STUDY OF A WASTE ENERGY DRIVEN ORGANIC RANKINE CYCLE USING FREE PISTON LINEAR EXPANDER FOR MARINE APPLICATIONS

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ABSTRACT

Installation of Organic Rankine Cycle (ORC) waste heat recovery systems have been reported on at least six sea-going ships since 2012 and is expected to gain more interest as a means to reduce fuel consumption to meet increasing stringent environmental regulations. In contrast with land-based ORC systems for biomass and geothermal applications, wide-spread application of ORC onboard ships can only be possible if it is optimised for weight, volume, power output to meet actual electrical demands and importantly address concerns of the shipowner in return on capital. Previous studies by the authors have explored the economic aspects by looking at potential fuel savings and payback time of such a system onboard a ship. Selection of expander type for the ORC system is very important and linear piston expanders are expected to yield economic and thermodynamic advantages due to their simpler design and high isentropic efficiency. This paper presents the feasibility of the application of ORC using a linear piston expander onboard a sea-going ship. The proposed ORC system using both thermal waste heat from main engines and waste cryogenic energy from Liquefied Natural Gas fuel considers the ship's actual design like general arrangement plan and operational data like operational profile. A dynamic simulation method using a Siemens Simcenter Amesim will be used for the design and optimisation process. Results from the study show that the free piston linear generator to provide stable output suitable for electrical generation. However, the mechanical efficiency is found to be low which indicates that various parts of the expander design needs to be optimized. Due to this, the economics of an earlier study needs to be reduced from 7% to 5.9% for fuel savings and 2.7 years to 3.1 years for payback period which could impact project viability if the dynamics of the expander is considered.

1. INTRODUCTION

Increasing demand for decarbonisation in the maritime industry will change how ships will be powered in the future. International Maritime Organisation (IMO) is taking steps as the global regulator to implement measures to control Greenhouse Gases (GHG) and other noxious emissions from the marine industry. In an ambitious move in 2018, IMO agreed on an initial strategy to cut shipping's total greenhouse gases (GHG) by at least 50% from 2008 levels by 2050 (IMO, 2018).

While there is general consensus in the industry that the cleaner Liquefied Natural Gas (LNG) will replace the conventional marine fuel oils, this is expected to contribute to a reduction of only 20% in GHG emissions from ships (ignoring methane slip). Hence, other measures like energy efficiency will need to be considered holistically to meet the stringent target set by IMO stated earlier.

1.1 Marine Waste Heat Recovery Systems

Energy efficiency measures include advanced hull form with refined hydrodynamics, machinery improvements, hybridisation and operational measures. Another measure is the application of waste heat recovery systems that could provide fuel savings of up to 8% depending on ship type and size (DNV GL, 2017).

Waste heat recovery systems are not new for ship design either. It is a common design to recover waste heat energy from diesel engines using a composite boiler to generate steam to provide heat tracing in Heavy Fuel Oil (HFO) tanks and other steam consumers. Other than this application of reusing waste as thermal energy, the interest in converting to other forms of energy like electrical power is only starting to gain traction.

Recovering waste heat from large diesel engines onboard ships, the popular options are to install a power turbine generator (PTG) which is driven by the kinetic energy or a steam turbine generator (STG) that runs on a steam Rankine cycle. More than a hundred ships, almost all large container vessels are installed with either options (Ng and Tam, 2019). This is also recommended by Virtasalo and Vänskä (2012) who estimated that waste heat recovery system running on PTG or STG will be economical with installed engine power more than 20MW which are fulfilled by large two-stroke engines.

For smaller ships, organic Rankine cycle (ORC) may prove to be the choice for recovering waste heat as the power of main engine is smaller and their operational profile varies more. As an example for a smaller ship like a LNG-fuelled platform supply vessel, an ORC system will help to provide an annual fuel savings of about 7% and an investment payback of about 2.7 years (Ng et al., 2019).

Ultimately, the actual installation of ORC is the most important indicator on whether the technology has gained acceptance from shipowners. In the past few years, it has been reported in the media that at least 6 sea-going ships had been installed with ORC onboard as shown in Table 1 with a few others in the laboratory or prototype stage.

Table 1: List of reported maritime applications of Organic Rankine Cycle plants

Ship Name (Year)	MV Figaro (2012)	Viking Grace (2015)	Arnold Maersk (2016)	Asahi Maru (2017)	Orizzonte (2017)	Panerai I & II (2018)
Vessel type	PCTC	Cruise Ferry	Container	Bulk	Fishing Vessel	Fast ferry
ORC Maker	Opcon	Climeon	Calnetix	Kobe Steel	Enogia	Orcan Energy
Capacity	500kW	150kW	125kW	125kW	4.8kW	154kW
Expander type	Twin screw	Turbine	Radial turbine	Semi-hermetic	Microturbine	Screw
Fuel savings	4-6%	Up to 5%	Up to 10-15%	3%	5%	6-9%
References	(Opcon Energy Systems AB, 2016)	(Viking Line, 2014)	(Marinelog, 2016)	(Kobelco, 2017)	(Enogia, 2015)	(Orcan Energy AG, 2019)

It is shown in the list that most the generator output is about 150-200kW range and this will be suitable for smaller two stroke and the four stroke diesel engines with fuel savings of 5-10%.

1.2 Development of Free Piston Linear Expander

The overall performance of ORC system is strongly influenced by the performance of the expander (Lemort and Legros, 2017). While rotodynamic or turbine expanders have been proven in large ORC plants with higher flow rates, in some applications like marine, the positive displacement expanders that include screw, scroll, piston and vane type may prove to be more effective in dealing with smaller flow rates, high expansion ratio with low enthalpy drops and two-phase flow. This can be observed from Table 1 where half of the existing ORC shipboard projects are using positive displacement expanders of the screw type.

Although screw and scroll expanders are the most matured expander technology compared with the rest (Imran et al., 2016), piston expanders could be an interesting alternative to these in marine application utilising high temperature exhaust and consequently high expansion ratio and varying operating conditions. In terms of simplicity, the piston expander is something that the marine engineer will be familiar with.

This paper examines a special case of the piston expander in that unlike the conventional reciprocating piston expander, the piston motion is not constrained by the crankshaft which is removed with main advantages of simple mechanical structure, low frictional losses and high efficiency. This is known as the Free Piston Linear Expander (FPLE).

The use of FPLE is an extension of the research on the Linear Joule Engine and was first studied for transcritical CO_2 cycle for power recovery and subsequently applied for ORC cycle. Recent research on FPLE on ORC has focused on experimental studies in laboratories designed for application for small scale ORC system in automotives. These experiments were conducted without a full ORC setup i.e. only with compressed air from a pressurised tank up to a few bars piped to drive the FPLE before being exhaust into the surrounding in an open cycle.

Most of current research focus on how the intake pressure, operating frequency, external load, linear generator design, valve timings, impacts the piston motion dynamics (displacement, velocity, stroke) and output performance like work output and efficiency.The indicated efficiency which is the ratio between actual work done to the theoretical work done is calculated for these experimental studies shown in Table 2:

Table 2: Experimental results for indicated efficiency

Reference	Indicated efficiency	Operating frequency (Hz)	Intake pressure (bar)	Load resistance (Ω)
(Li et al., 2016)	66.2%	3	2	5
(Hou et al., 2017)	92.8%	2	1.4	-
(Xu et al., 2018)	66.2%	3	1.9	3
(Xu et al., 2018)	89.3%	1.5	1.9	9

In another experimental study, Wang *et al.* (2017) calculated the energy conversion efficiency which is the ratio between the electrical power output and the work input to be 55% at 3.75 bar. The authors conclude that FPLE is a promising expander system for low grade heat for power generation due to its low frictional losses, compact structure and operational flexibility.

Hou *et al.* (2019) found in a recent research that a maximum energy conversion efficiency of 74% can be obtained for intake pressure, operating frequency and external load resistance of 2.8 bar, 1.5Hz and 20Ω respectively.

Due to the fact that many of these previous studies were based on experiments, the use of simulation methods to aid in the preliminary design of the FPLE needs to be further explored. This paper will present the building of the FPLE in system simulation software Siemens Simcenter Amesim as a tool to study the behavior of a FPLE with real working fluid data, pressure and temperature.

2. MODELLING & SIMULATION

Based on an earlier research by the authors on the application of an ORC system onboard a 4,800dwt LNG-fuelled platform supply vessel (Ng et al, 2019), it was found that working fluid using n-Heptane (C_7H_{16}) provides higher efficiency and net work output and will also be selected as working fluid in this paper.

The evaporation pressure, P_{evap} is set at 9bara taking into account that the evaporating temperature should not exceed the autoigition temperature for safety reasons. With LNG cooling, it is possible to adopt a condensing pressure, P_{cond} of 0.01bara. These operating data will be used as the input and output to the FPLE.

The proposed design of FPLE used in this study is as below which is that of a dual free piston expander. The two pistons are set in a to-and-fro motion from the actuation of the high pressure organic working fluids via the inlet and exhaust valves. A connection rod joins the two pistons and where a permanent magnet is mounted that is part of a linear generator consisting of a stationary stator coil that generates electrical energy to the external electrical load.

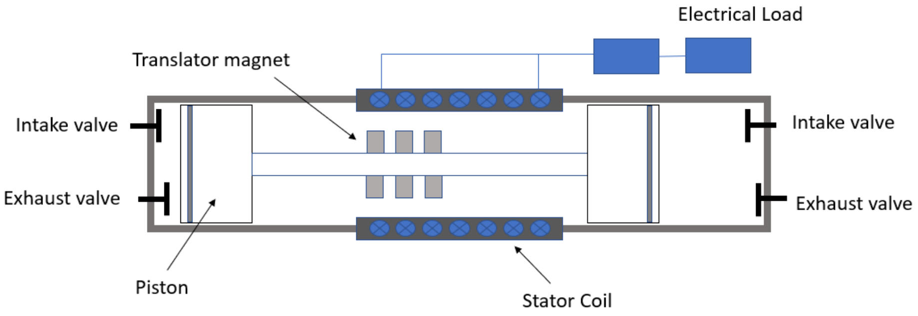


Figure 1: Layout of a FPLE

2.1 Modelling and simulation of Free Piston Linear Expander

The modelling and simulation of the FPLE is carried out in the commercial-off-the-shelf software, Siemens Simcenter Amesim which is a multi-disciplinary 1-dimensional software which means that it can analyse across multiple domains of thermal, fluid, mechanical, electromechanical, control, etc.

In this study, the two-phase library of the software is used with some sub-models from the mechanical library for the moving mass. The model developed is shown in Figure 2 below.

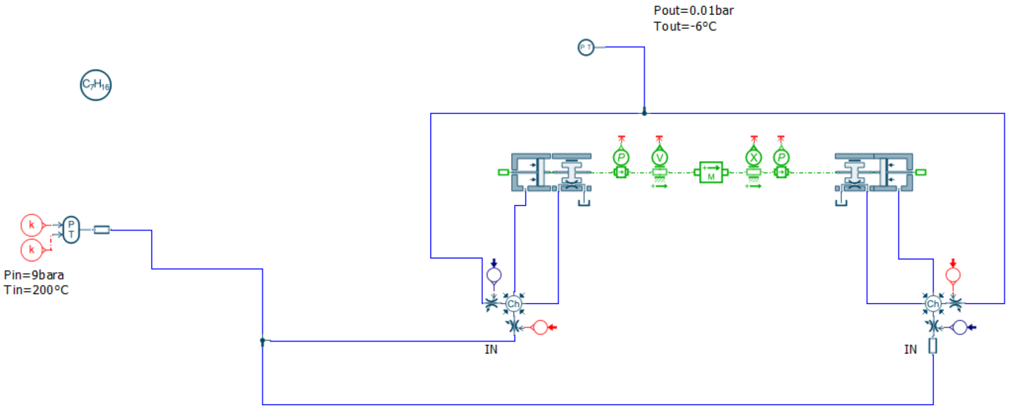


Figure 2: Amesim model sketch

The model consists of two pistons at each end with the pressure force acting on one side of each piston. Each piston is also connected to a submodel accounting for leakage past the piston and also a flow chamber which is itself connected to the inlet and outlet valves. Control signals are passed to the inlet and outlet valves to control the intake and exhaust of working fluid in the piston. For this study, simple sinusoidal wave signals are passed to the valves to effect the opening and opening sequences at opposite ends to drive the to-and-fro motions of the piston assembly.

The two piston assemblies are connected mechanically via rod and a moving mass that form the translator of the linear generator. Various sensors for power, velocity and displacement is added on the rod provide data output for analysis.

2.2 Comparison with earlier experimental data

The Amesim model is compared with the results that has been presented by Wang et al. (2017) in their experimental study of a FPLE driven by compressed air. The simulation parameters are used for the comparison as shown in Table 3.

Table 3: Parameters used in simulation

Parameters	Quantity
Piston diameter	39mm
Moving mass	2 kg
Operating frequency	3.5 Hz
Inlet pressure and temperature	3 barg @ 15°C

Figure 3 shows the comparison of the experimental and simulation results. Maximum deviations for piston displacement and velocity are found to be around 25% at certain part of the cycle. This deviation could be due to the fact that nitrogen is being selected as the working fluid in the simulation model as air data is not available in the Amesim two-phase library. This error will be expected to be smaller with the correct working fluid being modelled in the simulation.

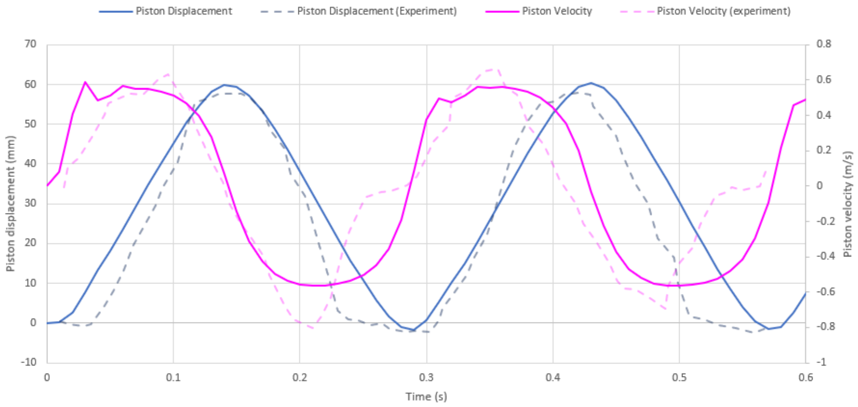


Figure 3: Comparison of simulation and experimental results

3. RESULTS AND DISCUSSIONS

A reference case is established for a FPLE with the following specifications: piston of diameter of 40mm, moving mass of 5 kg, and operating frequency of 5 Hz. The piston dynamics for displacement, velocity acceleration and mechanical power is plotted against time for first 10 seconds as shown in Figure 4. Data for piston displacement, velocity and acceleration is found from the various sensors output. The mechanical power is found from averaging the two power sensors across the moving mass.

A general sinusoidal motion is observed for piston motion of the reference case. Stable oscillations are achieved with a stroke of 0.18m within 1 second of starting and achieving a peak mechanical power output of 6kW is also achieved in that time period. The steady behavior exhibited indicates that it is possible to extract the mechanical energy into electrical energy via the use of linear generators.

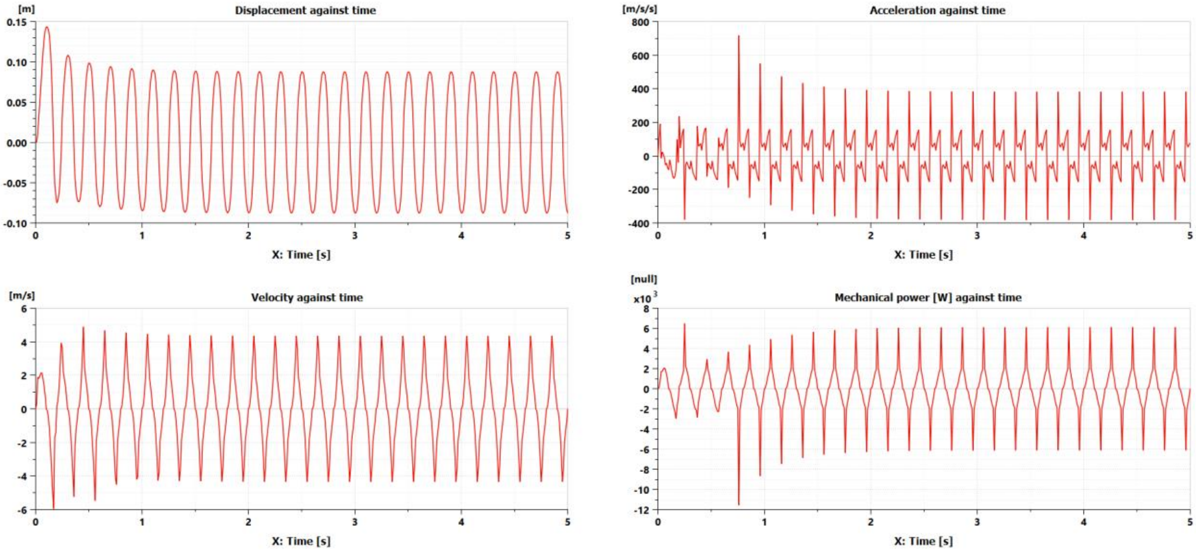
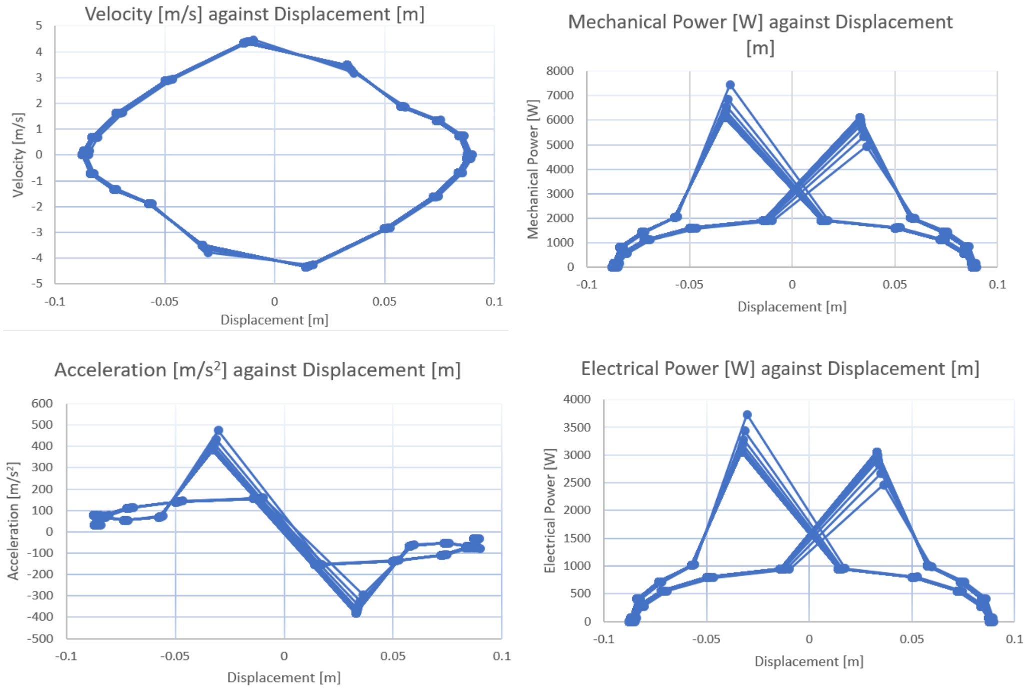


Figure 4: Piston Dynamics against time (Top left: Displacement, Bottom left: Velocity, Top right: Acceleration, Bottom right: Mechanical Power)

The piston velocity and acceleration are plotted against displacement to observe variations during oscillations, neglecting the initial 1 second of transient behaviour and the results are shown in Figure 5 (Top left and bottom left). Maximum velocity of 4 m/s is obtained at mid-stroke and zero velocity at the end of each stroke while acceleration is maximum each quarter stroke. The dispersion of these data is quite tight that suggest that stability of the cycle.

The mechanical power and electrical power are also plotted against displacement. The electrical power is obtained by assuming a conservative electrical efficiency of 50%. Peak electrical power of about 3kW can be obtained from the reference case of FPLE design.


Velocity [m/s] against Displacement [m]

Mechanical Power [W] against Displacement [m]

Acceleration [m/s²] against Displacement [m]

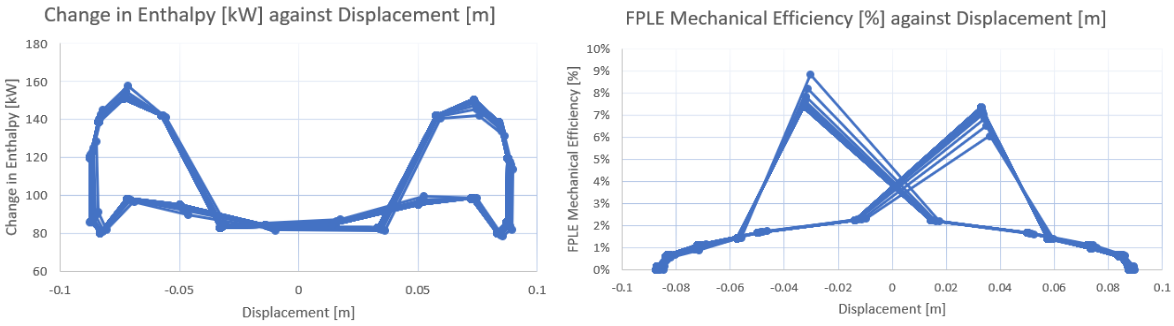
Electrical Power [W] against Displacement [m]

Figure 5 Piston dynamics against displacement (Top left: Velocity, Bottom left: Acceleration, Top right: Mechanical Power, Bottom right: Electrical Power)

The maximum amount of energy available for FPLE can be measured by the change in enthalpy of the fluid entering and leaving the FPLE. The mechanical efficiency of the FPLE can be derived by dividing the mechanical power by the change in enthalpy flow rate:

$$\text{Mechanical efficiency, } \eta_m = \frac{Mechanical\ power, P_m}{Change\ in\ enthalpy, \Delta h}$$

Figure 6 shows the change in enthalpy and mechanical efficiency of FPLE against the displacement. The change in enthalpy is observed to be higher at either ends of the stroke and provides more enthalpy that can be changed to work. The mechanical efficiency follows closely that of the mechanical power and peaks at the quarters of each stroke.


Change in Enthalpy [kW] against Displacement [m]

FPLE Mechanical Efficiency [%] against Displacement [m]

Figure 6: Change in Enthalpy (left) and Mechanical Efficiency (right) against Displacement

3.1 Marine application of FPLE

It will be interesting to study how the reference case of FPLE can be utilised in a proposed ORC system onboard a LNG-fuelled platform supply vessel that is the case ship of investigation (Ng et al., 2019). In that study, a dual fuel marine diesel engine exhaust provides the heat source while the cryogenic LNG fuel is used as heat sink. The maximum required mass flow rate of working fluid, n-Heptane was found to be 0.72 kg/s.

For the single cylinder FPLE reference case, the variation of the mass flow rate is found to be as shown in Figure 7 with a maximum of 0.13 kg/s. This will require a FPLE of at least 6 cylinders so that the mass flow from the main ORC system can be distributed. In terms of space for installation, it should not be a problem to find an empty space to house a module that consists of 6 cylinders of 40mm. However, the peak electrical power is only about 3kW for each cylinder with the total peak electrical power to be 18kW.

As the earlier study had envisaged an ORC system with electrical output of 120kW, the 6-cylinder FPLE will be able to provide one-sixth of the electrical power that was required. This will affect the economics of the ORC installation meaning that potential fuel savings of 7% and payback of 2.7 years will be too optimistic and will probably be closer to 5.9% and 3.1 years respectively.

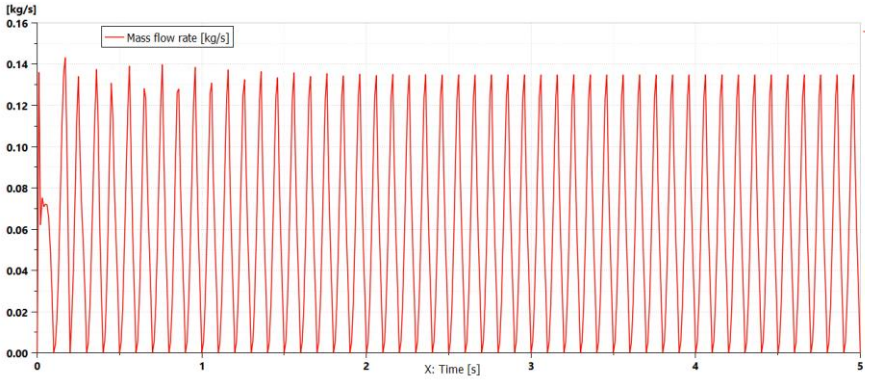


Figure 7: Mass flow rate into FPLE against time

4. CONCLUSIONS

Free Piston Linear Expanders (FPLE) in Organic Rankine Cycle onboard ships has been proposed for its potential high efficiency, compactness and operational flexibility. From a dynamic study conducted using Siemens Simcenter Amesim, to-and-fro motions in the FPLE can be created using simple sinusoidal inputs for the inlet and exhaust valves. Piston motion dynamics compare well with experimental results which can be further improved with alternative working fluids.

The reference case of FPLE appears to be underperforming with low mechanical efficiency of about 5%, meaning that more will need to be done to optimise the various parts of design, for example, valve opening and closing. This is very important as this could affect the thermo-economic analysis performed earlier and reduces the actual gain from ORC projects. As such, the fuel savings and payback time needs to be revised from 7% to 5.9% and 2.7 years to 3.1 years respectively. It is important to simulate the dynamics of expander in the design of ORC system. The opportunities offered by dynamic system engineering offers better possibility of optimizing the FPLE design

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