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Design, modelling and validation of a linear Joule Engine generator designed for renewable energy sources

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ABSTRACT

The Linear Joule Engine Generator (LJEG) incorporates the Joule Engine technology and the permanent magnet linear alternator design, which is a promising power generation device for the applications of range extenders for electric vehicles, Combined Heat and Power (CHP) systems, or as a stand-alone power unit. It combines the advantages from both a Joule Engine and a linear alternator, *i.e.* high efficiency, compact in size, and flexible to renewable energy integration, etc. In this paper, the background and recent developments of the LJEGs are summarised. A detailed 0-dimentional numerical model is described for the evaluation of the system dynamics and thermodynamic characteristics. Model validation is conducted using the test data obtained from both a reciprocating Joule Engine and a LJEG prototype, which proved to be in good agreement with the simulation results. The fundamental operational characteristics of the system were then explained using the validated numerical model. It was found that the piston displacement profile has certain similarity with a sinusoidal wave function with an amplitude of 51.0 mm and a frequency of 13 Hz. The electric power output from the linear alternator can reach 4.4 kW_e. The engine thermal efficiency can reach above 34%, with an electric generating efficiency of 30%.

1. Introduction

The Linear Joule Engine Generator (LJEG) is derived from the Joule Engine technology and incorporates a permanent magnet in a linear alternator design. The Joule Engine technology uses a free piston configuration with a potential high efficiency due to its mechanical simplicity and minimal frictional loss, in addition it employs an external (out-of-cylinder) heat addition method to adapt to various renewable energy sources [1–3]. The permanent magnet linear alternator is reported to be compact in size, and efficient in electricity generation [4–7]. The LJEG takes advantages of both a Joule Engine and the Linear Engine Generator, and it provides an alternative high-efficiency, renewable energy adaptive, prime mover for transportation and power generation applications. At the same time, it offers flexibility at a time when it is expected to see a major increase in the low-carbon/carbon-free fuel variety, e.g. biogas, biofuels, hydrogen and ammonia, in these sectors towards 2050.

1.1. Joule Engine technology

The Joule cycle (or Brayton Cycle) is widely employed in gas turbines, where air intake is compressed, before fuel is burnt under constant pressure, and then, the exhaust gas expands out to ambient pressure. Typically the compression and expansion processes are performed by turbomachinery [8]. In theory it has isobaric heat addition and heat rejection processes, and isentropic compression and expansion. The reciprocating Joule Engine technology applies split a reciprocating compressor and expander to improve its efficiency, which was proposed as an engine for application in the micro CHP systems [1,3,9].

Moss et al. estimated the performance of a Joule Engine in small size (1–10 kW) with a simple simulation model in Matlab [1]. Alaphilippe et al. provided a theoretical investigation on the coupling of a two-stage parabolic trough solar concentrator with a hot air Joule Engine [10]. The preliminary results were reported to be promising of coupling a simple parabolic though and a Joule Engine. Wojewoda and Kazimierski provided investigation on operation of an externally heated valve Joule Engine [11]. A numerical model was presented, and the heat exchanger operation was further investigated. Creyx et al. developed a numerical model of an open cycle Joule Engine, which was focused on the thermodynamic aspects [12]. The reported system thermodynamic efficiency was 37% after some optimisation work. Bell and

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Nomenclature

A_{com} (m^3)	compressor piston area
A_{exp} (m^3)	expander piston area
$A_{expsurf}$ (m^2)	surface are in contact with gas
A_d (m^2)	reference area of the flow
C_d (–)	discharge coefficient
C_e (N/(m s^{-1}))	load constant of alternator
C_k (–)	kinetic friction coefficient
C_s (–)	static friction coefficient
$\dot{m}_{flow}$ (kg/s)	mass flow rate through valve
$\dot{m}_{expi}$ (m/s)	mass flow rate in/out of the valve
$\overrightarrow{F_{exp}}$ (N)	pressure force from linear expander
$\overrightarrow{F_{expl}}$ (N)	pressure force from left expander
$\overrightarrow{F_{expr}}$ (N)	pressure force from right expander
$\overrightarrow{F_{com}}$ (N)	pressure force from linear compressor
$\overrightarrow{F_{coml}}$ (N)	pressure force from left compressor
$\overrightarrow{F_{comr}}$ (N)	pressure force from right compressor
$\overrightarrow{F_e}$ (N)	resistance force from alternator
$\overrightarrow{F_f}$ (N)	frictional force
i (A)	current in the circuit
p_{com} (Pa)	pressure in the compressor
p_{coml} (Pa)	pressure from left of compressor
p_{comr} (Pa)	pressure from right compressor
p_{comin} (Pa)	intake gas pressure of compressor
P_e (W)	electric power output of alternator
P_{ex} (W)	indicated power of the linear expander
$\dot{Q}_{ht}$ (J/s)	heat flow rate between cylinder wall and gas
p_d (Pa)	downstream air pressure
p_{exp} (pa)	pressure in linear expander
p_{expl} (Pa)	pressure from left chamber of expander
p_{expr} (Pa)	pressure from right expander
p_{expin} (Pa)	intake gas pressure of linear expander
R (Ω)	resistance of the circuit
R_S (Ω)	internal resistance
R_L (Ω)	resistance of the external load
T_u (K)	temperature of upstream
T_w (K)	average surface temperature of cylinder wall
v (m/s)	piston velocity
v_p (m/s)	average piston speed
V (m^3)	instantaneous cylinder volume
V_{com} (m^3)	working volume of linear compressor
V_{exp} (m^3)	working volume of linear expander
x (m)	piston displacement
γ (–)	heat capacity ratio
ε (V)	electromotive voltage

Partridge presented a first-order model of a Joule Engine, and the model included combustion, clearance volume, gas leakage, pressure drop, and friction [2]. Another system was reported by the researchers at Plymouth University, the system power output and efficiency were simulated, indicating an engine thermal efficiency of up to 33% [2]. The model validation was performed using the testing results of both a demonstration engine and a prototype engine [13].

1.2. Linear engine generator technology

The Linear Engine Generator is linear 'crank-less' power device that couples a linear internal combustion engine with a linear electric generator, it uses conventional diesel or Otto cycles [4,14,15]. The piston of the engine is connected with the translator of the generator. Combustion takes place in the engine cylinder, and the high pressure gas during the expansion process is used to drive the piston and the translator, and the linear generator produces electricity [16]. There have been different prototypes reported by different research groups [17–23]. Successful implementations of single cylinder Linear Engine Generators have been reported by Toyota Central R&D Labs Inc. and the German Aerospace Centre (DLR), which were both composed of a single cylinder engine, a linear electric generator, and a gas spring rebound chamber [23–26]. For the prototype developed at DLR, it was operated at 21 Hz, with an electric power output of approximately 10 kW [27]. The TDC achieve was found to be at 57.5% of the periodic time [28]. For the dual-piston dual-cylinder Linear Engine Generator, several prototypes have been designed in Beijing Institute of Technology [6,7]. Both 0/1 dimensional and multi-dimensional simulation were undertaken to predict the dynamic and thermodynamic performance of the system [29–31]. Successful engine cold start-up has been reported, and the combustion took place when the cylinder pressure reached the required level for ignition [7,32,33]. The piston was controlled to oscillate between two set positions with constant speed [34,35]. The predicted system efficiency was around 35%. The potential disturbances to the system were analysed, and a cascade control strategy was proposed for the piston stable control [36,37].

1.3. Linear Joule Engine generator development

The Linear Joule Engine Generator concept was first proposed by the authors' group, initially aiming for application for micro-scale CHP generation [3]. 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 could produce 4.5 kW of mechanical power. Whilst, through waste heat recovery technology, the total system could reach a promising efficiency of over 90%. Later on, a 3-dimentional diagram of the proposed LJEG system was presented by the authors [9]. The geometry parameters of the system were optimised in LMS AMESim software, which provided 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% [38].

1.4. Aims and methodology

In this research, the background and recent developments of the LJEG are summarised. A more detailed numerical model of the system will be described, which includes the sub-models for the piston dynamics, the reactor, the linear expander, the linear compressor, and the linear generator, etc. The model validation will be performed with the testing data from both a reciprocating Joule Engine, and a LJEG prototype developed by the authors' group. The system dynamics and thermodynamics characters will be identified with the validated model.

2. System configuration

For an ideal Joule Engine Cycle (as illustrated in Fig. 1), it usually consists of four processes, *i.e.* adiabatic compression process in the compressor, constant pressure fuel combustion process, adiabatic expansion process in the expander [39]. It should be noted that the "Combustor" shown in Fig. 1 can be replaced with any fuel combustion,