(a) and (b). Here the significant coefficients in the quadratic equation for the two response surfaces are plotted against the individual factors or their products. The predicted value of a response is calculated from the sum of the products of each coefficient and its appropriate factor, or product of factors. The factor-products are indications of interactions between factors, and the significant ones for both power loss and oil flow are as follows:

- scraper-tension/scraper-ring offset ratio (2*6);
- control-ring tension/scraper ring offset ratio (3*6);
- scraper-ring offset-ratio/scraper-ring curvature (6*9);
- scraper-ring offset-ratio/control-ring curvature (6*10),

Interactions 2*6 and 6*9 refer to the scraper ring geometry and tension, and are most likely linked through the film shape they produce. Interactions 3*6 and 6*10 are between the scraper and control-rings, and these probably arise because the two rings, at times, ride on the oil film left by the other.

The oil viscosity has only weak interactions with the other variables.

The interaction between factors is an issue which needs to be considered when performing test-bed measurements on engines. If the behaviour of the ring-pack in a real engine follows that predicted by the ring-pack simulation program, then experiments in which only one variable is changed at a time will not yield data that can be used to optimise performance.

The optimised values of the responses are power loss/cylinder = 0.129 kW, and oil flow/cylinder = 0.044 l/h. This new power loss prediction represents a 57% decrease on the value of

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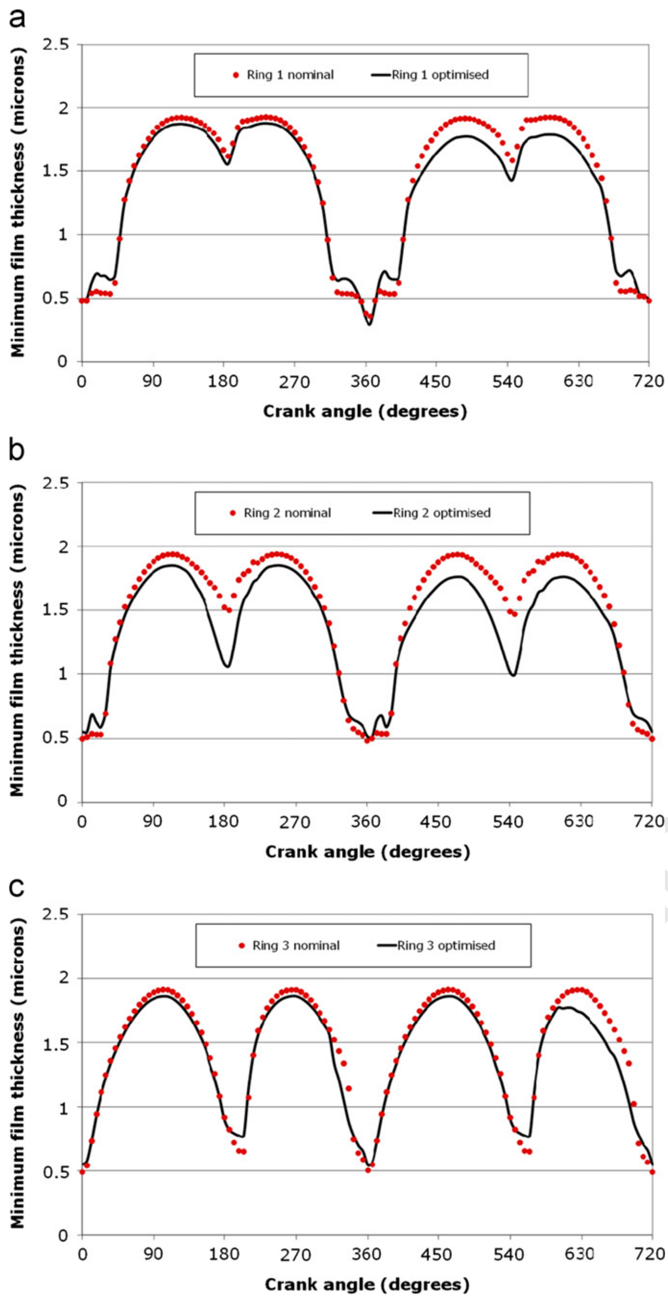


Fig. 7. Minimum film thickness predictions from the ring-pack program. Design 1: (a) ring 1, (b) ring 2 and (c) ring 3.

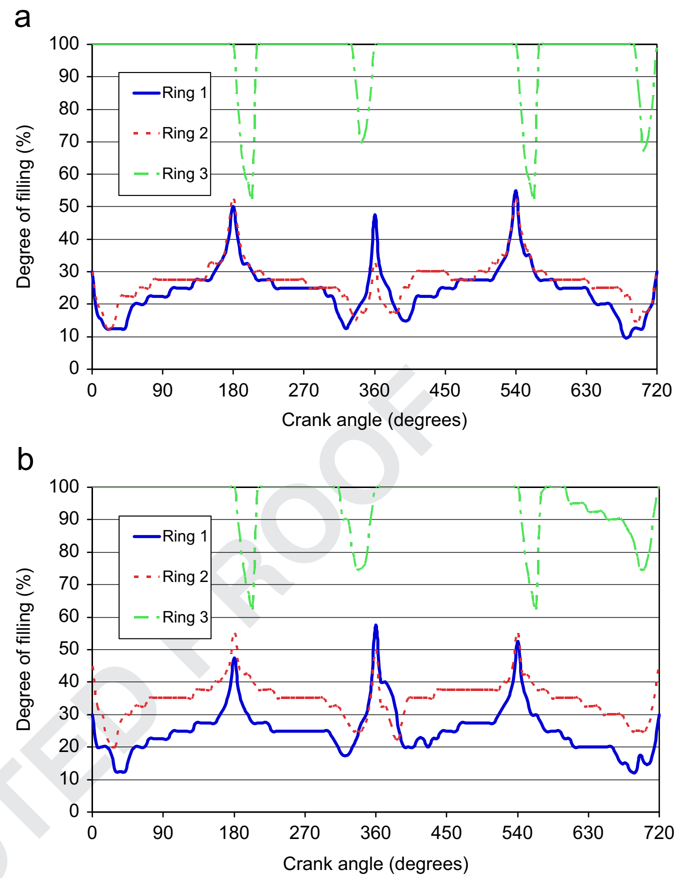


Fig. 8. Degree of filling as a percentage of ring-face width (100 is flooded, 0 is blowby). Design 1: (a) Original ring-pack and oil. (b) Optimised ring-pack and lower viscosity oil.

0.3011 kW predicted by the ring-pack program before any optimisation is introduced (see experiment 25, Table 4). To assess the significance of this power-loss reduction, assume that for every 100 units of energy in the fuel, on average, 10 units are wasted in friction (with 4 of these being lost in the piston-rings), and 30 units are available at the wheels. A 57% reduction in ring-friction will lead to an additional 2.3 units of energy being available at the wheels, i.e. 7.6% increase. This is a significant reduction and would map to about a 7% improvement in fuel economy and an equivalent reduction in CO_2 emissions. The oil flow is also predicted to decrease by 39%.

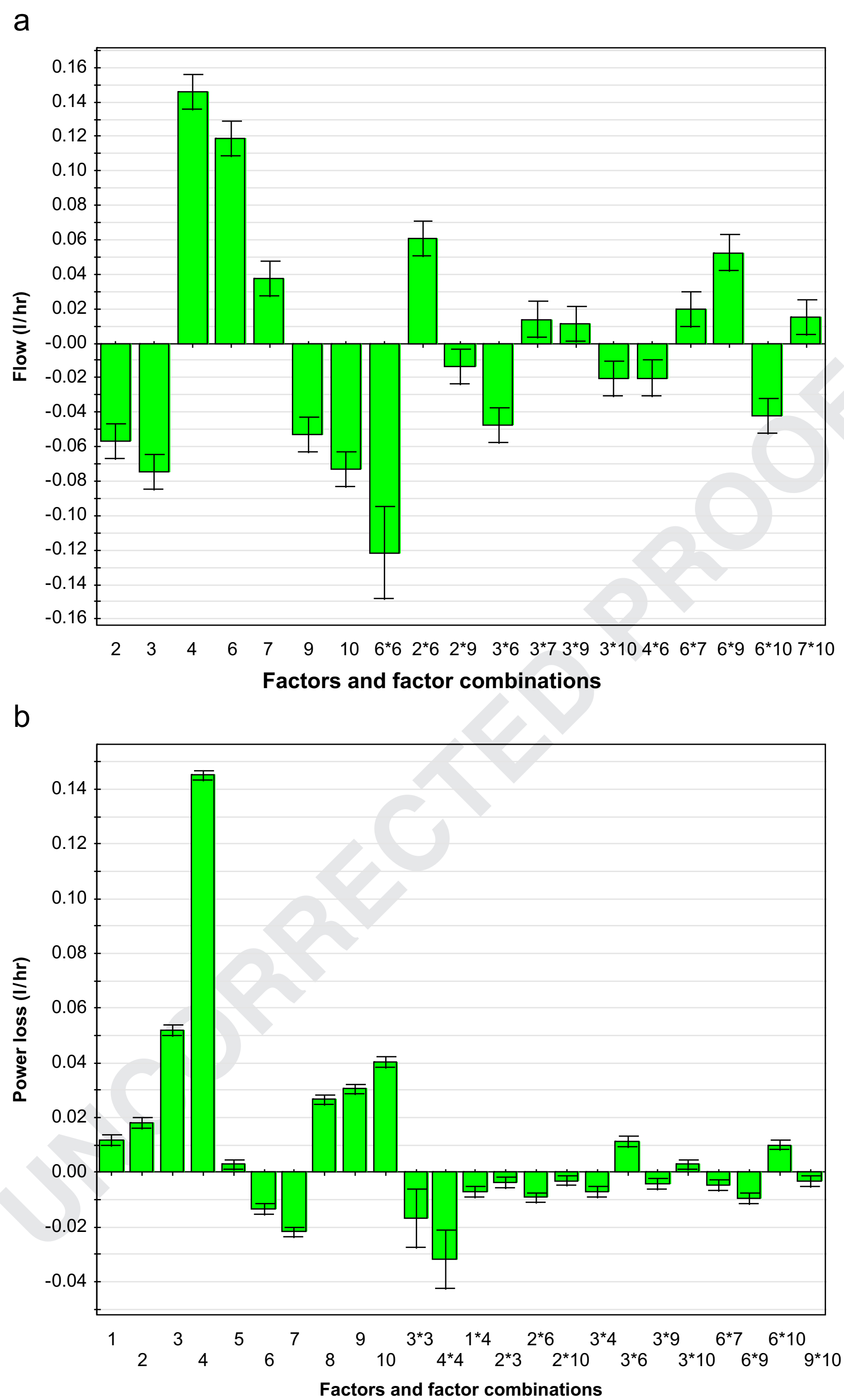
Examination of the minimum film thicknesses of the rings and degrees of filling showed little difference from the un-optimised case, so additional wear is not expected and blowby is not predicted.

Finally, the relative influence of the ring tensions was examined. A response plot is presented in Fig. 10. This is similar to that illustrated in Fig. 3, but only ring tensions are considered. The control-ring is seen to have the largest impact on power loss, with the other two rings exerting smaller, but not insignificant, influences. In terms of flow, the compression ring has no impact, the other two rings having similar levels of influence. Of course, there are interactions between factors, as illustrated in Fig. 9, but the charts in Fig. 10 give a good 'feel' for the influence of the ring tensions. Consider, for example, the effect of compression-ring tension on flow. In Fig. 9(a), the flow is not influenced by this factor (i.e. factor 1 has been excluded by the analysis). This lack of influence is also reflected in Fig. 10. Staying with flow, Fig. 10 suggests that the scraper and control rings have similar impact, and indeed they display similar coefficients (factors 2 and 3) in Fig. 9(a). The effects of ring tensions on power loss shown in Fig. 10 are also mirrored in the relative sizes of the coefficients in Fig. 9(b).

4. Conclusions

It has been shown that a DoE approach can be used to predict response surfaces for the performance of a piston-ring pack. This enables rapid determination of optimum values for ring-pack design parameters. Significant reductions in frictional power loss can be achieved, without increasing oil consumption, by adjusting the tensions, offset ratios and curvatures of the three rings and the viscosity of the lubricating oil. This is achieved by the following:

(a) reducing oil viscosity by 50%;
(b) reducing the top-ring tension by 40%, and the two other ring tensions by 50%;



1	Top ring tension	6	Second-ring offset ratio
2	Second ring tension	7	Control-ring offset ratio
3	Oil control ring tension	8	Top-ring radius of curvature
4	Oil viscosity	9	Second-ring radius of curvature
5	Top-ring offset ratio	10	Control-ring radius of curvature

Fig. 9. (a) Significant coefficients for oil flow response surface and (b) significant coefficients for power loss response surface.

(c) giving the compression-ring an offset-ratio of −0.2;
(d) reducing the scraper-ring offset-ratio from −0.5 to −0.3;
(e) reducing the oil-control ring offset-ratio from 1.0 to 0.96;
(f) halving the compression ring's radius of curvature;
(g) reducing the scraper ring's radius of curvature by 48%;
(h) halving the oil control ring's radius of curvature.

By doing this, a 57% reduction in ring power loss can be achieved with a 39% reduction in net upward oil transport. Of course, reducing oil viscosity by 50%, as suggested, is likely to cause damage to other components of the engine unless preventive actions are taken, but such large potential reductions in piston-ring losses suggest that improvements in fuel economy

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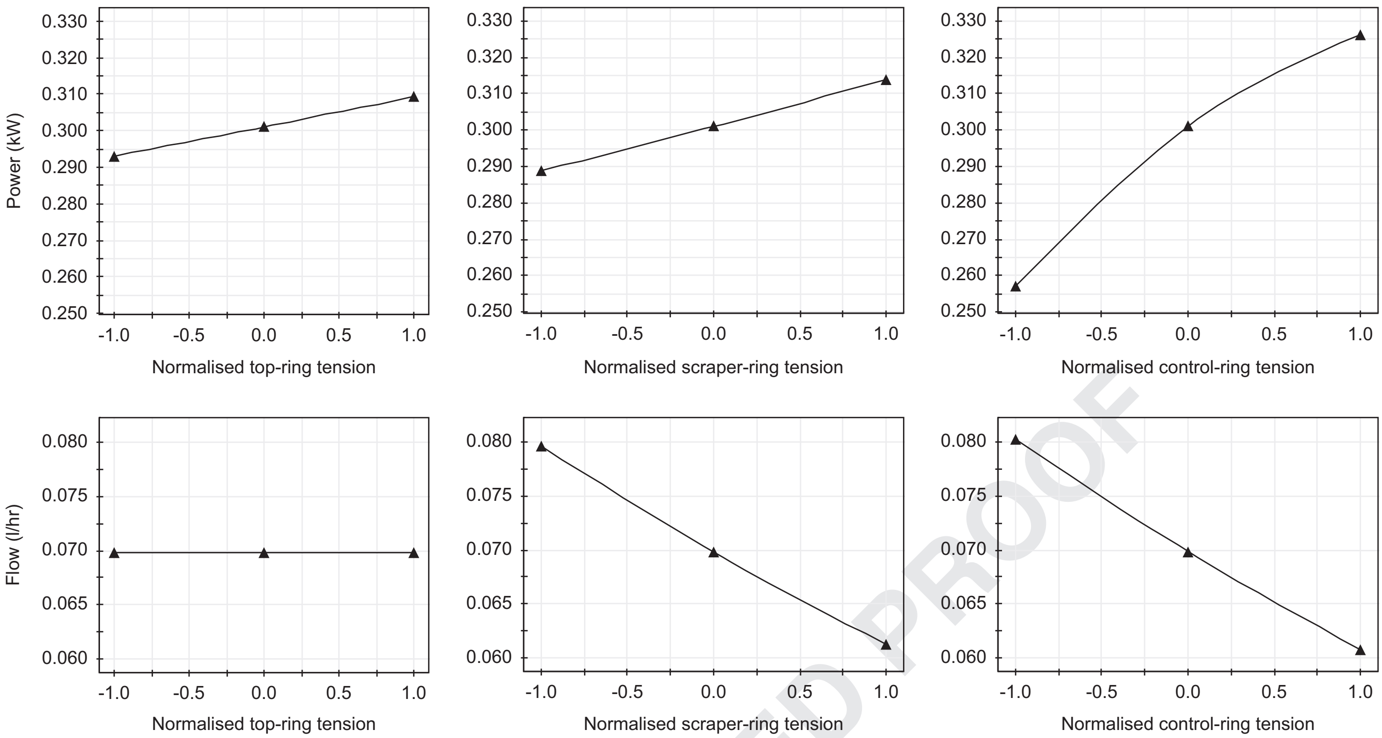

Fig. 10. DoE predictions of power loss and oil flow and their dependence on ring tensions. Design 3. (In each plot, all other factors are set at their nominal values.)

Table A1
Design table for Design 3.

Factor value										
Experiment	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
1	−1	−1	−1	−1	−1	−1	−1	+1	+1	+1
2	+1	−1	−1	−1	−1	−1	−1	−1	+1	−1
3	−1	+1	−1	−1	−1	−1	−1	−1	−1	+1
4	+1	+1	−1	−1	−1	−1	−1	+1	−1	−1
5	−1	−1	+1	−1	−1	−1	−1	−1	−1	−1
6	+1	−1	+1	−1	−1	−1	−1	+1	−1	+1
7	−1	+1	+1	−1	−1	−1	−1	+1	+1	−1
8	+1	+1	+1	−1	−1	−1	−1	−1	+1	+1
9	−1	−1	−1	+1	−1	−1	−1	+1	−1	−1
10	+1	−1	−1	+1	−1	−1	−1	−1	−1	+1
11	−1	+1	−1	+1	−1	−1	−1	−1	+1	−1
12	+1	+1	−1	+1	−1	−1	−1	+1	+1	+1
13	−1	−1	+1	+1	−1	−1	−1	−1	+1	+1
14	+1	−1	+1	+1	−1	−1	−1	+1	+1	−1
15	−1	+1	+1	+1	−1	−1	−1	+1	−1	+1
16	+1	+1	+1	+1	−1	−1	−1	−1	−1	−1
17	−1	−1	−1	−1	+1	−1	−1	+1	−1	+1
18	+1	−1	−1	−1	+1	−1	−1	−1	−1	−1
19	−1	+1	−1	−1	+1	−1	−1	−1	+1	+1
20	+1	+1	−1	−1	+1	−1	−1	+1	+1	−1
21	−1	−1	+1	−1	+1	−1	−1	−1	+1	−1
22	+1	−1	+1	−1	+1	−1	−1	+1	+1	+1
23	−1	+1	+1	−1	+1	−1	−1	+1	−1	−1
24	+1	+1	+1	−1	+1	−1	−1	−1	−1	+1
25	−1	−1	−1	+1	+1	−1	−1	+1	+1	−1
26	+1	−1	−1	+1	+1	−1	−1	−1	+1	+1
27	−1	+1	−1	+1	+1	−1	−1	−1	−1	−1
28	+1	+1	−1	+1	+1	−1	−1	+1	−1	+1
29	−1	−1	+1	+1	+1	−1	−1	−1	−1	+1
30	+1	−1	+1	+1	+1	−1	−1	+1	−1	−1
31	−1	+1	+1	+1	+1	−1	−1	+1	+1	+1
32	+1	+1	+1	+1	+1	−1	−1	−1	+1	−1
33	−1	−1	−1	−1	−1	+1	−1	+1	+1	−1
34	+1	−1	−1	−1	−1	+1	−1	−1	+1	+1
35	−1	+1	−1	−1	−1	+1	−1	−1	−1	−1
36	+1	+1	−1	−1	−1	+1	−1	+1	−1	+1

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Table A1 (*continued*)

Factor value										
Experiment	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
37	−1	−1	+1	−1	−1	+1	−1	−1	−1	+1
38	+1	−1	+1	−1	−1	+1	−1	+1	−1	−1
39	−1	+1	+1	−1	−1	+1	−1	+1	+1	+1
40	+1	+1	+1	−1	−1	+1	−1	−1	+1	−1
41	−1	−1	−1	+1	−1	+1	−1	+1	−1	+1
42	+1	−1	−1	+1	−1	+1	−1	−1	−1	−1
43	−1	+1	−1	+1	−1	+1	−1	−1	+1	+1
44	+1	+1	−1	+1	−1	+1	−1	+1	+1	−1
45	−1	−1	+1	+1	−1	+1	−1	−1	+1	−1
46	+1	−1	+1	+1	−1	+1	−1	+1	+1	+1
47	−1	+1	+1	+1	−1	+1	−1	+1	−1	−1
48	+1	+1	+1	+1	−1	+1	−1	−1	−1	+1
49	−1	−1	−1	−1	+1	+1	−1	+1	−1	−1
50	+1	−1	−1	−1	+1	+1	−1	−1	−1	+1
51	−1	+1	−1	−1	+1	+1	−1	−1	+1	−1
52	+1	+1	−1	−1	+1	+1	−1	+1	+1	+1
53	−1	−1	+1	−1	+1	+1	−1	−1	+1	+1
54	+1	−1	+1	−1	+1	+1	−1	+1	+1	−1
55	−1	+1	+1	−1	+1	+1	−1	+1	−1	+1
56	+1	+1	+1	−1	+1	+1	−1	−1	−1	−1
57	−1	−1	−1	+1	+1	+1	−1	+1	+1	+1
58	+1	−1	−1	+1	+1	+1	−1	−1	+1	−1
59	−1	+1	−1	+1	+1	+1	−1	−1	−1	+1
60	+1	+1	−1	+1	+1	+1	−1	+1	−1	−1
61	−1	−1	+1	+1	+1	+1	−1	−1	−1	−1
62	+1	−1	+1	+1	+1	+1	−1	+1	−1	+1
63	−1	+1	+1	+1	+1	+1	−1	+1	+1	−1
64	+1	+1	+1	+1	+1	+1	−1	−1	+1	+1
65	−1	−1	−1	−1	−1	−1	+1	−1	+1	+1
66	+1	−1	−1	−1	−1	−1	+1	+1	+1	−1
67	−1	+1	−1	−1	−1	−1	+1	+1	−1	+1
68	+1	+1	−1	−1	−1	−1	+1	−1	−1	−1
69	−1	−1	+1	−1	−1	−1	+1	+1	−1	−1
70	+1	−1	+1	−1	−1	−1	+1	−1	−1	+1
71	−1	+1	+1	−1	−1	−1	+1	−1	+1	−1
72	+1	+1	+1	−1	−1	−1	+1	+1	+1	+1
73	−1	−1	−1	+1	−1	−1	+1	−1	−1	−1
74	+1	−1	−1	+1	−1	−1	+1	+1	−1	+1
75	−1	+1	−1	+1	−1	−1	+1	+1	+1	−1
76	+1	+1	−1	+1	−1	−1	+1	−1	+1	+1
77	−1	−1	+1	+1	−1	−1	+1	+1	+1	+1
78	+1	−1	+1	+1	−1	−1	+1	−1	+1	−1
79	−1	+1	+1	+1	−1	−1	+1	−1	−1	+1
80	+1	+1	+1	+1	−1	−1	+1	+1	−1	−1
81	−1	−1	−1	−1	+1	−1	+1	−1	−1	+1
82	+1	−1	−1	−1	+1	−1	+1	+1	−1	−1
83	−1	+1	−1	−1	+1	−1	+1	+1	+1	+1
84	+1	+1	−1	−1	+1	−1	+1	−1	+1	−1
85	−1	−1	+1	−1	+1	−1	+1	+1	+1	−1
86	+1	−1	+1	−1	+1	−1	+1	−1	+1	+1
87	−1	+1	+1	−1	+1	−1	+1	−1	−1	−1
88	+1	+1	+1	−1	+1	−1	+1	+1	−1	+1
89	−1	−1	−1	+1	+1	−1	+1	−1	+1	−1
90	+1	−1	−1	+1	+1	−1	+1	+1	+1	+1
91	−1	+1	−1	+1	+1	−1	+1	+1	−1	−1
92	+1	+1	−1	+1	+1	−1	+1	−1	−1	+1
93	−1	−1	+1	+1	+1	−1	+1	+1	−1	+1
94	+1	−1	+1	+1	+1	−1	+1	−1	−1	−1
95	−1	+1	+1	+1	+1	−1	+1	−1	+1	+1
96	+1	+1	+1	+1	+1	−1	+1	+1	+1	−1
97	−1	−1	−1	−1	−1	+1	+1	−1	+1	−1
98	+1	−1	−1	−1	−1	+1	+1	+1	+1	+1
99	−1	+1	−1	−1	−1	+1	+1	+1	−1	−1
100	+1	+1	−1	−1	−1	+1	+1	−1	−1	+1
101	−1	−1	+1	−1	−1	+1	+1	+1	−1	+1
102	+1	−1	+1	−1	−1	+1	+1	−1	−1	−1
103	−1	+1	+1	−1	−1	+1	+1	−1	+1	+1
104	+1	+1	+1	−1	−1	+1	+1	+1	+1	−1
105	−1	−1	−1	+1	−1	+1	+1	−1	−1	+1
106	+1	−1	−1	+1	−1	+1	+1	+1	−1	−1
107	−1	+1	−1	+1	−1	+1	+1	+1	+1	+1
108	+1	+1	−1	+1	−1	+1	+1	−1	+1	−1
109	−1	−1	+1	+1	−1	+1	+1	+1	+1	−1
110	+1	−1	+1	+1	−1	+1	+1	−1	+1	+1

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Table A1 (*continued*)

Factor value										
Experiment	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
111	−1	+1	+1	+1	−1	+1	+1	−1	−1	−1
112	+1	+1	+1	+1	−1	+1	+1	+1	−1	+1
113	−1	−1	−1	−1	+1	+1	+1	−1	−1	−1
114	+1	−1	−1	−1	+1	+1	+1	+1	−1	+1
115	−1	+1	−1	−1	+1	+1	+1	+1	+1	−1
116	+1	+1	−1	−1	+1	+1	+1	−1	+1	+1
117	−1	−1	+1	−1	+1	+1	+1	+1	+1	+1
118	+1	−1	+1	−1	+1	+1	+1	−1	+1	−1
119	−1	+1	+1	−1	+1	+1	+1	−1	−1	+1
120	+1	+1	+1	−1	+1	+1	+1	+1	−1	−1
121	−1	−1	−1	+1	+1	+1	+1	−1	+1	+1
122	+1	−1	−1	+1	+1	+1	+1	+1	+1	−1
123	−1	+1	−1	+1	+1	+1	+1	+1	−1	+1
124	+1	+1	−1	+1	+1	+1	+1	−1	−1	−1
125	−1	−1	+1	+1	+1	+1	+1	+1	−1	−1
126	+1	−1	+1	+1	+1	+1	+1	−1	−1	+1
127	−1	+1	+1	+1	+1	+1	+1	−1	+1	−1
128	+1	+1	+1	+1	+1	+1	+1	+1	+1	+1
129	−1	0	0	0	0	0	0	0	0	0
130	+1	0	0	0	0	0	0	0	0	0
131	0	−1	0	0	0	0	0	0	0	0
132	0	+1	0	0	0	0	0	0	0	0
133	0	0	−1	0	0	0	0	0	0	0
134	0	0	+1	0	0	0	0	0	0	0
135	0	0	0	−1	0	0	0	0	0	0
136	0	0	0	+1	0	0	0	0	0	0
137	0	0	0	0	−1	0	0	0	0	0
138	0	0	0	0	+1	0	0	0	0	0
139	0	0	0	0	0	−1	0	0	0	0
140	0	0	0	0	0	+1	0	0	0	0
141	0	0	0	0	0	0	−1	0	0	0
142	0	0	0	0	0	0	+1	0	0	0
143	0	0	0	0	0	0	0	−1	0	0
144	0	0	0	0	0	0	0	+1	0	0
145	0	0	0	0	0	0	0	0	−1	0
146	0	0	0	0	0	0	0	0	+1	0
147	0	0	0	0	0	0	0	0	0	−1
148	0	0	0	0	0	0	0	0	0	+1
149	0	0	0	0	0	0	0	0	0	0
150	0	0	0	0	0	0	0	0	0	0
151	0	0	0	0	0	0	0	0	0	0

Table A2
Power and oil flow. Design 3. Not optimised.

Exp.	Power(kW)	Flow(l/h)	Exp.	Power(kW)	Flow(l/h)	Exp.	Power(kW)	Flow(l/h)
1	0.2114	0.0308	51	0.1572	0.0769	101	0.2295	0.0317
2	0.1775	0.024	52	0.2366	0.0465	102	0.1745	0.0531
3	0.1756	0.0271	53	0.2586	0.0206	103	0.2369	0.0302
4	0.1942	0.0266	54	0.249	0.0448	104	0.2245	0.0557
5	0.1779	0.0406	55	0.2758	0.0227	105	0.307	0.1033
6	0.2716	0.0196	56	0.2129	0.0422	106	0.2872	0.1733
7	0.2666	0.0139	57	0.4349	0.0788	107	0.3954	0.1023
8	0.2816	0.0103	58	0.3158	0.1346	108	0.2921	0.1704
9	0.3148	0.1026	59	0.3601	0.0798	109	0.39	0.0973
10	0.3456	0.0786	60	0.3341	0.1161	110	0.4587	0.0587
11	0.4115	0.0329	61	0.356	0.0768	111	0.3247	0.0981
12	0.5274	0.0326	62	0.5323	0.0433	112	0.481	0.0587
13	0.4761	0.0434	63	0.4601	0.0768	113	0.119	0.0978
14	0.4621	0.0612	64	0.5383	0.0437	114	0.1826	0.0541
15	0.5065	0.0433	65	0.1733	0.0287	115	0.1537	0.092
16	0.3785	0.0587	66	0.193	0.0278	116	0.1865	0.0593
17	0.1879	0.0451	67	0.1894	0.0277	117	0.2569	0.0331
18	0.1444	0.0584	68	0.1608	0.0239	118	0.1957	0.0559
19	0.2255	0.0126	69	0.1795	0.0551	119	0.219	0.0311
20	0.256	0.0155	70	0.2127	0.028	120	0.2117	0.055
21	0.2056	0.0331	71	0.2187	0.0117	121	0.3436	0.1038
22	0.2956	0.0236	72	0.2957	0.0121	122	0.3128	0.0905
23	0.2239	0.0311	73	0.2599	0.1031	123	0.3607	0.1025
24	0.259	0.0172	74	0.3539	0.1001	124	0.2655	0.1326
25	0.4021	0.0604	75	0.4522	0.033	125	0.3574	0.0976

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Table A2. (*continued*)

26	0.4023	0.0605	76	0.4374	0.0321	126	0.4148	0.0591
27	0.3213	0.0589	77	0.4779	0.0586	127	0.3643	0.0982
28	0.4212	0.0586	78	0.3834	0.0609	128	0.5325	0.059
29	0.4378	0.044	79	0.3964	0.058	129	0.3089	0.0646
30	0.4072	0.0764	80	0.4019	0.0581	130	0.3233	0.064
31	0.5733	0.0332	81	0.1462	0.0535	131	0.3108	0.064
32	0.4712	0.033	82	0.1535	0.0487	132	0.3228	0.0638
33	0.164	0.0748	83	0.2436	0.0144	133	0.2675	0.09
34	0.1986	0.0395	84	0.2137	0.0111	134	0.3518	0.0514
35	0.1393	0.0739	85	0.2169	0.0347	135	0.213	0.0434
36	0.2127	0.0424	86	0.2378	0.0301	136	0.4122	0.0786
37	0.2298	0.0194	87	0.1798	0.0292	137	0.3142	0.0639
38	0.2235	0.0412	88	0.2577	0.0316	138	0.3178	0.0648
39	0.2955	0.0212	89	0.332	0.0608	139	0.3303	0.041
40	0.2287	0.0392	90	0.4308	0.0592	140	0.322	0.0639
41	0.3916	0.0789	91	0.3532	0.0579	141	0.3403	0.0543
42	0.2843	0.1339	92	0.3489	0.0587	142	0.3011	0.0723
43	0.4011	0.0791	93	0.437	0.059	143	0.2938	0.0639
44	0.3645	0.1319	94	0.3192	0.0973	144	0.3317	0.0635
45	0.3939	0.0763	95	0.4754	0.033	145	0.2993	0.0642
46	0.5795	0.0437	96	0.508	0.0331	146	0.3287	0.0647
47	0.4135	0.0768	97	0.1292	0.0932	147	0.2751	0.0887
48	0.4784	0.0432	98	0.1954	0.0577	148	0.3463	0.0521
49	0.1523	0.076	99	0.1381	0.1036	149	0.3169	0.0637
50	0.1826	0.0418	100	0.1652	0.0538	150	0.3169	0.0637
						151	0.3169	0.0637

are achievable – possibly as high as 7% – provided attention is paid to lubricant and material properties in other areas of the engine.

It has also been shown that experimental tests on engines need to consider interactions between factors if the radii of curvature and offset-ratios of the rings are to be varied.

Appendix

See Tables A1 and A2.

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