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A preliminary experimental study on a lab-scale Linear Joule Engine prototype

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Abstract

A lab-scale prototype of Linear Joule Engine has been developed with the optimized design parameters from previous studies. The Linear Joule Engine applies free-pistons in double acting cylinders and Joule Cycle with an external combustor or heater as heat addition component in the cycle. It offers an alternative prime mover technology using different low carbon or zero carbon fuels, e.g. hydrogen, bio-methanol, ammonia, etc. in the energy transition period. A series of preliminary experiments was conducted to reveal the relationships between moving mass, valve timing, supply pressure and dynamic equilibrium. The experiment results were also used to provide guidance on the prototype design of linear alternator and heat addition component. A scaled-up and modularized Linear Joule Engine system integrated with linear alternator would have an exciting potential to be used as ship main engine, range extender of hybrid vehicles, etc.

Keywords: Linear Joule Engine, low carbon fuel, zero carbon fuel

1. Background

The International Energy Agency (IEA) estimated that hydrogen production in the UK, Germany, France and Italy will exceed 120TWh during 2030-2050 [1]. In the marine sector, the International Maritime Organization (IMO) determined that, by 2050, global shipping shall reduce its CO_2 emissions by at least 50% compared with 2008 and subsequently head for a complete phase-out [2]. This represents a systematic shift towards using low or zero carbon alternative fuels in the global economy driven by the new agreements and governments' commitment.

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In order to achieve the commitment, it is crucial to identify potential low and zero carbon alternative fuels and associating technologies. Liquified Natural Gas (LNG) powered ships are increasing exponentially due to their relative cleaner emissions and low cost in recent years. In 2017, Royal Caribbean Cruises Ltd. (RCCL) announced the world-first hydrogen fuelled Proton-Exchange Membrane fuel cell demonstrator for power supplement on their new 200,000 GT LNG powered Icon Class vessel, expected in 2022. The hydrogen used on the Icon Class vessel is generated from an on-board LNG reforming process, therefore it cannot be regarded as a low carbon or zero carbon fuel. In the marine sector, renewable energy derived hydrogen and ammonia, and bio-resource derived methanol are generally viewed as potential alternative fuels. In the Figure 1, it is illustrated that the volumes of different alternative fuels to replace 400 liter LNG storage on a 2000 passenger cruise ferry. Liquified and compressed hydrogen are stored at -253˚C (1 atm), and 700bar (ambient temperature) respectively, while methanol and liquified ammonia are stored at 20˚C and -34˚C under ambient pressure.

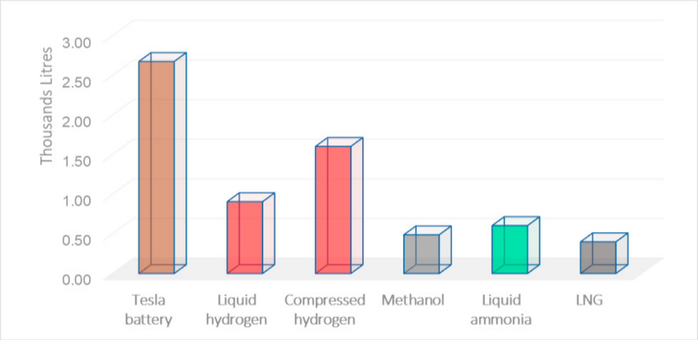

Fig. 1. Storage volume comparison of low carbon/zero carbon fuels

Internal combustion engines (ICE), including diesel engines, gas engines and dual/triple fuel engines, have been extensively studied to adapt to low carbon/zero carbon fuels. A review paper [3] summarized that, although hydrogen supply in engines provides significant reduction in HC, CO, CO2 and smoke, the high energy rates of hydrogen may lead to high in-cylinder temperatures and NOx formation. Compared to automobile applications, the fundamental difficulty obstructing hydrogen engine applications in the marine sector lies on volumetric efficiency of hydrogen storage, besides the NOx emissions, which affects cruising radius, space usability and consequently vessel profitability. Internal combustion engines have less problems to apply bio-methanol, although the carbon contained fuel cannot provides a thorough carbon-free solution. Similar to potential hydrogen applications on engines, ammonia engines have been extensively investigated with slight engine modifications. The inherent difficulty lies with the fast-intermittent combustion in internal combustion engines against the properties of ammonia, i.e. high ignition energy, high auto-ignition temperature, narrow flammability range, low flame temperature and propagation velocity. A subtle balance of the in-cylinder combustion is difficult to achieve to avoid either ammonia slip (unburnt ammonia escaping from exhaust) or high NOx emissions (high in-cylinder temperature caused by co-firing diesel and gasoline). However, ammonia is regarded as an ideal hydrogen carrier due to its safer and efficient storage.

Fuel cells (FCs) using hydrogen have long been considered as the future power technology [4]. Large scale FCs have the drawbacks of slow starting-up/shutdown, and poor durability to thermal cycling (repeated extreme temperature alternation during starting and load shifting process causes permanent structural damage), which need backup batteries to form a much heavier power system to meet fluctuated propulsion and hotel loads on board ships. This would cost their comparable power density as engine technologies. The inherent cell performance degradation and short lifespan also hamper FCs from becoming ‘main power’ for long lifecycle (30+ years) marine applications which demand self-sustainability and durability. To overcome the hydrogen storage problem and eliminate reforming process of carbon contained fuels, e.g. LNG and methanol, research efforts have been made to use ammonia directly in FCs. PEM FC and Alkaline FC are susceptible to trace ammonia presence, which causes their irreversible damage. Solid oxide fuel cell (SOFC), Alkaline polymer electrolyte FC and Anode-less PEMFC are resilient to ammonia slip through an integrated cracking process. However, thorough decomposition of ammonia to hydrogen and nitrogen is an endothermic reaction suffering from its thermodynamic penalty that decreases overall system efficiency.

2. Progress on Linear Joule Engine development

During the imminent energy transition towards using low carbon and zero carbon alternative fuels, a new prime mover technology is desired to adapt to most of alternative fuels and avoid those difficulties of ICE and FC technologies. Linear Joule Engine has the potential to use alternative fuels with external combustion configuration, which enables various methods to overcome the inherent difficulties of high NOx emissions in hydrogen engines and auto-ignition issue in ammonia engines. Linear Joule Engine can fully integrate with linear alternator to make it a highly efficient 'chemical energy to electricity' energy convertor, which is analogous to FC technologies, but built upon the existing engine and alternator technology basis to make it an easy approach. Linear Joule Engine is able to be driven by waste thermal energy, which makes it also possible to pair with FC technologies to form an ultra-high thermal efficiency prime mover system for large scale applications.

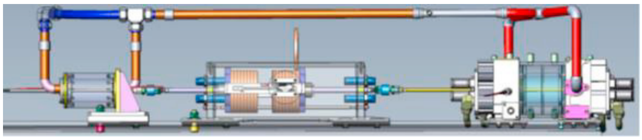

Fig. 2. The first design of the Linear Joule Engine prototype [5]

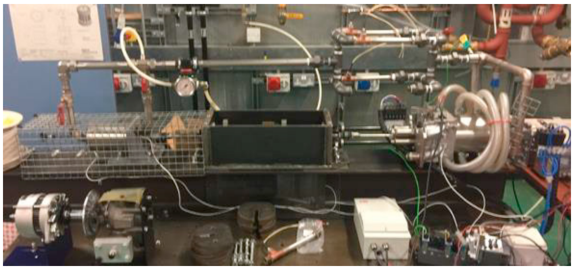

Fig.3. Overview of the test rig

The first design of the Linear Joule Engine was proposed by Wu and Roskilly [5], shown in Fig. 2. In the paper, the working principle of the Linear Joule Engine was introduced, and a parametric study was conducted to determine optimal geometry parameters, e.g. cylinder diameters, piston stroke, volume ratio of split cylinders, moving mass weight, etc. An optimal thermal efficiency of 32.2% was predicted with the engine split cylinders' diameters of 80mm and 66mm, the piston stroke of 120mm, and the moving mass of 8kg, while the engine works with highest pressure and temperature of 5.9bar and 800˚C respectively. A more sophisticated dynamic model incorporating both the mechanical part (Linear Joule Engine) and the electrical part (linear alternator) was developed by Wu, Jalal, and Baker [6]. The first coupled model simulated the engine with the optimal geometric parameters from [5] with some further improved design on valve settings and control algorithm, which estimated that a small-scale Linear Joule Engine generates around 2kW output with a thermal efficiency of 34% (1.8kWe, 30% efficiency of the Linear Joule Engine-Generator). It also revealed that the major impact brought by the linear alternator integration on the dynamic equilibrium of the Linear Joule Engine. The papers [7], [8] were published to give more details of the design of a linear alternator to match with the design specification of the Linear Joule Engine. More recently, Jia, Wu, et al. [9] published a theoretical model of the Linear Joule Engine Generator validated with experimental data from other literatures to provide insightful guidance on the design. In this study, the lab-scale prototype of the Linear Joule Engine has been developed and tested in preliminary experiments to evaluate the effects of adjusting key parameters on its performance and provide further guidance on the design optimization and integration with linear alternator.

3. The lab-scale prototype of Linear Joule Engine

The lab-scale prototype is shown in Fig.3. The components were compressor, expander, heater (combustor) and damping force generating device (moving case in the middle) which simulated a linear induction alternator. Two double-acting free pistons were placed in the compressor (left end) and the expander (right end) respectively, which separated cylinders into two opposite chambers. A rigid piston rod connected the two pistons, with the moving case in the middle of the rod, which acted as the translator of the linear alternator. The weight of the moving case was 4kg and a total of 16 weights, 1kg each, could be inserted to change the weight of the moving case. The heater (out-of-cylinder combustor) was placed between the compressor and expander and connected with pipes.

On the expander, there were intake and exhaust pneumatic valves to intake and expel working fluid, which was air. The valves were supplied with compressed air of 6 bar for all the tests. The valves were controlled by a Labview program to decide the opening and closing length of the valves, based on the displacement of the piston. The engine control signals were synchronized with the displacement encoder to open and close the intake and exhaust valves at the correct piston position.

A NI CompactRio connected the Linear Joule Engine prototype to the computer. Five modules were inserted into the CompactRio. The NI 9411 module was the encoder for the displacement sensor of the moving mass, the NI9474 modules were the encoder for the intake and exhaust valves on the expander, the NI9205 module was the encoder for the pressure sensors and the NI9213 module was the encoder for the temperature sensor.

The preliminary experiments incorporate: firstly, to use supply compressed air with different pressures to drive the moving mass with various weights, which validates the working frequency and the stroke length for the linear alternator design; secondly, to change intake and exhaust valve opening timings to understand their impact on dynamic equilibrium.

4. Results and discussion

The prototype of Linear Joule Engine operated on supply compressed air from 2bar to 4.5bar, while different weights of the moving mass, from 4kg to 20kg, have been tested. The intake valve opening timing on the expander was set as from 0mm to 15mm displacement of strokes in both direction, and the exhaust valve closure timing was from 60mm until the end of stroke. The frequency and the total displacement of the piston of each run are shown in the graphs in Fig.4 and Fig.5. The total displacement of the piston is defined as: Total Displacement (mm) = Frequency (Hz) × Stroke Length (mm).

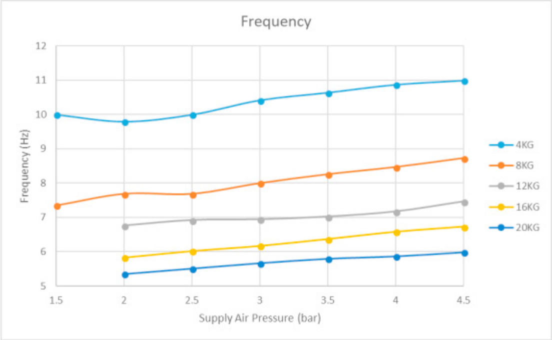

Fig.4. Frequency of piston against supply air pressure

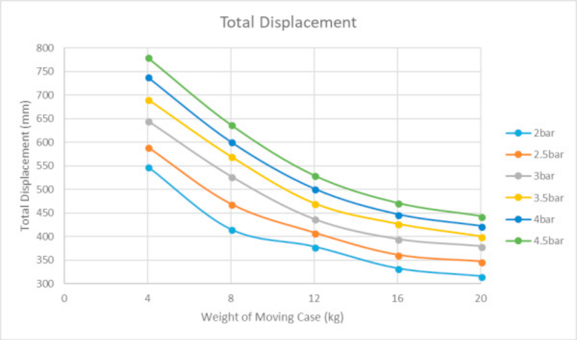

Fig.5. Total displacement of piston against weight of moving case

It was observed in Fig.4 that for each moving mass weight series, the increase in frequency as the supply air pressure increase has a linear relationship. The frequency is an important variable for electromotive force in linear alternator [6], which also determines the electricity output from linear alternator integrated to the linear engine. The frequency also decides the highest velocity and the velocity profile in a stroke, in turn, significantly affects peak values of electrical responding forces from linear alternator. The impact of moving mass weights revealed from Fig.4 provides important information for the constraint of the weight of permanent magnets on the translator. The moving mass on the Linear Joule Engine-Generator incorporates two pistons, piston rod, permanent magnets on translator and associated translator frame. To achieve a designated power output from linear alternator, adequate permanent magnets within the weight limit need to be mounted on the translator.

In Fig.5, with each increase of 4kg weight of the moving mass, for a fixed supply air pressure, the total displacement decreased exponentially. It is predicted in the initial design [5] that increasing moving mass would slow down the piston/translator. The piston/translator needs to be designed to cover as much distance as possible in terms of the external constraints, i.e. supply pressure, and moving mass weight. However, although the 4kg moving mass travels the longest distance, it carries less permanent magnets with less magnetic flux generated. A further optimization study on the trade-off between weight and total displacement to maximize electricity generation from linear alternator is required.

Further experiments were conducted with variable intake and exhaust valve timings of the expander while the moving mass weight and the supply pressure are fixed. Although different moving mass weights and different supply pressures have been tried, the results of the 8kg weight and 4.5 bar supply pressure are presented as an example. Four different valve timing combinations were scrutinized, which are Case 1 (0-20 mm Intake valve opening; 0-80 mm exhaust valve opening); Case 2 (0-20 mm Intake valve opening; 0-70 mm exhaust valve opening); Case 3 (0-25 mm Intake valve opening; 0-85 mm exhaust valve opening); and Case 4 (0-25 mm Intake valve opening; 0-55 mm exhaust valve opening).

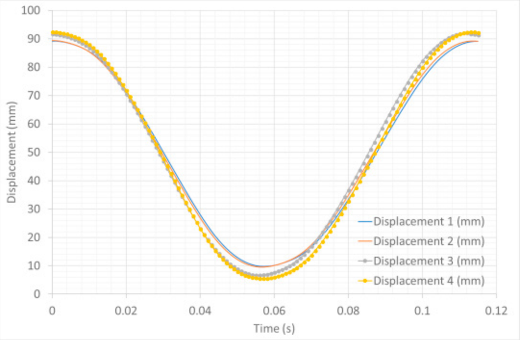

Fig.6. Displacement of the moving mass with various valve timings

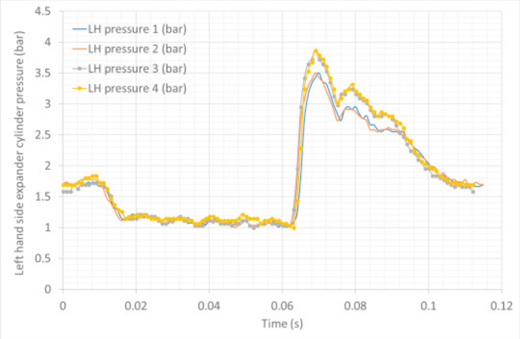

Fig.7. Left hand side expander in-cylinder pressure comparison

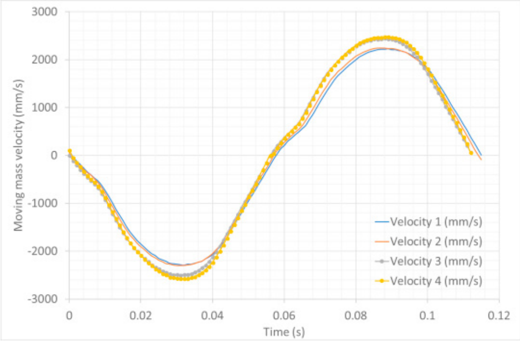

Fig.8. Velocity of the moving mass with various valve timings

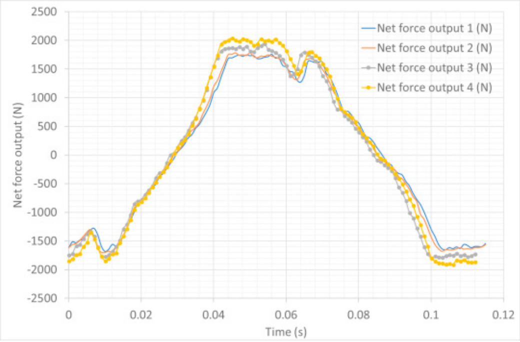

Fig.9. Net force output comparison with different valve timings

In Fig.6, it illustrates the displacements in the four cases within one cycle (two strokes). The Case 3&4 with longer intake valve opening show an extended stroke and a shortened cycle time compared to the Case 1&2. In a stroke, the Case 3&4 intake more energy from compressed air, therefore they show more steep displacement indicating higher acceleration. There is no significant difference of the displacement profiles between the Case 1&2, as the exhaust valve opening timing difference is small (80mm vs. 70mm). In the Case 3&4, the larger exhaust valve opening timing (85mm vs. 55mm) leads to a small difference on cycle times, as the Case 4 with an early exhaust valve closure has extra resistance from the other side of the expander cylinder, in turn, having a slightly longer cycle time. In Fig. 7, a close-up illustration of the in-cylinder pressure of the left-hand side expander cylinder is presented. The supply pressure is 4.5bar, while the highest pressures in the Case 1&2 and Case 3&4 are 3bar and 3.9bar respectively. The major reason causes the pressure loss is that a relatively large clearance of at least 10 mm is kept in order to protect the engine from unexpected cylinder head knock by the moving mass. With a longer intake valve opening, more air flow would be intake by the Case 3&4, which causes the higher peak pressure in cylinder. The pressure drop happens fast towards the end of a stroke for the Case 3 can be explained by the longer exhaust valve opening.

In Fig.8, the moving mass velocity profiles within one cycle also demonstrate the shorter cycle time and higher frequency of the Case 3&4, which was explained in the Fig.6 already. The velocity is a key indicator and parameter for linear alternator. The peak velocity of 2.6 m/s is achieved with a supply pressure of 4.5bar; higher peak velocity can be expected if the supply pressure increases to 7bar or even more. It may be noticed that the slope of the velocity after the peak value is steeper than that before the peak value, indicating more rapid deceleration than acceleration of the moving mass, which can be explained again with the relatively large clearance kept in the experiment series. An insightful net force profile comparison is presented in Fig.9. The positive force indicates the direction of the force is from left to right. From around 0.03s, the net force becomes positive, while the velocity value is still negative from the Fig.8, which means the moving mass is travelling from right to left and doing deceleration. The moving mass would stop and start to do a return stroke around 0.05s, while the net force is kept high positive value in the plateau of the profile. When the net force profile crosses the zero point, the velocity reaches its peak value in the positive direction stroke, from left to right.

In Fig. 10, the power outputs in one cycle are demonstrated. The positive power indicates the Linear Joule Engine is producing work and the negative value shows the energy consumption process while the work produced starts to be used on air compression and other losses, e.g. friction. The high negative value of the Case 4 means that extra energy is consumed due to early closure of exhaust valves, which also means the longer stroke of the Case 4 may compress air to higher pressure, in turn, consuming extra energy.

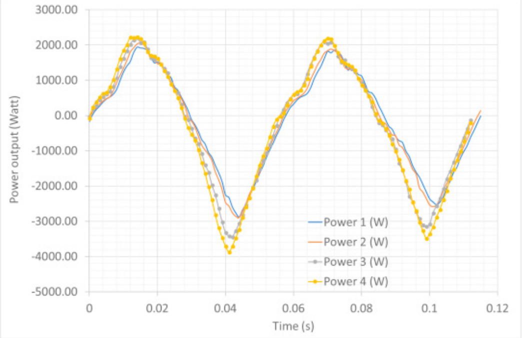

Fig.10. Power output comparison with different valve timings

5. Conclusion

A first experiment study on the lab-scale prototype of Linear Joule Engine was conducted to understand important parameters of moving mass weight, valve timings, supply pressure, and their impacts on dynamic equilibrium indicating variables, e.g. velocity, displacement, forces, etc. Ongoing experimental and simulation study will further reveal impacts from heating addition components (combustor or heater) and linear alternator. A lab-scale prototype of Linear Joule Engine-Generator would provide an alternative prime mover technology to use various low carbon or zero carbon clean energy for automobile and marine applications.

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