Energy Conversion and Management 173 (2018) 375–382

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

Dynamic and thermodynamic characteristics of a linear Joule engine generator with different operating conditions

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ARTICLE INFO

Keywords:
Linear Joule engine
Linear alternator
Numerical model
Power generation
High efficiency engine

ABSTRACT

The Linear Joule Engine Generator is an energy conversion system made up from a linear expander, a linear compressor, and a linear alternator. It is adaptable to variable renewable energy fuel sources, e.g. biogases, biofuels, hydrogen and ammonia, etc. In this paper, an investigation on the system dynamics and thermodynamic characteristics under different operating conditions is presented. Real time adjustable parameters were identified, i.e. the system pressure, the valve timings, and the coefficient of electric resistance force. Their influence on the indicated power of the expander, the electric power output from the linear alternator and the energy conversion efficiency are scrutinised using a validated numerical model. In order to achieve stable operation of the system, each parameter is controlled within a practical range, and optimised to maximise the electricity generation efficiency. The system pressure was proved to be the most effective parameter to alter the system power output. The indicated power of the expander with the existing dimensions can reach up to 11.0 kW by adjusting the system pressure, and it cannot exceed 8.0 kW by just tuning valve timings or optimising the coefficient of electric resistance force. The coefficient of electric resistance force is found to be the most influential parameter to maximise the electricity generation efficiency up to 80%.

1. Introduction

The Linear Joule Engine Generator (LJEG) concept was first proposed by the authors' group [1], and a working prototype has been developed aiming for potential applications of micro-scale Combined Heat and Power (CHP) systems [2]. The LJEG system is considered to combine the technologies of the Joule Engine and Linear Engine Generator [3]. The Joule cycle (or Brayton Cycle) is widely employed in gas turbines, whereas a reciprocating Joule Engine uses a separate compressor and expander to improve system efficiency [3]. The intake air is compressed, and combustion takes placed under constant pressure [4]. The exhaust gas drives the expander which is connected with a generator that generate electricity [5]. The Linear Engine Generator integrates a free-piston engine with a linear electric alternator, and in principle has the advantages of a compact structure, high thermal efficiency, and multi fuel/multi combustion mode potential [6].

There have been researches reported on the Linear Engine. A four-stroke linear engine generator prototype was developed with a reported generating efficiency of 32% [7]. A two-stroke dual-piston dual-cylinder type prototype was developed by Zuo et al., with successful engine cold start-up and combustion reported [8]. A single-piston linear engine generator with gas spring prototype was developed by researcher from Toyota Central R&D Labs Inc [9]. A dual-piston with shared-combustion chamber linear engine generator was designed and tested at Sandia National Lab [10]. Linear engine combustion with homogeneous charge compression ignition model was reported with a detailed numerical approach [11]. Piston dead center determination for linear engine was investigated and new approach was proposed by Zhao et al. [12]. The LJEG system is considered to offer the advantages of both Joule Engine and Linear Engine Generator. Thus it is of potential high efficiency and is adaptable to renewable energy applications due to the external combustion process, and efficient in generating electricity [13]. To date, there has been research on the modelling and estimation on the system performance, these have been based on simple calculations without any model validation based on experimental data.

Moss et al. developed an engine preliminary design tool in Matlab for a conventional Joule Engine [3]. The code took the following input parameters, power output, engine speed, pressure ratio, cylinder stroke/bore ratios, heat-exchanger effectiveness, combustor pressure drop and peak temperature. The code was able to predict the sizes of

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https://doi.org/10.1016/j.enconman.2018.07.098
Received 10 April 2018; Received in revised form 24 July 2018; Accepted 28 July 2018
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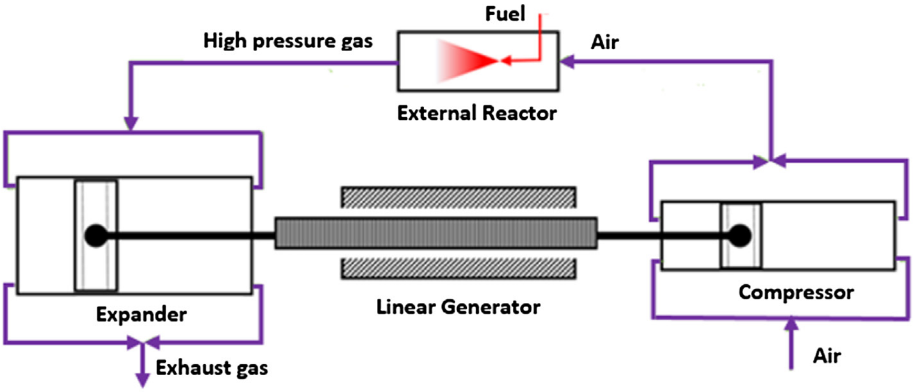
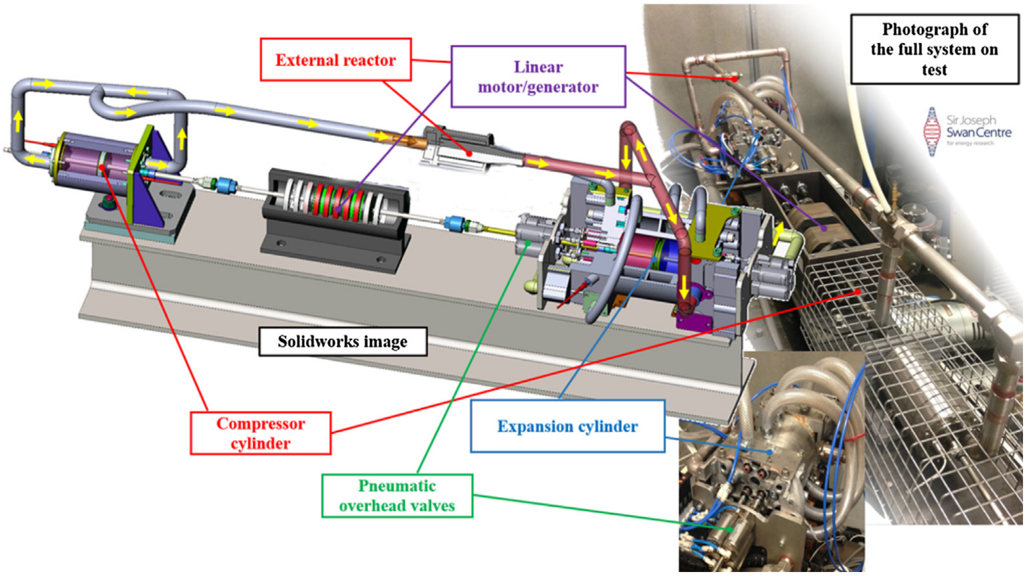


(a) Schematic configuration



(b) Prototype illustration

Fig. 1. The LJEG prototype at Newcastle University.

cylinders required at given speed and stroke/bore ratio, mechanical efficiency, valve pressure drops, size of heat exchanger, and engine efficiency. The designed Joule Engine was found to be well suited to small CHP systems with a potential electrical generation efficiency of 33%. Multi-fuel capability was expected to burn natural gas, bio fuels, hydrogen, etc. The system efficiency was found to depend on the thermodynamic parameters such as pressure ratio, effectiveness, peak temperature. It was also affected by the system mechanical losses, which could be reduced with low mean effective pressure. The cylinder clearance volumes were suggested to be kept as small as possible to improve the volumetric efficiency and minimise the required cylinder size [3].

A conventional Joule Engine was also designed by researcher at Plymouth University [4]. A mathematical model of the system was developed, aiming to simulate the actual process and predict the performance. The modelling was undertaken in three stages: a basic engine model was used to determine the likely performance, then a more detailed model was adopted to calculate the specific losses and thus refine the basic engine model, the detailed engine model was finally used to determine the performance of the CHP system. The basic engine model considered the ideal p-V diagram to determine the ideal work per cycle. The detailed model took into account the frictional, thermal, and pressure losses, and it predicted that the engine was suitable for micro CHP applications with a maximum thermal efficiency of 33%. The engine mathematical model was validated through the processes of design, build, and testing of both an engine for technology demonstration and a prototype engine. When the sub-models were combined to model a CHP system, with the engine exhaust heat used to preheat the combustion air, the overall maximum system efficiency achiever could be up to 79% [14].

The Linear Joule Engine Generator concept was first proposed by the authors' group, initially aiming for application for micro-scale CHP generation [1]. Simple calculations were undertaken, and the simulation results suggested that a domestic CHP plant based on the proposed technology could reach an electric generating efficiency of above 30%. With a heating temperature of around 1100 K and a compressor outlet pressure of 6 bar, the engine was able to produce 4.5 kW of mechanical power. Whilst, through waste heat recovery technology, the total system could show a promising efficiency of over 90%. Later on, a 3-dimentional diagram of the proposed LJEG system was presented by the authors [2]. The geometric parameters of the system were optimised in LMS AMESim software, which provide a solid basis for the manufacturing of the prototype. Meanwhile, Wu et al. presented a coupled dynamic model of the Linear Joule Engine and the connected permanent magnet linear electric generator, aiming to provide a better prediction of the system performance. It was estimated that the LJEG system could generate 1.8 kW electricity, with an engine thermal efficiency of 34% and electric generating efficiency of 30% [15].

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