THE FREE-PISTON RECIPROCATING JOULE CYCLE ENGINE: A NEW APPROACH TO EFFICIENT DOMESTIC CHP GENERATION

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ABSTRACT

Current commercially available micro-CHP systems typically have electrical efficiencies of less than 20% with thermal efficiencies of approximately 70%. This paper presents a new concept for micro-scale CHP generation, based around an external combustion Joule cycle with a reciprocating, free-piston engine power converter. Simulation studies carried out at Newcastle University and reports by other researchers suggest that a domestic CHP plant based on the proposed technology could reach an electric efficiency of above 30%, whilst, through waste heat recovery, maintaining a total system efficiency of over 90%.

Keywords: free-piston, reciprocating Joule/Brayton cycle, micro-CHP

1. INTRODUCTION

Governments around the world are committed to reducing carbon dioxide emissions under the Kyoto Protocol and Johannesburg follow-up, and climate change is a key environmental, political, and social issue of today. The Stern Review [1], published in 2006, highlighted the need for urgent action to be taken to reduce greenhouse gas emissions and states that the 'development and deployment of low carbon technologies is essential.'

Studies show that domestic energy consumption increased by 36% between 1971 – 2001 [2] and 15% from 1990 – 2005 [3]. 58% of energy consumed in the domestic setting is for space heating; space and water heating combined account for 82% of energy consumed. With improvements in the thermal efficiency of homes and future increases in electricity use, there will be a shift in the balance of energy demand which will put further strain on the electricity generation and transmission capacity. In order to meet the carbon dioxide emissions commitments, in the micro-generation strategy (March 2006) [4], the UK government proposed that micro-generation could provide 30-40% of the UK's electricity needs by 2050 and help reduce household carbon emissions by 15% per annum with 'CHP leading the way.' A significant barrier to the take-up of domestic micro-generation is, however, the long payback time, even with the aid of government grants [5]. In the case of micro-CHP, this is due mainly to the low electrical efficiency of the systems currently available or under development.

For domestic applications, Stirling engine systems are often preferred due to their low noise and the availability of natural gas fuel. While there are many advantages associated with Stirling engine CHP systems, their market penetration is fundamentally hindered by low efficiency and high acquisition costs. For example, the Whispergen micro-CHP unit manufactured by WhisperTech Ltd produces electric and thermal power outputs of 1 kW and 7-12 kW respectively, i.e. with an electrical efficiency of below 13%. In addition, poor dynamic performance in the form of long warm-up periods has been reported for Stirling-based systems [5]. Internal combustion engine based micro-CHP systems provide significantly better performance (efficiencies above 20%), however such systems suffer from noise, vibration, and higher exhaust gas emissions, which are clear drawbacks for domestic use [6]. However, internal combustion engine micro-CHP units have seen some commercial success, most notably the Honda ECO-WILL 1kW system, of which several thousand units have been installed in Japan [6].

1.1 The reciprocating Joule cycle

One concept that has been proposed to provide more efficient micro-CHP generation is the reciprocating Joule cycle (RJC) engine. The RJC engine is based around an external combustion Joule/Brayton cycle, i.e. that used in gas turbine engines. The recuperated gas turbine cycle is highly efficient, however rotodynamic machinery (compressors and turbines) suffers from poor efficiency when scaled down to small sizes. The RJC engine utilizes reciprocating machinery for the power conversion, which can provide much higher compression and expansion efficiencies at small scale, albeit with significantly lower power density. The latter is, however, of less importance for CHP systems, in which efficiency is usually the main priority.

The RJC engine has been studied by a number of authors [7-10], generally indicating a very promising efficiency potential. Moss et al. [8] studied a two-cylinder RJC engine (one compressor and one expander cylinder) using advanced thermodynamic cycle analysis and concluded that an electrical efficiency of 33% is possible

Bell and Partridge [9] predicted even higher efficiencies, reaching 50% with the use of exotic materials to allow high peak cycle temperatures.

Previous reports on RJC engines generally point out two key characteristics and challenges for this engine concept:

(a) The use of a high peak cycle temperature benefits efficiency, hence components (cylinder units and, in particular, valve systems) which can operate at high temperatures are highly desirable.

(b) The total efficiency is highly sensitive to frictional losses, hence the use of a low-friction energy converter is critical. This is a challenge for crankshaft engines, in which the mechanical losses become increasingly influential for low mean effective pressure cycles, such as the RJC cycle.

1.2 Free-piston engines

The free-piston engine is an old concept, which was in use in the mid-20th century for stationary power generation and some transport applications, such as locomotive engines and marine power plants [11]. In the recent years, there has been much interest in the concept for the generation of hydraulic or electric power in applications such as hybrid electric vehicles (for an overview, see the review paper by these authors [11]).

Free-piston engines are linear, 'crankless' engines, in which the complete crank system known from conventional engines is removed and the power is taken out via a linear load device, such as a linear electric generator. One key advantage of such engines is the significantly reduced frictional losses, since the number of moving components is reduced and any load-carrying bearings (such as the big end bearing in crankshaft engines) are removed.

As noted above, a mechanically efficient design is highly beneficial for the total efficiency of the RJC engine [9]. The use of a free-piston engine power converter in the RJC engine, as opposed to a slider-crank engine reported by previous authors, was proposed by Mikalsen and Roskilly [12] and promises significant advantages.

2. THE FREE-CHP CONCEPT

The proposed free-piston reciprocating Joule cycle engine system, labelled Free-CHP, operates on an external combustion Joule (or Brayton) thermodynamic cycle; that is, with essentially constant pressure combustion, similar to that of a gas turbine. Figure 1 illustrates the Free-CHP system and its key components. The system is based around a linear, free-piston configuration, and the basic working principle of the engine is as follows: as the piston assembly reciprocates between its endpoints, atmospheric air is compressed in the compressor and supplied to the combustor, in which fuel is added and ignited. The combustion products are allowed to expand down to the start-of-compression pressure through an expander ("hot cylinder"), and the excess work from the cycle is used to drive a linear electric generator. In order to improve the efficiency of the system, a regenerative heat exchanger ("recuperator") is included, in which heat from the combustion products is transferred to the working fluid prior to combustion. Finally, a hot water heat exchanger allows utilisation of the exhaust gas heat for hot water and space heating. The compressor and expander in the engine comprise, unlike in a gas turbine, of double-acting piston-cylinder arrangements, giving high compression and expansion efficiencies also for small scale systems. The gas flow to and from the cylinders is controlled by actively actuated valves, allowing valve timing to be used for engine operational optimisation and control purposes.

2.1 Key advantages

The use of a linear, free-piston configuration with double-acting piston compressor and expander in an external combustion Joule cycle engine represents an innovation in CHP system design. This design improves on current IC or Stirling engine systems in several respects. First, the engine will have inherently low exhaust gas emissions levels (compared with conventional IC engines) due to the use of external, lean-burn constant pressure combustion and fuel flexibility is possible, including the possibility to use liquid or gaseous fuels. Second, the use of reciprocating machinery in
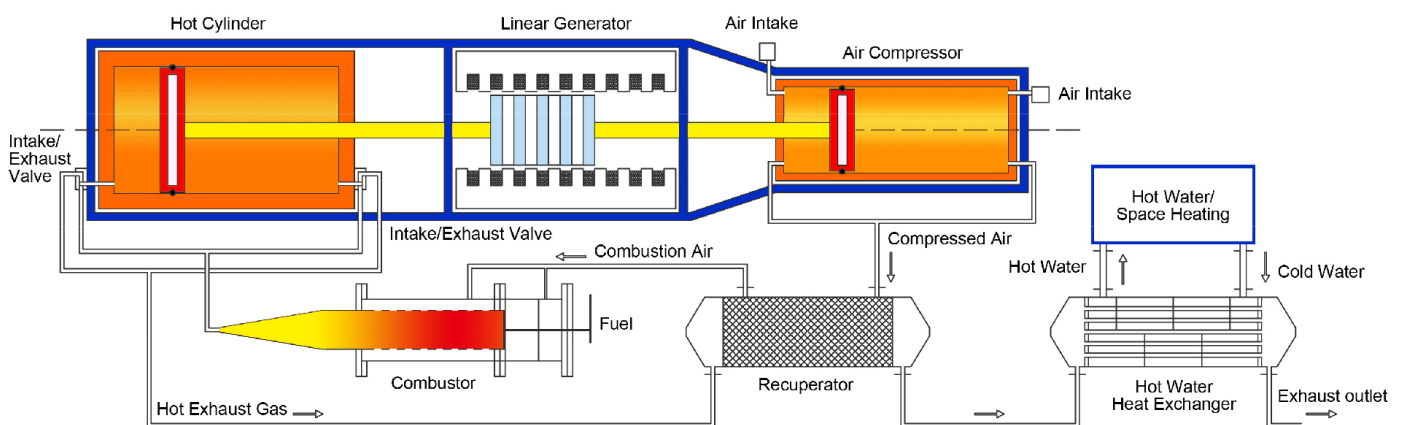

Figure 1: Free-piston reciprocating Joule cycle system overview.

the compressor and expander (as opposed to rotodynamic machinery used in gas turbines) for domestic scale significantly improves compression and expansion efficiencies. While efficient gas turbine systems can be realised in large scale, small-scale rotodynamic machinery suffer from poor efficiencies due to problems with sealing and frictional losses. (The smallest commercially available gas turbine systems today have power outputs of approximately 30kW.) The Free-CHP system can be scaled down to small sizes without major efficiency penalties and also allows efficient part load operation due to the operational flexibility of the system. Finally, the use of a double-acting free-piston configuration in the reciprocating Joule cycle engine, as opposed to a conventional, slider-crank engine proposed by Warren and Bjerklie [7], Moss et al. [8], and Bell and Partridge [9], significantly reduces the frictional and heat transfer losses of the unit and gives a more compact system. In addition to having a reduced number of moving parts, the free-piston reciprocating Joule cycle engine utilises the linear motion of the piston directly to generate electricity, thereby eliminating any load-carrying bearings, such as those between the piston and the crankshaft in conventional engines. Moreover, the absence of a crank mechanism eliminates any side forces on the piston from the connecting rod, further reducing engine frictional losses. The simplicity and low friction and wear reduces service downtime and increases system lifetime.

2.2 Main challenges

As is well known from standard thermodynamics theory, the efficiency of a heat engine depends heavily on the peak cycle temperature. While it has been shown that acceptable performance can be achieved using standard materials, the use of high temperature materials to allow higher operating temperatures will significantly improve the fuel efficiency of the reciprocating Joule cycle engine [8,9]. Much research effort is going into the development of high temperature materials for gas turbine engines, however in the Free-CHP system, the issues associated with materials will be of a different nature. The main challenge is the need for a valve system directly downstream of the combustor. The temperature in which this can operate will be the factor limiting the peak cycle temperature, and the valve system must therefore be carefully designed in order to maximise the allowable gas temperature. Issues such as cooling and lubrication must be resolved, and the use of various valve configurations (e.g. poppet, rotating, or sliding valves) should be investigated. In the expansion cylinder, issues related to the lubrication and sealing of the sliding interfaces must be resolved.

A further challenge with the Free-CHP system is related to the regenerative heat exchanger and combustor. Unlike in a gas turbine, these components will be subjected to non-steady flow conditions, and the effects of this on the heat transfer and combustion processes must be identified. Design modifications, for example through the implementation of pulsed fuel injection, may be required in

order to ensure efficient combustion and low emissions formation. Finally, due to the spring-mass nature of the system, sufficiently low-weight components must be used in order to obtain an acceptable operating frequency and power to weight ratio. The translator of the electric machine will make up a significant fraction of the moving mass, and the use of a low-weight machine is therefore essential. Research on linear electromagnetic generators is therefore required to achieve thrust force densities and efficiency meeting the demand in this highly challenging application. Development of power electronics converters (intelligent power modules), control strategies, and digital control platforms is further required to facilitate the necessary drive and power conditioning, and computational capability to control the complete system.

3. SYSTEM PERFORMANCE ANALYSIS

Reciprocating Joule cycle engines in general and the free-piston RJC concept in particular have been under investigation for some time at Newcastle University, UK. Both thermodynamic cycle models [8] and dynamic free-piston engine models [13,14] have been used to study the performance of such systems. This paper presents preliminary results from a newly developed full-cycle simulation model of the Free-CHP system, which allows coupled analysis of the mechanics and the thermo- and fluid dynamics in the system.

3.1 Engine modelling framework

The modelling framework is developed in the AMESIM simulation software. The model developed is a full-cycle model and accounts for the complex interaction between the mechanics and thermodynamics in free-piston engine systems. Crucially, the interaction between the piston motion in the free-piston engine and the gas dynamics is important, since the piston dynamics at any point in the cycle is a result of the operating conditions of the system and not a controlled variable, as in a crankshaft engine. Importantly, the stroke length of the free-piston engine is not fixed, but will vary according to the system operating conditions. Moreover, the use of reciprocating compressor and expander cylinders will lead to a pulsating gas flow through the recuperator and combustor, and it is essential to understand the nature and magnitude of these flow variations in order to evaluate the feasibility of the concept.

3.2 Engine design

Table 1 shows the engine design parameters chosen for this study. These values were chosen based on experience and on preliminary simulation results, to provide a semi-optimised starting point for the analysis.

Table 1: Free-CHP engine design parameters

Variable	Value
Combustion temperature	800 degree C
Target stroke length	116 mm
Piston assembly mass	1 kg

Compression cylinder diameter	66 mm
Expansion cylinder diameter	80 mm
Cylinder length	120 mm

Table 2 shows the predicted performance at the base operating point with the system parameters listed above. It can be seen that even for a design which is not fully optimised, an efficiency of above 30% for a 4 kW unit (accounting for some electric machine losses) appears possible. This corresponds well with previous reports from other authors [8.9].

Table 2: Predicted Free-CHP engine performance

Variable	Value
Combustor power	13.90 kW
Mechanical power out	4.47 kW
Power lost over air inlet and exhaust	8.46 kW
Additional power loss	0.97 kW
Compression cylinder output pressure	5.9 bar
Frequency	36.4 Hz
Efficiency	32.2 %

3.3 Effect of combustion temperature

Basic cycle analyses dictate that a higher peak cycle temperature will lead to higher thermal efficiency. In real engines, the relationship is not that straight-forward due to effects of, among other things, heat transfer losses. Moreover, material properties will limit the maximum temperatures that can be used, hence one may not be fully free to choose a design value for optimal efficiency.

Figure 2 shows the effect of combustion temperature on engine performance. It can be seen that increasing temperatures lead to improved efficiency for temperatures at least up to 1200 degree C. The limit for the use of standard materials is believed to be around 800 degree C [9], for which an efficiency of just above 32% is predicted.
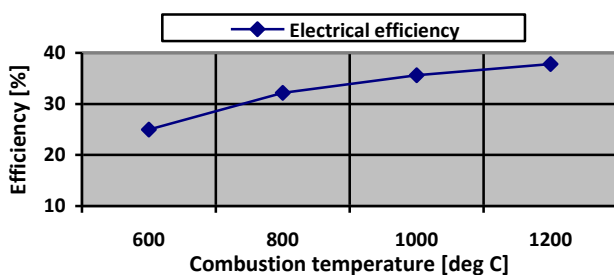
Figure 2: Effect of combustion temperature on engine performance.

3.4 Effect of moving mass

The mass of the piston assembly has high influence on the operational characteristics of the engine, since the free-piston engine will resemble a spring-mass system [11-13].
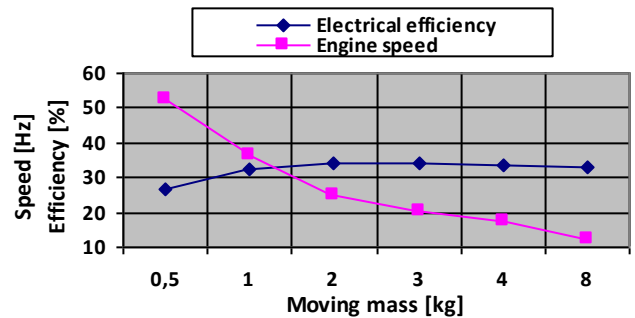
Figure 3: Effect of piston assembly mass on engine performance.

Figure 3 shows the effect of moving mass on electrical efficiency and engine speed. As expected, the engine speed is heavily influenced by the piston assembly mass. A reduction in speed also leads to a significant reduction in power output; the output varies from 5 kW for 0.5 kg piston mass to 1.8 kW for an 8 kg piston assembly.

A higher speed leads to increased gas flow losses, since the gas flow rates through the system will be higher, and this effect reduces efficiency. Conversely, at very low speeds, heat transfer losses become more influential. Hence, there will be an optimum point for high efficiency; for the current base configuration this appears to be around 2 kg.

The operating frequencies predicted here generally lie within the normal operating ranges for piston engines; the mean piston speed varies from 12.2 m/s at the highest speed (0.5 kg piston mass) down to 2.8 m/s (8 kg piston mass). For that what appears to be close to an optimum mass, 2 kg, the mean piston speed is 5.8 m/s. This is well within the range used in conventional engines. Hence, one would not expect excessive pumping losses in the Free-CHP system, even with the use of standard poppet valves for inlet and exhaust.

3.5 Compression cylinder size

The size of the compression cylinder influences the pressure ratio, and therefore the operating speed of the system to a large extent. Further, as is known from standard gas turbine cycle analysis, the pressure ratio influences the efficiency of the cycle. For a recuperated Joule cycle there will exist a pressure ratio for optimum efficiency which is lower than that of the simple cycle, since the efficiency of the latter theoretically increases indefinitely with pressure ratio.
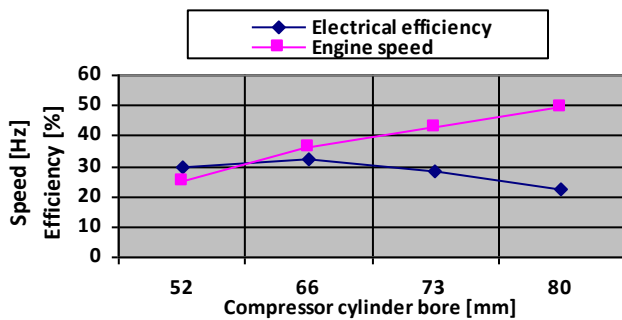
Figure 4: Effect of compressor cylinder bore on engine performance.

Figure 4 shows the predicted effect of compressor cylinder bore on engine performance. A significant increase in engine speed can be seen for increasing compressor bore; this is due to a higher cycle pressure ratio as more air is supplied to the system. (Considering the spring-mass analogy, a higher pressure will make the system 'stiffer' and hence increase bouncing frequency.) Over the range shown, the pressure in the high-pressure side ranged from 3.9 bar for the smallest compressor cylinder bore to 7.6 bar for the largest. For low compression cylinder bore values the power output is also reduced heavily, as the compressor is unable to supply sufficient amount of combustion air.

There is a penalty in both the efficiency and power output for very high pressure ratios, as this means that the compression air has a higher temperature and therefore a smaller amount of heat can be supplied by the combustor while staying within the limits for the combustion temperature (800 degree C). In that case the net energy output per cycle is reduced and the influence of frictional and heat transfer losses increases, reducing efficiency. The power output finds its optimal value for a pressure ratio of approximately 7, which is achieved with a 73 mm bore.

3.6 Expansion cylinder size

For changes in the expansion cylinder size, one would expect similar effects as for the compression cylinder, since they influence similar variables, namely the pressure ratio and the mass flow through the system.
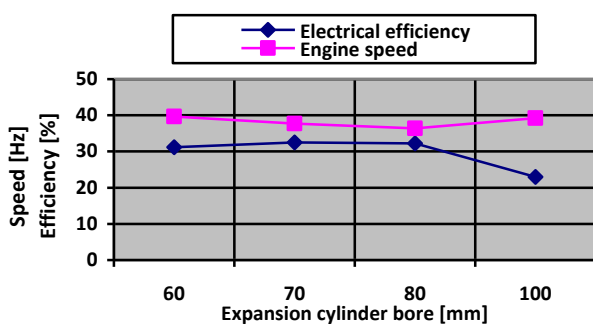

Figure 5: Effect of expansion cylinder bore on engine performance.

Figure 5 shows the effect of variations in expansion cylinder bore on engine speed and efficiency. It can be seen that the

speed is less sensitive to changes in expansion cylinder bore than for compression cylinder bore. As above, an optimum cylinder size for high efficiency can be found. The effect of variations in expander bore on system pressure ratio is similar as above, ranging from 9.0 bar for the smallest expansion cylinder bore to 4.2 bar for the largest.

4. CONCLUSIONS

Preliminary performance results for a free-piston reciprocating Joule cycle (RJC) engine were presented. The results corresponds well with those presented previously for conventional, crankshaft based RJC engines. A fuel efficiency of above 32% was predicted for a semi-optimised system at 4.5 kW power output.

The system comprises a very high number of operational and design variables, hence significant efforts are required to determine the optimal design configuration. Hence there is probably a potential to improve somewhat on the performance predictions presented above. This work is currently underway, both experimentally and through simulation, at Newcastle University.

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