Performance simulation of a spark ignited free-piston engine generator. ⋆

R. Mikalsen, A.P. Roskilly *

Sir Joseph Swan Institute for Energy Research, Newcastle University, Newcastle upon Tyne, NE1 7RU, United Kingdom.

Abstract

Free-piston engines are under investigation by a number of research groups worldwide due to potential fuel efficiency and engine emissions advantages. The free-piston engine generator, in which a linear electric generator is fixed to the mover to produce electric power, has been proposed as an alternative prime mover for hybrid-electric vehicles. This paper investigates the performance of a spark ignited free-piston engine generator and compares it to a conventional engine using a computational fluid dynamics simulation model. The particular operating characteristics of the free-piston engine were not found to give noticeable performance advantages, and it is concluded that the main potential of this technology lies in the simplicity and flexibility of the concept.

Key words: free-piston, spark ignition, two stroke, linear engine, CFD

1. Introduction

Ever-tightening environmental legislation drive a significant research effort to reduce the environmental impacts of hydrocarbon fuel combustion in internal combustion engines. Within the automotive industry, the hybrid-electric vehicle (HEV) has gained much attention in recent years and such technology is becoming commercially available from an increasing number of manufacturers.

HEVs employ an electric drive with an energy storage device, which partly or fully separates the combustion engine from the mechanical drive chain. This reduces the load variations on the engine and allows it to work closer to its optimum operating conditions, resulting in increased fuel efficiency and reduced emissions.

Moreover, eliminating the need for a wide load and speed range may allow a more optimised engine design, further enhancing engine performance. Changing the prime mover requirements may also allow the implementation of alternative technologies such as fuel cells or other types of internal or external combustion engines.

A similar concept with the same motivations and potential advantages, currently being explored within the marine industry, is the all-electric ship concept.

1.1. *Free-piston engines*

After some degree of success in the mid-20th century, the free-piston engine has in recent years mainly been regarded a curiosity of the past. A number of free-piston engines served successfully as air compressors and gas generators in the period 1930-1960, with some reported advantages over

⋆ This is a preprint version. This paper was published as: Applied Thermal Engineering, Volume 28, Issues 14–15, October 2008, Pages 1726–1733.

* Corresponding author.

Email addresses: rikard@mikalsen.eu (R. Mikalsen), tony.roskilly@ncl.ac.uk (A.P. Roskilly).

present-time conventional technology. However, as conventional engine and gas turbine technology matured, the free-piston engines lost their advantages and the concept was eventually abandoned.

In recent years, attempts to employ free-piston engines to generate electric and hydraulic power have been reported. Potential advantages include: a compact and simple design with low maintenance costs, high controllability, allowing operation optimisation for varying operating conditions, and multi-fuel possibilities. In addition, the free-piston engine should be well suited for homogeneous charge compression ignition (HCCI) operation due to lower ignition timing control requirements, as has been proposed by some authors.

Free-piston engines are characterised by a purely linear piston motion that is not restricted by a crank mechanism. Figure 1 shows a dual piston free-piston engine with a linear electric machine as a load device. A number of variations exist, and another common configuration is the single piston unit which employs a single combustion cylinder and a rebound device to return the piston. The rebound device can for example be a gas filled bounce chamber, or it can be incorporated into the load device. An example of the latter is the hydraulic free-piston engine reported by Achten et al. [1], in which a single hydraulic cylinder is used to utilise parts of the generated hydraulic energy to return the piston.

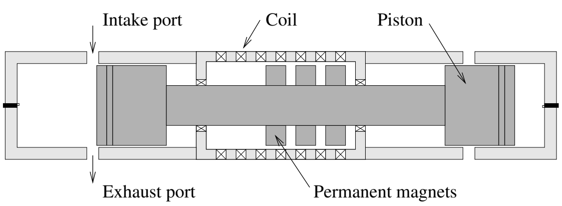

Fig. 1. Illustration of a dual piston free-piston engine generator [2].

1.2. *Reported free-piston engine applications*

The vast majority of free-piston engines reported in the mid-20th century were diesel engines, but many of the recent approaches have employed spark ignition. This paper is concerned with spark ignited free-piston engines only, for an overview of reported diesel-powered units and their performance the reader is referred to [3].

Goertz and Peng [4] evaluated the feasibility of free-piston engines as prime movers in HEVs, and identified the main challenges and advantages associated with such technology. The free-piston engine was considered a promising candidate for such applications, however with possible challenges in piston motion control and the possible influence of the piston motion profile (a very short time spent at TDC) on the combustion process.

A research group at University of West Virginia developed a dual piston free-piston engine generator prototype, described by Famouri et al. [2] and Clark et al. [5]. They have thoroughly documented their findings, and this group is one of the most successful free-piston engine developers within academia to date. The engine was reported to have achieved 316 W power output, operating at 23.1 Hz, with 36.5 mm bore and 50 mm maximum stroke. High cycle-to-cycle variations were reported, in particular at low loads.

Carter and Wechner [6] presented the design of a "Free Piston Power Pack", a unit consisting of four dual piston free-piston engines, intended for HEVs. Total power output is 100 kW, and proposed advantages of the unit include high power density, long life, dynamic balance and multi-fuel capability.

Braun and Schweitzer [7] described the design of a single piston free-piston air compressor. Counterweights were applied to make the engine completely balanced, and extensive testing was reported, including 15,000 hours of operation without breakdown and 40,000 consecutive starts without a miss.

Baruah [8] presented detailed modelling and simulation of a single piston free-piston engine, comparing the unit to a conventional engine. It was found that the free-piston engine has clear advantages over conventional engines in terms of nitric oxides emissions formation, with up to a 50 per cent reduction reported. No thermodynamic advantages were found, and the levels of carbon monoxide emissions were comparable between the two engines.

For a comprehensive review of reported free-piston engine applications and their features, see Mikalsen and Roskilly [3].

1.3. *Free-piston engine particular features*

A number of authors have reported that the main difference between conventional engines and free-piston engines is the piston motion profile, with a significantly faster expansion shortly after TDC in the free-piston engine. In conventional engines the piston motion is controlled by the crankshaft and the high inertia in the system means that the piston motion cannot be influenced within the timescale of one cycle. In free-piston engines, the piston motion is determined by the instantaneous force balance on the mover, which means that the progress of the combustion will influence the speed of expansion. A further consequence of this is that the piston motion profile may differ between different operating conditions.

The simple design of the free-piston engine and the reduced number of moving parts minimise frictional losses. Crankshaft bearing losses are eliminated, and the piston friction is reduced due to the purely linear motion, giving very low side forces on the piston. Not having the piston motion restricted by a crankshaft further allows the free-piston engine to operate with variable stroke length and compression ratio. This possibly gives extensive engine operation optimisation possibilities, but requires a piston motion control system to be realised.

The fast power stroke expansion in the free-piston engine potentially leads to reduced heat transfer losses and reductions in the formation of temperature-dependent emissions. However, high piston acceleration around TDC leads to higher volume changes during combustion, which may reduce thermal efficiency.

1.4. *Challenges with the design*

The free-piston engine is restricted to the two stroke operating principle, since a power stroke is required every cycle. Small two stroke engines, such as those found in small motorcycles, are usually port scavenged to keep the design simple and reliable. Operating with pre-mixed charge, these engines suffer heavily from short-circuiting, i.e. that part of the inlet charge passes through the cylinder and out with the exhaust. This gives penalties in both fuel efficiency and exhaust gas emissions, and is a major problem for small, spark ignited two stroke engines. For larger applications, where engine simplicity is less important, the engine can be designed with exhaust valves in the cylinder head. This allows the more efficient uniflow scavenging to be employed, which will reduce the problem of short circuiting, but this problem will always be present in pre-mixed two stroke engines. An alternative is the use of direct injection spark ignition (DISI, also known as gasoline direct injection), which will eliminate the problem completely.

A further potential challenge with the free-piston design is the control of the engine. Referring to the engine illustrated in Figure 1, it is seen that the compression stroke is driven by the power stroke expansion in the opposite cylinder. Variations in the combustion progress in one cylinder will therefore have high influence on the compression and combustion in the other, and such errors may accumulate. For the free-piston concept to be feasible, a control system which can secure stable and smooth engine operation must be realised.

2. Simulation methodology

Most reported modelling of free-piston engines is based on zero-dimensional, single-zone models, in which the cylinder charge is assumed homogeneous and uniform in temperature and heat is added to the charge according to a pre-defined fuel burn rate. (See Goertz and Peng [4] and Atkinson et al. [9] for examples. A slightly more advanced approach was presented by Baruah [8].) While this may be sufficient to model basic engine performance, for example in the early stages of a design process, such models do not account for factors such as in-cylinder gas motion and cannot accurately predict emissions formation. Moreover, most such models have been developed for, and calibrated against, conventional engines, and it is questionable whether they are suitable for modelling free-piston engines without modifications.

Modern computational fluid dynamics (CFD) codes provide powerful tools to investigate the highly complex interaction between in-cylinder gas motion, heat transfer, combustion and chemical kinetics in internal combustion engines, and such codes are widely used in engine research. Although computationally intensive, CFD codes are particularly well suited for problems such as the one presented in this paper, where effects of single parameters are to be investigated with other variables constant.

2.1. *Simulation model*

The simulations in this paper were performed using the open source CFD toolkit OpenFOAM [10]. Written in the object oriented C++ programming language and released under the GNU General Public Licence, OpenFOAM gives the user considerable power to modify the code to suit specific needs, for example with the implementation of new submodels or modification of existing solvers. After its release under an open source licence in 2004 the software has enjoyed a rapidly increasing user base, particularly within academia where a transparent and easily extendable code is of high importance.

Ready-made solvers for a wide range of applications are shipped with the toolkit, including fluid flow, electromagnetics, solid mechanics and combustion. Implemented in the toolkit is the Weller combustion model [11] for simulating spark ignited combustion, and this was used in the simulations presented in this paper. Jasak et al. [12] described the capabilities of the toolkit for combustion engine simulations and presented some examples. Further examples of the use of OpenFOAM in engine research can be found in the reports of Cerri et al. [13] and Onorati et al. [14].

The simulation model, including the code for engine emissions predictions described below, was validated against experimental data from a Rover K-16 1400TBI engine, presented by Wang and Ruxton [15].

2.2. *Case setup*

A simple piston and cylinder design is sufficient for a comparative study such as the one presented here. The engine geometry is assumed to be symmetric around the cylinder axis, allowing a wedge geometry with cyclic boundary conditions to be used. This simplification reduces the computational costs significantly. Figure 2 shows the computational mesh used in the simulations. The mesh is a 30-degree wedge with 9200 cells, equivalent to more than 110000 cells for the full cylinder.

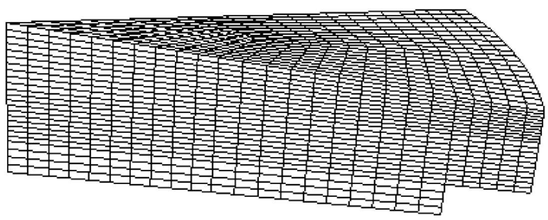

Fig. 2. Computational mesh used in the simulations.

The engine has 60mm bore, 60mm stroke, a nominal compression ratio of 8:1, and the fuel used is iso-octane at a fuel-air equivalence ratio of 1. Turbulence is modelled with a standard k–ϵ model with wall functions, and constant wall temperatures were used. As the engine is two stroke, the simulations were run between the points of exhaust ports closing and exhaust ports opening. Swirl was introduced at the start of compression, and the swirl level was assumed to be constant for all engine speeds.

2.3. *Modifications to the code*

The piston dynamics of a free-piston engine were investigated by Mikalsen and Roskilly [16]. A continuation of that work showed that the piston motion profile varies only slightly between different free-piston engine configurations, and that the main difference to conventional engines, namely the motion around TDC, is present for all designs. Hence, the results presented here should be valid for most types of free-piston engines.

The simulated piston motion profile of a single piston free-piston engine compared to that of a conventional engine is shown in Figure 3. The fast power stroke expansion and significantly shorter time spent around TDC is evident, consistent with that reported by other authors [1,17]. The piston motion profile was described mathematically through least square error fitting to a high-order polynomial and implemented into the OpenFOAM code. This allows a direct comparison between the free-piston and conventional engines for identical engine design and operating conditions.

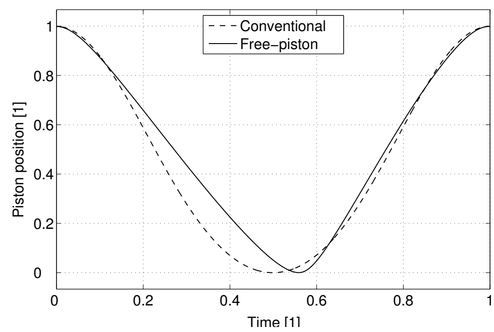

Fig. 3. Simulated piston motion profile for a single piston free-piston engine and that of a conventional engine [16]. (TDC at position 0.)

The comparison in Figure 3 was done on a time basis since the piston motion in the free-piston engine cannot be measured in crank angles. It is seen that the piston motion in the single piston free-piston engine is slightly asymmetric, i.e. the engine spends more time in the compression stroke than in the expansion stroke. (Note that this will not be the case for a dual piston engine, like the one illustrated in Figure 1.) To allow an easier comparison, this piston motion profile was normalised around TDC and 'translated' into crank angles, and this notation is used in the investigations below.

3. Simulation results

To allow a direct comparison between the free-piston engine and a conventional one, the engines must run at comparable operating conditions. While all the externally set conditions, such as engine speed and intake air pressure and temperature, are identical, the optimum ignition timing may vary between the two engines. A series of simulations were run to identify the optimum spark timing, and all results presented below are run at maximum brake torque (MBT) ignition timing.

3.1. *Basic engine performance*

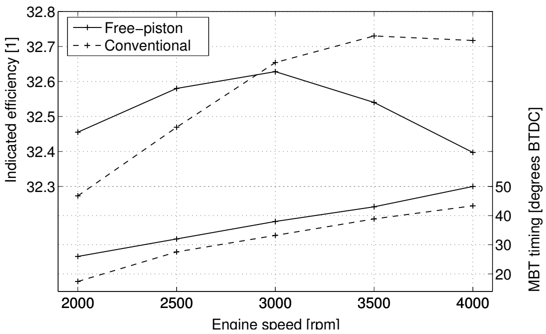

Fig. 4. Engine efficiency and MBT ignition timing of the free-piston engine compared to a conventional engine.

The simulations showed that the free-piston engine requires advanced spark timing compared to the conventional one, which is likely to be due to the faster expansion just after TDC. Figure 4 shows the spark timing required for maximum brake torque for the two engines.

Figure 4 further shows the predicted indicated efficiency of the two engines. It can be seen that the free-piston engine has a slight efficiency advantage over the conventional engine at low speeds, but that the efficiency of the free-piston engine drops as the speed increases. This is likely due to the effects of volume change during combustion having greater impact at higher speeds. Overall, only very small differences in indicated efficiency between the two engines are found.

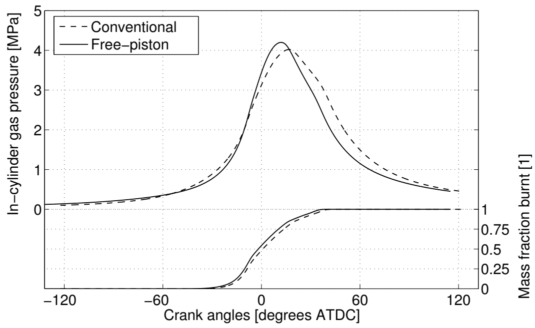

Fig. 5. Simulated in-cylinder pressure and mass fraction burnt for the free-piston and conventional engines running at 3000rpm.

Figure 5 shows the in-cylinder gas pressure plot for the two engines. It is seen that the free-piston engine has a slightly higher peak in-cylinder pressure, due to the advanced spark timing. The pressure drops more rapidly in the free-piston engine due to the faster power stroke expansion.

For some diesel-powered free-piston engines, higher heat release rates compared to conventional engines have been reported [1,17]. It has been suggested that this is due to the high piston acceleration around TDC, increasing in-cylinder gas velocities and turbulence levels. Although the gas motion and turbulence levels in a spark ignition engine are significantly lower than those of a diesel engine, any such differences will influence the flame speed and this may have effects on engine performance. Figure 5 shows the mass fraction burnt for the two engines as a function of crank angle. With the exception of the advanced spark timing in the free-piston engine, no noticeable differences in the fuel burn pattern were found.

3.2. *Part load performance*

For lean mixtures (mixtures with fuel-air equivalence ratios of less than 1) the flame speed is reduced, giving a decrease in engine efficiency. Although the flame speed of a mixture peaks for slightly rich of stoichiometric conditions, the indicated efficiency usually peaks for slightly lean mixtures, since the efficiency also depends on factors such as heat transfer losses and the chemical composition of the burnt gases.

Figure 6 shows the predicted part load performance of the two engines. For both engines, the efficiency penalty occurs immediately on the lean side of stoichiometric. This is due to the poor compact-

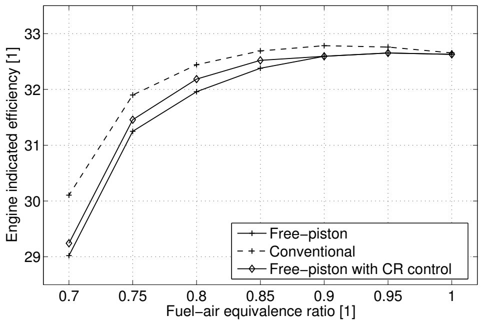

Fig. 6. Part load performance of the free-piston and conventional engines.

ness of the combustion chamber, penalising even small reductions in flame speed. The higher volume change during combustion in the free-piston engine makes the efficiency drop more rapidly as the charge is diluted, decreasing its part load performance compared to the conventional engine.

Variable stroke length

While the compression ratio in a conventional engine is fixed (with the exception of small variations depending on the valve timings and valve flow characteristics), the free-piston engine can be designed to allow variation practically without limits. The compression ratio can be varied continuously during engine operation by varying the TDC setpoint, and this may provide operation optimisation possibilities at part load.

The limitation in compression ratio lies in the fuel quality and its knock (self-ignition) characteristics, and is commonly between 7:1 and 11:1 for ordinary gasoline fuels. The limitation in compression ratio typically occurs for fuel-air equivalence ratios of around 0.9, i.e. slightly lean of stoichiometric. For leaner mixtures, the knock limit increases drastically, and may exceed a compression ratio of 15:1 for very lean mixtures.

Figure 6 shows the simulated part load performance of the free-piston engine with such compression ratio control. For equivalence ratios, ϕ, of 0.9 and lower, the compression ratio was increased linearly between the nominal 8:1 to 10:1 at $\phi = 0.7$. A small efficiency improvement is seen, however, due to the knock limitations, increasing the compression ratio cannot offset the efficiency disadvantage of the free-piston engine. At very low loads, where the compression ratio can be increased significantly more, these effects are expected to be higher. However, from an engine fuel economy perspective, the load range presented here will be of highest interest.

3.3. *Multi-fuel operation*

The high operational flexibility in the free-piston engine may provide significant multi-fuel possibilities. High engine performance can be achieved for a variety of fuels, which allows the operator to select the fuel based on current fuel prices, emission targets or other factors. For example, ethanol-gasoline blends are becoming increasingly common and are widely available at petrol stations in many countries. Utilising the variable compression ratio together with modern engine technology such as electronically controlled, variable spark timing and accurate knock sensors, the engine operation can be optimised based on the properties of a given fuel.

The most important characteristics of a fuel are flame speed, knock limit and heat content. For example, ethanol has a flame speed that is approximately 30 % higher than that of ordinary gasoline fuel, in addition to a higher knock limit. Hydrogen has a flame speed that is one order of magnitude higher than these fuels.

It was seen above that the free-piston engine appeared to suffer more from reduced flame speed than the conventional one. To investigate the sensitivity to, and effects of, flame speed in the free-piston and conventional engines, a correction factor was introduced into the OpenFOAM code to modify the calculated flame speed.

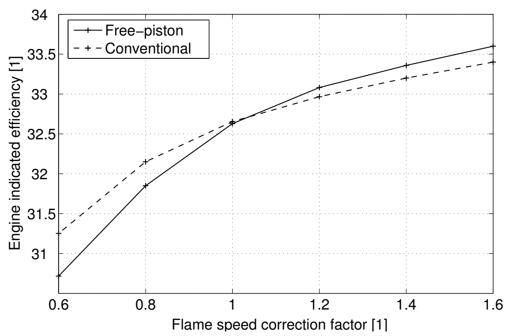

Fig. 7. Effects of varying flame speed on engine performance.

Figure 7 shows the effects of varying flame speed on engine performance predictions. It is seen that the free-piston engine has advantages for fast-burning fuels, since this reduces the negative effects of high volume change during combustion, but that the efficiency drops rapidly for lower flame speeds.

One reason for the latter is that the ignition timing in the free-piston engine had to be advanced significantly for the combustion process to finish in time, more than in the conventional engine. (The fact that the graphs intersect for a correction factor of around one is coincidental.)

3.4. *Engine emissions*

The main emissions from spark ignited engines are carbon monoxide (CO), nitric oxides (NO_x) and unburnt hydrocarbons (HC). In addition to these comes carbon dioxide (CO_2), which is a product of hydrocarbon fuel combustion and can only be reduced by improving fuel efficiency.

HC emissions mainly result from incomplete combustion, e.g. in crevices within the cylinder. The operational differences between free-piston and conventional engines are not believed to result in differences in HC emissions formation, and these are therefore not further investigated in this paper. The formation of CO and NO_x emissions depend highly on the temperature of the in-cylinder gases and the time spent in the high-temperature parts of the cycle, and may therefore be influenced by the particular operating characteristics of the free-piston engine.

Both CO and NO_x are formed at high temperatures and pressures around TDC, where the equilibrium values of these species are significantly higher than those for exhaust gas conditions. As the cylinder gases are cooled during the expansion, the destruction mechanisms for these species become slower and the concentrations 'freeze' at a value higher than the equilibrium values in the exhaust gas. The shorter time spent around TDC and the faster expansion in the free-piston engine may therefore influence the levels of NO_x and CO emissions.

Methodology

A solver for the chemical composition of the in-cylinder gases, based on the approach presented by Olikara and Borman [20], was implemented into the OpenFOAM code. The equilibrium concentrations for a set of species was solved, along with the kinetics of NO_x and CO formation and destruction. 10 species were considered: CO_2, H_2O, N_2, O_2, CO, H_2, H, O, OH and NO.

The extended Zeldovich mechanism, described by Heywood [18], was employed to model the formation of nitric oxides:

$$\begin{aligned} \mathrm{O} + \mathrm{N_2} &\rightleftharpoons \mathrm{NO} + \mathrm{N} \\ \mathrm{N} + \mathrm{O_2} &\rightleftharpoons \mathrm{NO} + \mathrm{O} \\ \mathrm{N} + \mathrm{OH} &\rightleftharpoons \mathrm{NO} + \mathrm{H} \end{aligned}$$

Ramos [19] described the main reactions governing CO formation, and these were implemented in the simulation model:

$$\begin{aligned} \mathrm{CO} + \mathrm{OH} &\rightleftharpoons \mathrm{CO_2} + \mathrm{H} \\ \mathrm{CO_2} + \mathrm{O} &\rightleftharpoons \mathrm{CO} + \mathrm{O_2} \end{aligned}$$

In order to predict NO_x and CO formation, the concentration of the other species must be estimated. These are commonly assumed to be in chemical equilibrium, and their concentrations can be found using a set of reaction equations with appropriate equilibrium constants. For the 8 remaining species, consisting of 4 chemical elements, 4 independent chemical reactions can be written. The following reactions were chosen [21]:

$$\begin{aligned} \frac{1}{2}\mathrm{H_2} &\rightleftharpoons \mathrm{H} \\ \frac{1}{2}\mathrm{O_2} &\rightleftharpoons \mathrm{O} \\ \frac{1}{2}\mathrm{H_2} + \frac{1}{2}\mathrm{O_2} &\rightleftharpoons \mathrm{OH} \\ \mathrm{H_2} + \frac{1}{2}\mathrm{O_2} &\rightleftharpoons \mathrm{H_2O} \end{aligned}$$

Together with the four element balance equations this gives eight equations with eight unknowns. This set of equations was solved using Newton-Raphson iteration. The chemical composition was solved for each cell in the domain, giving a significant penalty in computational time. For this investigation, the simplified mesh and the limited number of simulations required made this approach acceptable.

Results

Figure 8 shows the predicted concentration of NO_x and CO emissions in the cylinder gases at the time of exhaust port opening. As above, the engines run at MBT ignition timing, with no exhaust gas recirculation and at stoichiometric conditions, giving somewhat high NO_x emissions levels. It is seen from the figure that noticeable differences between free-piston and conventional engines could be found neither in the NO_x nor in the CO emission levels.

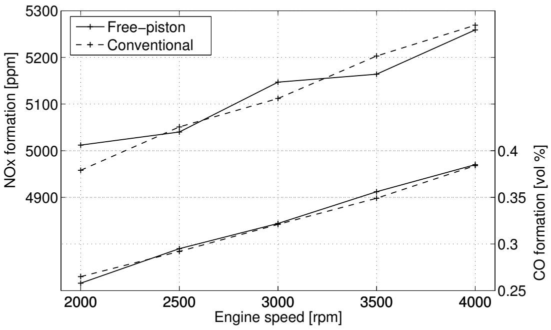

Fig. 8. Predicted engine emissions from the free-piston and conventional engines.

Baruah [8] reported that a significant reduction in NO_x emissions was obtained in the free-piston engine due to the fact that the ignition timing could be retarded with low penalties in engine efficiency. It was shown above that the MBT ignition timing is advanced in the free-piston engine compared to the conventional one, and it was found that the free-piston engine has no advantages in terms of emissions compared to conventional engines at MBT spark timing. Simulations were run to investigate the sensitivity of the free-piston engine to the spark timing, compared to that of a conventional engine, and the effects of spark timing on engine emissions. Figure 9 shows the effects of advancing or retarding spark ignition timing for both engine types. It is seen that the efficiency penalty of retarding spark timing is similar for the two engines, but that the free-piston engine benefits slightly more from this in terms of NO_x emissions than the conventional one.

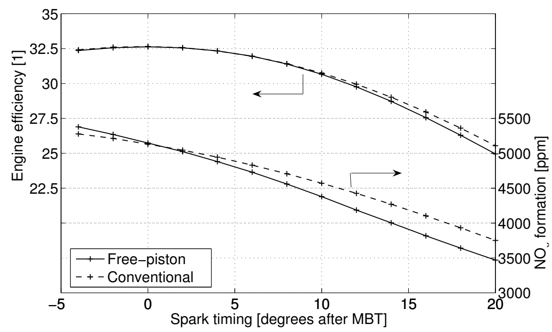

Fig. 9. Engine sensitivity to changes in spark timing and effects on NO_x emissions formation.

4. Conclusions

The performance of a spark ignited free-piston engine was simulated and directly compared to that simulated for a conventional engine. The aim of the work was to investigate potential advantages of the free-piston engine and identify effects of the particular piston motion profile of such engines. The simulations showed only minor differences in engine performance, and no thermodynamic advantages were identified. It was found that the free-piston engine suffers more from reductions in flame speed, such as that occurring at part load operation. The variable compression ratio in the free-piston engine could only partly compensate for this, due to the fuel knock limit. For faster-burning fuels, the free-piston engine showed a slight performance advantage over the conventional engine.

Carbon monoxide and nitric oxide emissions were investigated but only minor differences were found between free-piston and conventional engines. The free-piston engine was found to benefit slightly more from retarded spark timing with regards to nitric oxide emission.

The variable compression ratio in the free-piston engine provides extensive operation optimisation possibilities if operating on varying fuels. The multi-fuel possibilities are, in addition to the reduced frictional losses from the simple free-piston design, considered the main advantages of this concept. Piston motion control issues were not investigated, but must be resolved for the free-piston engine concept to be viable.

Experimental investigations into the performance and controllability of free-piston engines are currently in progress at the Sir Joseph Swan Institute for Energy Research, University of Newcastle upon Tyne. Due to the failure to identify significant advantages of the spark ignited free-piston engine through engine simulation, and the potential difficulties associated with scavenging in pre-mixed, two stroke engines, future work will focus mainly on direct injection compression ignition free-piston engines.

References

[1] Achten PAJ, van den Oever JPJ, Potma J, Vael GEM. Horsepower with brains: The design of the Chiron free piston engine. SAE Paper 2000-01-2545, Society of Automotive Engineers, 2000.

[2] Famouri P, Cawthorne WR, Clark NN, Nandkumar S, Atkinson CM, Atkinson RJ et al. Design and testing of a novel linear alternator and engine system for remote electrical power generation. Proc. IEEE Power Engineering Society winter meeting, pp. 108–112, 1999.

[3] Mikalsen R, Roskilly AP. A review of free-piston engine history and applications. Applied Thermal Engineering, 2007:27:2339–2352.

[4] Goertz M, Peng LX. Free Piston Engine – Its Application and Optimization. SAE Paper 2000-01-0996, Society of Automotive Engineers, 2000.

[5] Clark NN, Nandkumar S, Atkinson CM, Atkinson RJ, McDaniel TI, Petreanu, S et al. Modelling and development of a linear engine. ASME Spring Conference, Internal Combustion Engine Division, 1998:30(2):49–57.

[6] Carter D, Wechner E. The Free Piston Power Pack: Sustainable Power for Hybrid Electric Vehicles. SAE Paper 2003-01-3277, Society of Automotive Engineers, 2003.

[7] Braun AT, Schweitzer PH. The Braun linear engine. SAE paper 730185, Society of Automotive Engineers, 1973.

[8] Baruah PC. A free-piston engine hydraulic pump for an automotive propulsion system. SAE Paper 880658, Society of Automotive Engineers, 1988.

[9] Atkinson CM, Petreanu S, Clark NN, Atkinson RJ, McDaniel TI, Nankumar S et al. Numerical simulation of a two-stroke linear engine-alternator combination. SAE Paper 1999-01-0921, Society of Automotive Engineers, 1999.

[10] OpenFOAM project web site. `http://www.OpenFOAM.org`, 2007.

[11] Weller, HG. The development of a new flame area combustion model using conditional averaging. Thermo-Fluids Section Report TF 9307, Imperial College of Science, Technology and Medicine, 1993.

[12] Jasak H, Weller HG, Nordin N. In-cylinder CFD simulation using a C++ object-oriented toolkit. SAE Paper 2004-01-0110, Society of Automotive Engineers, 2004.

[13] Cerri T, D'Errico G, Lucchini T. Development and application of S.I. combustion models for emissions prediction. SAE Paper 2006-01-1108, Society of Automotive Engineers, 2006.

[14] Onorati A, D'Errico G, Piscaglia F, Montenegro G. Integrated 1D-MultiD fluid dynamic models for the simulation of I.C.E. intake and exhaust systems. SAE Paper 2007-01-0495, Society of Automotive Engineers, 2007.

[15] Wang Y, Ruxton T. An experimental investigation of NOx emission reduction from automotive engine using the Miller cycle. Proc. ASME 2004 Fall Technical Conference, Long Beach, CA, USA, 2004.

[16] Mikalsen R, Roskilly AP. The design and simulation of a two-stroke free-piston compression ignition engine for electrical
power generation. Applied Thermal Engineering (2007), doi:10.1016/j.applthermaleng.2007.04.009

[17] Tikkanen S, Lammila M, Herranen M, Vilenius, M. First cycles of the dual hydraulic free piston engine. SAE Paper 2000-01-2546, Society of Automotive Engineers, 2000.

[18] Heywood JB. Internal combustion engine fundamentals. McGraw-Hill, Inc., 1988.

[19] Ramos JI. Internal combustion engine modeling. Hemisphere Publishing Corp., 1989.

[20] Olikara C, Borman GL. A computer program for calculating properties of equilibrium combustion products with some applications to I.C. engines. SAE Paper 750468, Society of Automotive Engineers, 1975.

[21] Ferguson CR. Internal combustion engines: applied thermodynamics. John Wiley & Sons., 2000.