The fuel efficiency and exhaust gas emissions of a low heat rejection free-piston diesel engine

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Abstract: This article investigates the in-cylinder heat transfer losses of a free-piston diesel engine and compares the results with those of a conventional engine, using a multidimensional simulation model. In-cylinder heat transfer, fuel efficiency, and nitrogen oxides (NO) emissions formation are studied, along with the suitability of the free-piston engine to use a low heat rejection combustion chamber design. It is found that the high piston acceleration around top dead centre and the fast power stroke expansion in the free-piston engine lead to reduced heat transfer losses and reduced NO emissions formation, the latter in the order of 17 per cent compared with conventional engines. Even for highly insulated combustion chambers, the free-piston engine is predicted to have lower NO emissions than the conventional engine in the original configuration. The use of a low heat rejection combustion chamber is found to benefit engine fuel efficiency in both free-piston and conventional engines, with a 30 per cent heat loss reduction improving the indicated efficiency by approximately 3 percentage points. With a simpler implementation of combustion chamber insulation due to the low side forces on the piston, it is argued that the free-piston engine should be well suited for such an operation.

Keywords: free-piston, combustion, low heat rejection, heat loss, emissions

1 INTRODUCTION

The improving of internal combustion engine thermal efficiency has been studied ever since this type of engine came into widespread service nearly a century ago. Currently, increasing fuel prices and tightening environmental legislation present a great challenge for engine manufacturers: to achieve simultaneous reductions in engine fuel consumption and exhaust gas emissions levels. Much research, both within industry and academia, is dedicated to developing more efficient and environmentally friendly fuel chains.

The heat lost to in-cylinder heat transfer in internal combustion engines makes up a significant amount of the input fuel energy. Typically, around one-third of the input energy is converted into mechanical work, around one-third is lost as heat in the exhaust gases, and around one-third is lost as heat to the cooling system through mechanical friction and heat transfer losses within the engine. Approximately half of the latter (which equates to between 15 and 20 per cent of the fuel input energy) is lost to in-cylinder heat transfer, i.e. heat transfer from the hot gas to the combustion chamber surface area [**1**]. Clearly, there is a potential for improving engine fuel efficiency if this heat loss can be reduced and utilized either directly as piston work or via increased exhaust gas enthalpies in a bottoming cycle.

This article investigates the feasibility and performance of a free-piston engine with a low heat rejection combustion chamber using a multidimensional simulation model. The influence of reduced heat transfer losses on engine efficiency and emissions formation is studied and the free-piston engine is compared with a conventional engine to investigate whether the free-piston engine is better suited for this type of operation.

1.1 Low heat rejection engines

Low heat rejection internal combustion engines (also known as adiabatic engines) have been investigated by a number of researchers in recent years [**2–4**]. The principle behind such engines is the use of a coating

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material on the combustion chamber surface (i.e. the cylinder head, piston crown, and cylinder liner) to reduce thermal conductivity and thereby reduce heat transfer losses from the in-cylinder gases. This allows a larger proportion of the fuel energy to be converted into mechanical work or to leave the cylinder with the exhaust gases. Any increase in mechanical work done on the pistons will directly benefit the fuel efficiency of the engine, whereas increased energy in the exhaust gases can be utilized in a turbocharger or turbocompound system, or in a bottoming cycle such as a steam engine. Moreover, reduced in-cylinder heat transfer reduces the demands on the cooling system, which may allow a simpler design with lower energy consumption.

Jaichandar and Tamilporai [**2**] reviewed a number of reports on low heat rejection engines and showed that the reported effects of a low heat rejection combustion chamber vary. In general, however, improvements in fuel consumption with the use of a thermally insulating coating material on the combustion chamber surface area were reported. Simulation and experimental studies have shown that a reduction in combustion chamber heat transfer losses of between 30 and 50 per cent is possible, giving a fuel consumption improvement of 5–10 per cent for a turbocharged engine and up to around 15 per cent for a turbocompounded engine [**2**, **4**].

The disadvantage of reduced heat transfer from the in-cylinder gases is that higher gas temperatures may lead to an increase in the formation of temperature-dependent emissions, including nitrogen oxides (NO_x) [**4**]. Furthermore, a reduction in volumetric efficiency has been reported due to increased in-cylinder surface temperatures during the gas exchange stroke. However, the increased work output from the turbocharger has been reported to eliminate this problem [**3**].

1.2 The free-piston engine

The free-piston engine is a linear, ‘crankless’ engine in which the piston motion is not controlled by a crankshaft but by the interaction of forces from one or more linearly arranged combustion chambers, bounce chambers, and load devices. Such engines were in use in the period 1930–1960 as air compressors in – among others – marine applications and as gas generators supplying hot gas to a power turbine. In recent years, the free-piston engine concept has gained attention as a potential candidate for efficient generation of electric or hydraulic power. Notable modern free-piston engine developments include the hydraulic free-piston engines described by Achten *et al.* [**5**], Hibi and Ito [**6**], Tikkanen *et al.* [**7**], and Brunner *et al.* [**8**], and the free-piston engine generators described by Clark *et al.* [**9**], Carter and Wechner [**10**], and Van Blarigan *et al.* [**11**]. A comprehensive review of reported free-piston engine applications was presented by Mikalsen and Roskilly [**12**]. Previous work by the authors on the topic include investigations into the combustion process in spark ignition [**13**] and compression ignition [**14**] free-piston engines, as well as modelling and simulation of the complex interaction between mechanics and thermodynamics in such engines [**15**].

The main advantage of the free-piston engine concept is the simplicity of the design, leading to low manufacturing and maintenance costs, and low frictional losses. The absence of a crankshaft mechanism and high-load-carrying bearings allows engine operation at high pressures, along with a high level of operational optimization, including a variable compression ratio. The ignition timing control requirements in the free-piston engine are lower than those of conventional engines, making it suitable for homogeneous charge compression ignition operation. Since the piston motion is not restricted by a crankshaft, the high combustion pressures lead to a faster power stroke expansion and less time spent in the high-temperature parts of the cycle, compared with that of a conventional engine. This may reduce in-cylinder heat transfer losses and the formation of temperature-dependent emissions.

These characteristics suggest that the free-piston engine may be better suited for low heat rejection operation than are conventional engines. The faster power stroke expansion reduces the time available for NO_x emissions formation, which may allow free-piston engines to be designed with an insulated combustion chamber and still obtain acceptable exhaust gas NO_x concentrations. Furthermore, the purely linear motion of the piston assembly in the free-piston engine leads to very low side loads on the piston, reducing frictional losses and lubrication requirements. This makes the use of ceramic materials on the combustion chamber surface area significantly easier.

2 SIMULATION SET-UP

A multidimensional simulation model of a direct injection diesel engine was set up using the computational fluid dynamics (CFD) toolkit OpenFOAM [**16**]. The open source simulation code allows the user significant freedom to modify the code and implement new submodels, making it particularly useful in academic research. The engine simulation capabilities of the toolkit were described in detail by Jasak *et al.* [**17**]. Available submodels include the Chalmers PaSR combustion model and a CHEMKIN-compatible chemistry solver [**18**], Lagrangian fuel spray modelling [**19**], the Rayleigh–Taylor Kelvin–Helmholtz spray breakup model [**20**], and the Ranz–Marshall correlation for droplet evaporation [**21**]. For further information about the toolkit, the reader is referred to references [**16**], [**17**], and [**19**].

The simulation code was modified to accommodate for the particular operating characteristics of the free-piston engine and to allow the investigation of low heat rejection engines with different levels of combustion chamber insulation.

2.1 The modelled free-piston engine

A single piston free-piston engine with a variable-pressure bounce chamber was proposed by Mikalsen and Roskilly [**22**], and this engine is illustrated in Fig. 1. The engine operates on a turbocharged two-stroke diesel cycle and it is intended for stationary, large-scale electric power generation applications in which a number of such units will operate in parallel to produce power outputs equal to those of a multi-cylinder conventional engine. In such a plant, varying load demands can be accommodated for by switching on and off individual units, allowing the engines to operate close to design conditions at all times.

The main challenge with such free-piston engines is the piston motion control, as documented by several authors (see Tikkanen *et al.* [**7**] and Clark *et al.* [**9**] for examples, and Mikalsen and Roskilly [**12**] for an overview). The current design differs from that investigated by most authors in that it replaces a second combustion cylinder with a variable pressure gas-filled bounce chamber, adding a control variable to the system. Initial analyses indicate that for low load variations, the control problem can be resolved using standard techniques. Free-piston engine control issues will be treated elsewhere and are therefore not discussed further here. For further information and analyses of the engine system, the reader is referred to reference [**22**].

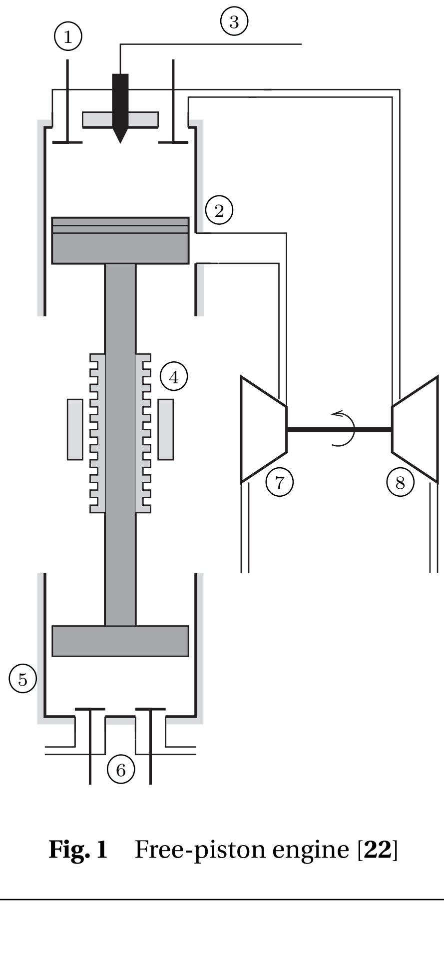


Fig. 1 Free-piston engine [**22**]

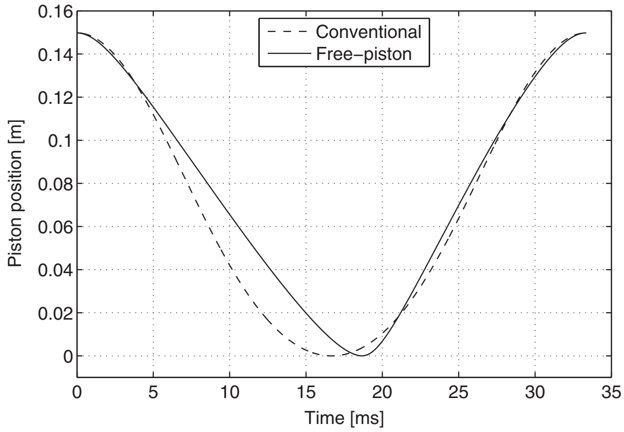
The main components of the engine illustrated in Fig. 1 are:

1. exhaust poppet valves;
2. scavenging ports;
3. common rail fuel injection;
4. linear alternator;
5. bounce chamber;
6. bounce chamber pressure control valves;
7. turbocharger compressor;
8. turbocharger turbine.

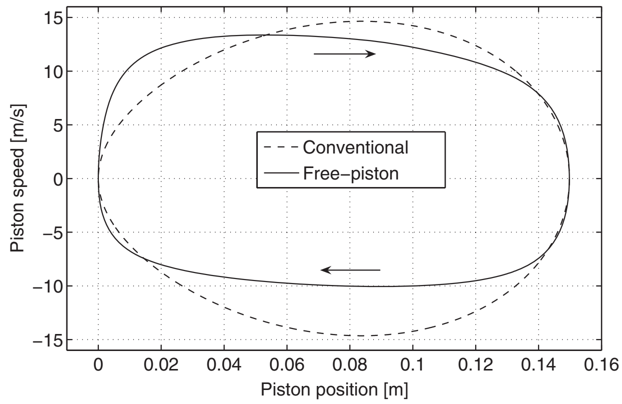
A full-cycle simulation model of the free-piston engine was described in reference [**22**] and simulations showed that the engine has operating characteristics significantly different from those of conventional engines. One of the main differences is in the piston motion profile, where the free-piston engine has a significantly higher piston acceleration around top dead centre (TDC) compared with the crankshaft-controlled piston motion of conventional engines. This leads to differences in the in-cylinder processes, most notably gas motion (squish effects), fuel–air mixing, and heat transfer to the combustion chamber walls. Previous work by the authors has shown that the average radial velocity of the in-cylinder gases around TDC (squish and reverse squish) is 15–30 per cent higher in the free-piston engine compared with a conventional engine, due with a higher piston speed around TDC [**14**].

Figure 2 shows the piston dynamics of the free-piston engine compared with those of a (crankshaft-controlled) conventional engine running at the same speed, obtained using a full-cycle simulation model [**22**]. The faster power stroke expansion and the shorter time spent around TDC in the free-piston engine can be seen in Fig. 2(a). Figure 2(b) shows the piston speed profile of the two engines. The significantly higher piston speed around TDC in the free-piston engine can be seen, in particular, in the start of the power expansion stroke.

To allow CFD simulations of the free-piston engine, a mathematical representation of the predicted piston motion profile was implemented into the CFD code using least square error fitting to a high-order polynomial. In order to use the standard engine terminology and to provide a better basis for comparison, the time-based free-piston engine piston motion was mapped on to a crank angle scale. For the investigations presented below, a notation of crank angle degrees relative to TDC position is therefore used for both the free-piston and conventional engines.



(a) Piston motion profiles



(a) Piston speed profiles

Fig. 2 Piston dynamics of a free-piston engine compared with those of a conventional engine [**22**]. (TDC is at position 0.)

2.2 Simulation case settings

In this work, an engine with design data similar to that described in reference [**22**] was studied. The engine achieves a full load electric power output of approximately 45 kW, with main design and operational data as listed in Table 1.

A standard bowl-in-piston combustion chamber design was used and a computational mesh, shown in Fig. 3, was generated. The combustion chamber was assumed to be symmetric around the cylinder axis and an eight-hole injector was used, allowing the use of a 45° wedge mesh with cyclic boundary conditions. A grid sensitivity analysis was performed to ensure the independence of the solution from the mesh density. The mesh used consisted of 60 000 cells; equivalent to 480 000 cells for the full cylinder.

Table 1 Engine design and operational specifications

Stroke	0.150 m
Bore	0.131 m
Scavenging ports height	0.022 m
Compression ratio	16 : 1
Speed	25 Hz (1500 r/min)
Fuel–air equivalence ratio	0.60
Mean piston speed	7.5 m
Boost pressure	1.68×10^5 Pa

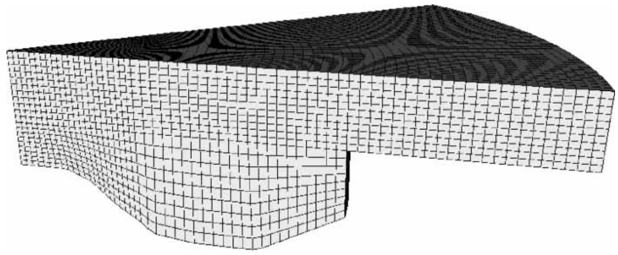


Fig. 3 Computational mesh

The fuel used was n-heptane (C_7H_{16}) and an injection duration of 25 crank angle degrees was used. Combustion was modelled with the Chalmers PaSR combustion model [**19**] and the chemistry model consisted of 15 species and 39 reactions. Turbulence was modelled with a standard k–ϵ model and the engine had an initial swirl per r/min ratio of 3.0. (For the free-piston engine, which has a linear motion only, r/min is taken as cycles per minute.)

2.3 Model validation

The simulation model had previously been validated against experimental results from a Volvo TAD1240 diesel engine generator set at the Newcastle University. The Volvo TAD1240 is a turbocharged, six-cylinder diesel engine with main design specifications similar to those of the free-piston engine studied here. Further information on the model validation can be found in reference [**14**].

2.4 Low heat rejection boundary conditions

The combustion chamber walls consist of three faces: the piston crown, the cylinder head, and the cylinder liner, for which separate boundary conditions can be defined. Commonly in engine CFD simulation studies, the wall temperature is taken as constant, since the high heat capacity of the metal and the short cycle time do not allow large temperature variations in the combustion chamber surface. Heywood [**1**] showed that the surface temperature in a conventional engine typically varies with less than 10 K over one engine cycle.

For a low heat rejection engine, the combustion chamber surface temperature will be higher due to the reduced heat conduction through the material. This can be readily implemented in the simulation model by varying the wall temperatures. Ceramic materials commonly used for this purpose typically have higher heat capacity than conventionally used metals and the assumption of constant wall temperature will therefore be acceptable for the low heat rejection simulations as well. In the original simulation set-up, wall temperatures of 435, 370, and 385 K were used for the piston crown, cylinder liner, and cylinder head, respectively. For the low heat rejection simulations, these were adjusted as described below.

3 SIMULATION RESULTS

Simulations were run for the free-piston engine and subsequently for an identical conventional crankshaft engine, in order to investigate differences between the two, as well as the potential advantages of the free-piston engine. All variables, such as engine speed, boost pressure, and injected fuel mass, were identical for the two engines, with the exceptions of the piston motion profile and the fuel injection timing. The injection timing will be different for the two engines due to the difference in piston motion profiles, and this was set to that value giving the highest cycle work output (equivalent to maximum brake torque timing) for all investigated cases. In practice, the optimal injection timing varied by no more than 3 crank angle degrees (−11 and −8 crank angle degrees after top dead centre for the free-piston and conventional engines, respectively), with the free-piston engine requiring a slightly advanced injection timing due to the faster power stroke expansion.

3.1 In-cylinder heat transfer losses

The rate of heat transfer from the in-cylinder gases to the combustion chamber walls depends on the gas temperature, the combustion chamber surface area and temperature, and the in-cylinder gas motion. While the fast power stroke expansion in the free-piston engine reduces the time available for heat transfer in the high-temperature part of the cycle, the high piston acceleration around TDC enhances in-cylinder gas flow, which may increase heat transfer losses.

Figure 4 shows the predicted in-cylinder gas temperature over one cycle for the free-piston and conventional engines, along with the total heat lost to the combustion chamber surfaces. The effect of the faster power stroke expansion in the free-piston engine can be seen, with the gas temperature in the free-piston engine dropping more rapidly after TDC than that in the conventional engine and the free-piston engine spending less time in the high-temperature part of the cycle.

The total heat transfer losses in the free-piston engine were found to be lower than those in the conventional engine, as can be seen from the figure. The heat lost to the combustion chamber surface was found to be equivalent to 15.1 per cent of the fuel energy in the conventional engine and 13.6 per cent

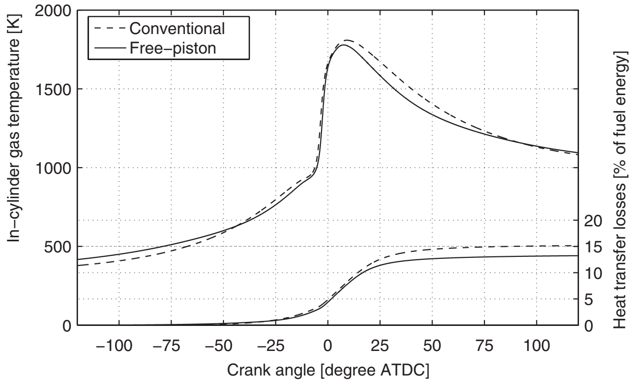


Fig. 4 Predicted average in-cylinder gas temperature and heat transfer losses for the free-piston and conventional engines in the original configuration

of the fuel energy in the free-piston engine – a 10 per cent reduction. Similar results have previously been obtained using a less advanced model [**22**].

Figure 5 shows the heat flux over the combustion chamber boundaries during the cycle for the two engines. It can be seen that the main heat transfer occurs over a limited period of the cycle, namely during the late stage of compression, the combustion, and the early power stroke expansion, and that the heat transfer in the other parts of the cycle is essentially zero. The figure further shows that the main heat losses are over the piston crown and cylinder head, due to their large surface areas.

The reduced heat transfer in the free-piston engine during the power stroke expansion can be seen in the heat flux plots. During the early stages of expansion,

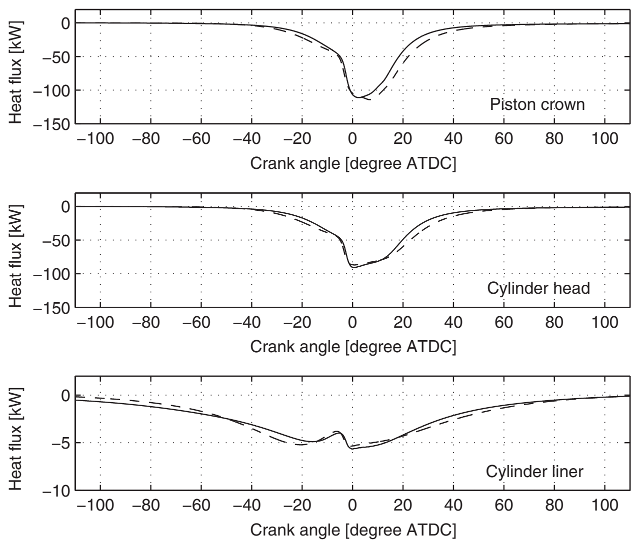


Fig. 5 Predicted heat flux over the combustion chamber boundaries for the free-piston engine (solid lines) and the conventional engine (dashed lines)

the in-cylinder gas velocities are higher in the free-piston engine due to enhanced reverse squish, which increases the heat transfer between the gas and the combustion chamber walls. The overall reduction in heat transfer losses, therefore, indicates that the speed of expansion and the amount of time spent in the high-temperature part of the cycle is the dominant mechanism on the heat transfer. This is in agreement with reports from other authors, such as that of Uludogan *et al.* [**23**], which showed that the benefits of enhanced in-cylinder gas motion by far outweighs the disadvantages of increased heat transfer losses.

3.2 Nitrogen oxides emissions formation

The formation of nitrogen oxides within the combustion chamber depends heavily on gas temperature and the residence time at high temperatures. Both these are influenced by the operating characteristics of the free-piston engine: the enhanced in-cylinder gas motion will increase the mixing of fuel, air, and combustion products, and thereby reduce the amount of high-temperature zones within the cylinder, whereas the faster power stroke expansion reduces the time available for NO_x formation.

Typically, more than 90 per cent of the nitrogen oxides present in engine combustion and exhaust gases is in the form of nitric oxide (NO) and the current investigation therefore considers only this species. The main formation reactions for NO, the extended Zeldovich mechanism, is included in the chemistry solver, and the effect of the free-piston operating characteristics on the nitric oxide emissions formation can therefore be studied.

Figure 6 shows the predicted NO concentration in the in-cylinder gases. A significant advantage for the free-piston engine can be seen, with the NO concentration in the cylinder gases at the time of exhaust valve opening being around 17 per cent lower than that of the conventional engine. This is due to the combination of a high level of reverse squish, enhancing fuel–air mixing during the late stages of combustion, and the temperature reduction due to the expansion, both being results of the higher piston acceleration shortly after TDC in the free-piston engine.

3.3 Low heat rejection design

In order to simulate a low heat rejection combustion chamber design, the wall temperatures in the simulation set-up were adjusted. The relative temperature distribution of the combustion chamber surfaces piston crown, cylinder head, and cylinder liner was kept constant, and the temperatures were increased in increments of 10 per cent of the original value. It was found that for low increases in the wall temperatures (less than 50 per cent), the reduction in heat transfer losses was approximately proportional to the wall temperature change.

As the simulations were run only for the 'closed cylinder' part of the cycle, effects of the wall temperature change on the scavenging process were not modelled.

Figure 7 shows the effects of reductions in in-cylinder heat transfer losses on engine indicated efficiency and nitric oxide emissions formation. (It should be noted that the differences in brake efficiency between the free-piston and conventional engines will be higher than that in indicated efficiency and in favour of the free-piston engine due to its significantly lower frictional losses). It can be seen that a reduction in heat transfer leads to a significant improvement in engine efficiency, with the conventional engine benefiting slightly more than the free-piston engine. This is due to the longer residence time around TDC and close to constant volume combustion in the conventional engine. As the two main factors influencing indicated efficiency are the volume change during

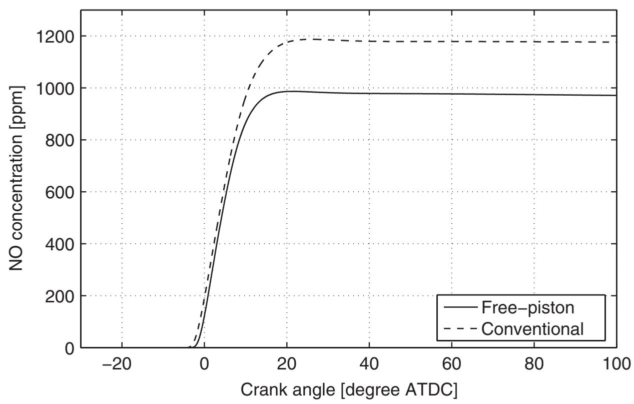


Fig. 6 Concentration of nitrogen oxide (NO) in the in-cylinder gases

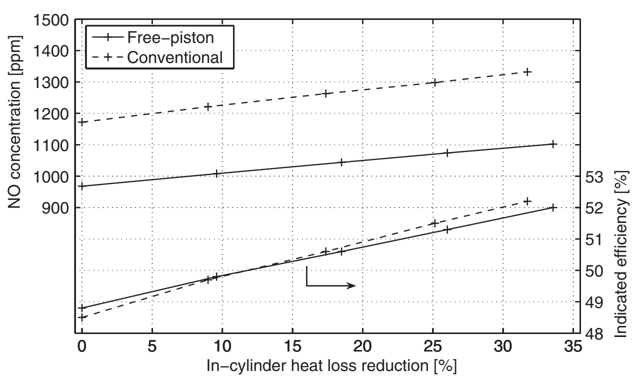


Fig. 7 Effects of reductions in in-cylinder heat transfer losses on engine indicated efficiency and NO formation

combustion and the heat transfer losses from the combustion chamber, the ideal case will be an engine with low piston speed around TDC, as is the case in the conventional engine, and a well-insulated combustion chamber.

The figure further shows the concentration of nitrogen oxide emissions in the exhaust gas. An increase in NO emissions can, as expected, be seen with the increase in gas temperature levels resulting from reduced heat losses. The advantage of the free-piston engine can, however, be seen throughout the investigated range, with the free-piston engine having approximately 17 per cent lower NO concentrations. Interestingly, it can be seen that the free-piston engine even with high insulation levels has lower NO levels than the conventional engine in the original configuration. This indicates that the free-piston engine should be able to provide efficient power generation with nitrogen oxides emissions levels substantially lower than those of conventional engines.

Figure 8 shows the predicted exhaust gas temperatures, taken as the average in-cylinder gas temperature at exhaust valve opening, for varying levels of combustion chamber insulation. The exhaust temperature can be seen to increase with reduced in-cylinder heat transfer losses, as one would expect. The temperature increase is of the same magnitude as those reported by other authors [**2**]. The exhaust gas temperatures of the free-piston engine is seen to be slightly higher than those of the conventional engine, which is due to the reduced in-cylinder heat transfer losses shown above.

Figure 8 further shows the energy available in the exhaust gases for the turbocharger or a turbocompound system. An estimation of the turbine work was made using standard equations, by assuming that the exhaust gases are expanded down from the exhaust back pressure to atmospheric pressure through a turbine with an isoentropic efficiency of 0.8. Due to the higher exhaust gas temperature in the free-piston engine, the turbine work available in this engine is 2.6 per cent higher than that of the conventional engine in the original configuration. The figure shows the

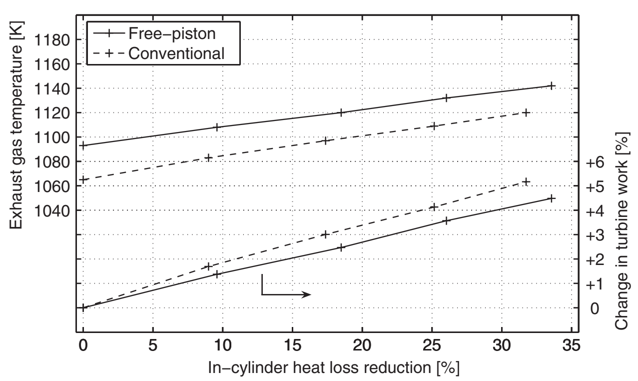


Fig. 8 Effect of combustion chamber insulation on exhaust gas temperatures and turbine work

increase in work that can be obtained as a result of using combustion chamber insulation; it can be seen that, for both engines, the work that can be extracted from the exhaust gases increases with reduced in-cylinder heat transfer. Due to the higher heat transfer losses in the conventional engine, this engine benefits slightly more from combustion chamber insulation than does the free-piston engine.

4 CONCLUSIONS

This article investigated the heat transfer losses in a free-piston diesel engine using a multidimensional simulation model and compared the findings with those predicted for a conventional engine. The feasibility of a low heat rejection free-piston diesel engine was studied and the influence of reduced combustion chamber heat transfer losses on engine efficiency and nitrogen oxides emissions was investigated for both free-piston and conventional engines.

Compared with a conventional engine, it was found that the faster power stroke expansion in the free-piston engine leads to a reduction in in-cylinder heat transfer losses, which increases the exhaust gas enthalpy. The predicted indicated fuel efficiency was similar to that of the conventional engine, however, brake fuel efficiency advantages are expected for the free-piston engine due to the lower frictional losses. Due to higher exhaust gas temperatures, additional benefits can be achieved by utilizing the exhaust gas energy in a bottoming cycle. The combination of enhanced in-cylinder gas motion and shorter time spent in the high-temperature part of the cycle reduces the formation of nitrogen oxides emissions significantly in the free-piston engine.

A low heat rejection combustion chamber design was found to improve fuel efficiency of both the free-piston engine and the conventional engine, the latter result being consistent with those reported by other authors. It was found that the free-piston engine benefited slightly less from combustion chamber insulation than did the conventional engine, due to its inherently lower heat transfer losses. It was, however, argued that due to the lower NO emissions levels in the free-piston engine, a higher level of combustion chamber insulation can be tolerated and such engines should therefore be well suited for low heat rejection design. It was found that even with an in-cylinder heat transfer reduction of 30 per cent, the NO emissions in the free-piston engine would still be lower than that of the conventional engine in the original configuration. It was predicted that a combustion chamber insulation of this level would improve the indicated efficiency in the order of 3 percentage points. Moreover, the implementation and use of ceramic materials on the combustion chamber surface areas should be simpler in the free-piston engine due to low side forces on the piston.

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