Linear free piston gas expander performance in organic Rankine cycle based waste heat recovery application

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Abstract:

This work is focused on the development of a free piston gas expander (FPGE) for organic Rankine cycle (ORC) application that can be developed into a low cost, high performance, modular and scalable FPGE unit for multiple distributed power applications in the range of 5-50kWe for automotive, biomass and concentrated solar power (CSP) applications. The linear piston expander incorporates a passive transfer valve for the controlled metering of a pressurized working fluid into an expansion chamber as part of an energy conversion device and in particular as part of a heat-to-power conversion device employing a Rankine thermodynamic cycle. The developed FPGE is expected to offer lower cost and higher efficiency due to integration of ORC heat exchanger and pump within the expander, elimination of mechanical drivetrain (Passive inlet valve, operated by bounce event), reduced component costs and losses, thermodynamic advantages of piston expanders over other expander types (variable expansion ratios, high isentropic efficiency), low bypass losses and tolerance of two-phase conditions. As suggested above, the expander is able to demonstrate variable volumetric expansion ratios, which can be changed during the operation through real-time control of piston motion. A multi-physics mathematical model is presented for the simulation of the said expander. The model that is developed as part of this work will provide a suite of analytical and development tools that can be used in the development of this and future free piston gas expander systems for a range of ORC applications. Model elements are developed to be reconfigurable so that parameters can be easily accessed and adjusted to accommodate alternative operating scenarios and input parameters such as alternative working fluids, expansion ratios, input temperatures and pressures. The developed model is experimentally validated for its dynamic simulation to predict the performance and design optimization of the machine itself.

Keywords:

Organic Rankine Cycle, Waste heat recovery, volumetric expander, R1233zde, linear piston expander.

1. Introduction

The modern world has agreed to contain global warming well below 2°C (COP21) [1]. The transport sector contributes approximately one-third of all CO_2 emissions around the globe [2]. Recently, the European Parliament proposed a target of $68gCO_2/km$ by 2025 [3]. The core of the transportation sector is still served by internal combustion engine-based powertrains. The internal combustion engine has been well studied and technological enhancements like turbocharging, exhaust gas recirculation (EGR), advanced fuel injection and combustion systems have significantly improved their performance. However, despite all the mentioned advancements, the efficiency curve is reaching its peak phase as the internal combustion engines, in general, can still only convert 30 - 40% of fuel energy into useful work on average [4]. As such, disruptive ideas are essential to improve the energy conversion efficiencies of conventional systems.

Organic Rankine cycle (ORC) based waste heat recovery (WHR) systems are considered promising to convert exhaust gas heat into useful power in an effective manner [5]. The ORC systems are similar to the conventional Rankine cycle system, but utilize an organic working fluid instead of water, thus allowing it to recover heat from a different range of temperatures than the Rankine cycle. Fig 1 presents the basic components of an ORC system along with the temperature-entropy (T-s) diagram of the process. The unmanned operation, low maintenance, favourable pressures, adaptability to match complex heat source conditions and part load operation make it a preferred choice for waste heat recovery application [6].

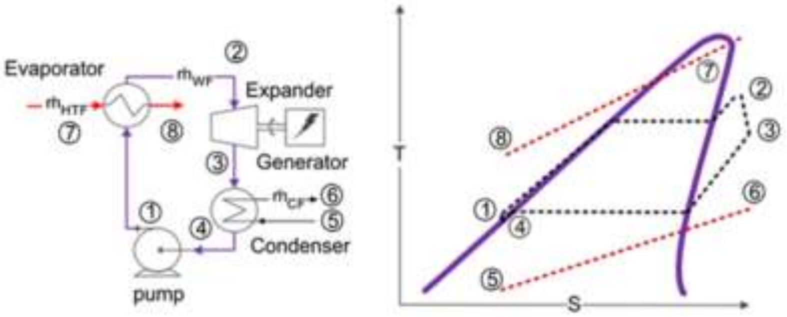
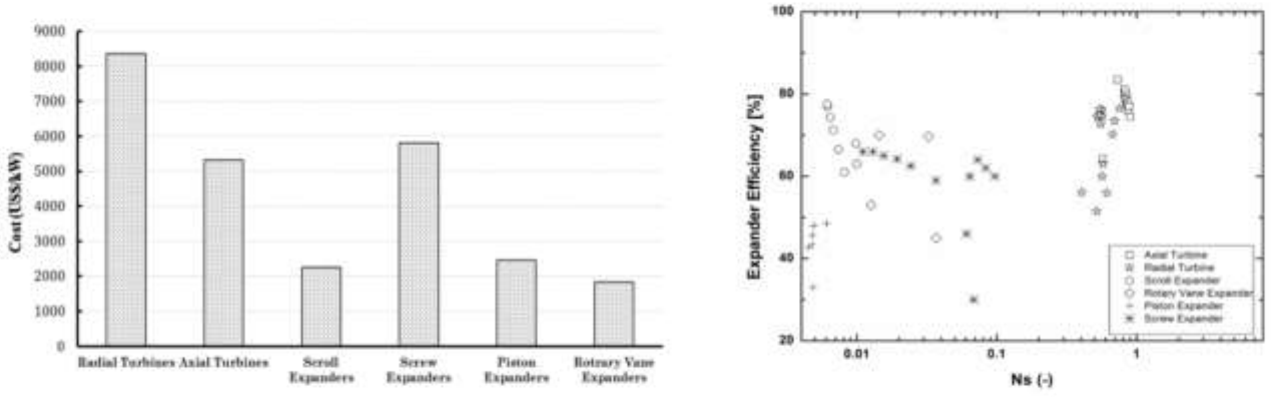


Figure 1. Schematic and Ts diagram of simple organic Rankine Cycle system [7]

The technology readiness level (TRL) is still low for ORC solutions to be considered for integration within vehicles for automotive exhaust heat recovery at present. The limited availability of cost-effective, efficient and compact systems have contributed towards the slow rate of commercialisation. The technological development of heat exchangers and pumping systems are considered mature for the application but suitable expansion machines and compact integration are core bottlenecks in the development phase.

The automotive waste heat recovery potential in general lies in mini-scale ORC systems <30kW. Compared to volumetric machines, turbines have higher conversion efficiencies, but the resulting designs are often high-speed (>20krpm)[8], which requires sophisticated bearings, lubrication system and generator. All these factors, significantly increase the cost of the unit. Fig 2 (adapted from [9]) presents the comparison of cost and efficiencies of expansion machines according to their type.



Cost estimation of expanders according to their types

Expander efficiency vs. specific speed for different expanders

Figure 2. ORC expansion machine cost and efficiencies based on types

Volumetric expanders are more common for small scale applications although, with relatively lower efficiencies compared to the turbomachines, the lower cost and ease of availability often lead to their preferential selection.

The current work is focussed on the development of a volumetric type, linear expansion machine for ORC applications, which can be further optimised by integrating the working fluid pump, and heat exchanger within the linear electrical machine and thermofluidic system to provide a compact, integrated and modular ORC solution with high power-to-weight/volume ratio and performance applicable to vehicle waste heat recovery requirements, to pave a path for faster commercialisation.

2. Materials and Methods

The proposed machine is being developed by Libertine FPE Ltd. [10], a company specialising in the development of linear machines for power and motion. The proposed expander comprises a linear piston expansion machine directly coupled to an electrical machine. The flow control valves are actuated by motion of the prime mover, so no complex mechanical valve timing components are required. Fig 3 presents the expansion machine which houses an expansion chamber at either end of a linear electrical machine stator, where a central translator – driven by the gas expansion – oscillates within the electrical machine stator to generate electrical energy.

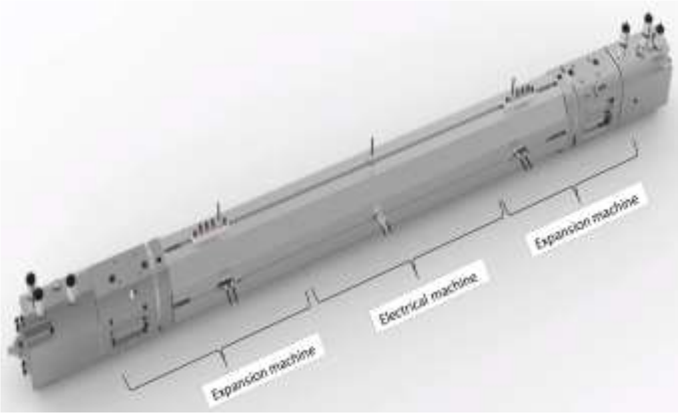


Figure 3. CAD of Linear piston expander with an integrated electrical machine

The high-pressure gas expansion in one chamber causes the piston/translator to move, and the relative motion of the translator with respect to the static coils of the electrical machine stator, generate electrical power as illustrated in Fig 4. The chamber at the other end, undergoes a compression stroke, while the other end is in expansion mode, the compression event occurs with a relatively lower mass fraction of gas which is used only to activate transfer chamber activation as illustrated in Fig 5.

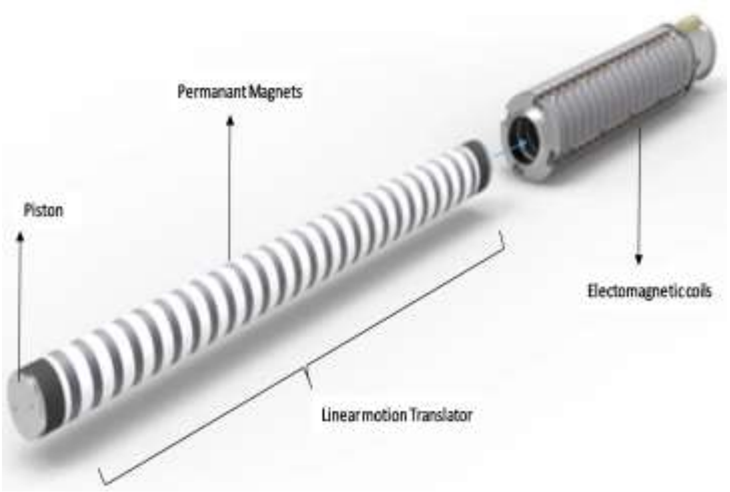


Figure 4. Translator and coil arrangement used in the electrical machine

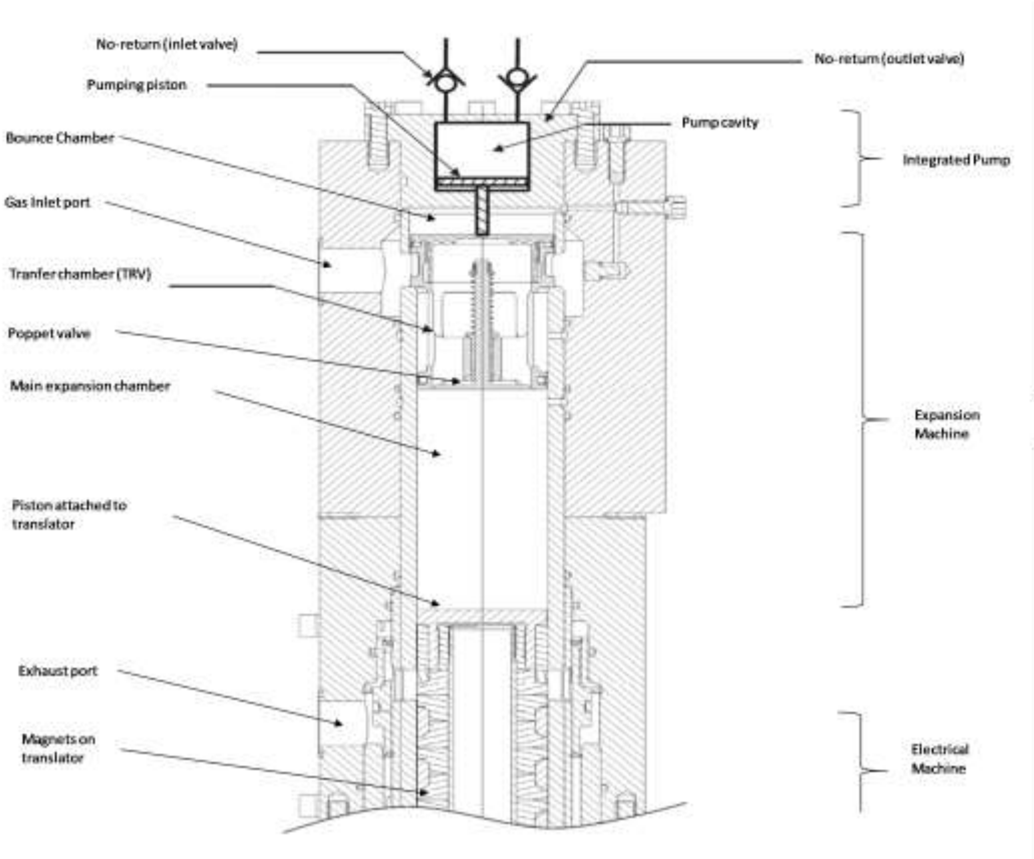


Figure 5. Cross-section of linear piston expander

Fig 5 presents a cross-section through one end of the proposed expansion machine. The overall expansion cycle is achieved by first pushing the piston upwards while the pressure in the main chamber starts increasing from an initial condenser/exhaust pressure. The transfer chamber is designed in such a way that when main chamber pressure exceeds inlet pressure, during the compression, the transfer chamber is displaced and the transfer chamber volume is connected with the inlet port volume. The bounce chamber acts as a cushion to push the transfer chamber back to its seated (closed) position once it has been filled with gas at inlet pressure. As the piston moves back the reduction in pressure in the main chamber causes a poppet valve to open, which allows the gas in the transfer chamber to move into the main chamber at the inlet port pressure, where the high-pressure fluid then exerts a force on the piston to drive further motion of the translator through the stator coils thus inducing the generation of electrical power. The passive design also lends itself to the introduction of a working fluid pump as presented in Fig 5, which acts to pressurise the inlet fluid as a result of the transfer valve motion. The overall machine can also be integrated with a heat exchanger to further reduce losses and enhance cycle efficiency, but the first prototype machine will only investigate expansion and linear electrical machine performance.

A multi-physics model is developed to simulate the performance of the machine to validate the design and ensure the system is optimized for the target application prior to production of the physical hardware and also to tune the controller of machine during its operation at different operating conditions. The model will provide a suite of analytical and development tools that can be used in the development of this and future free piston gas expander systems for a range of ORC applications.

Model elements are developed to be reconfigurable so that parameters can be easily accessed and adjusted to accommodate alternative operating scenarios and input parameters such as:

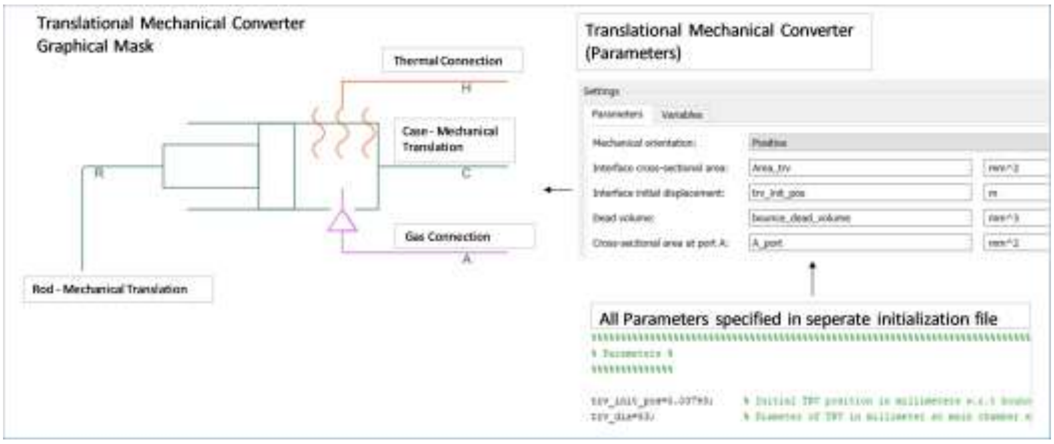
- Alternative working fluids
- Expansion ratios
- Input temperatures and pressures

This paper presents a 1-D model focussed on the thermo-fluid interactions which considers the gas physics, valve characteristics, leakage losses, bounce event (recompression event at end of each stroke to activate transfer chamber volume pressurization) and heat losses. The model provides pressure and force values as a function of time and position of translator which is combined with an electrical machine model to evaluate the performance of the overall machine and test the controllability of the machine at various operating conditions.

A 1-D model was setup up for modelling thermo-fluid interactions of the described expansion machine in Mathworks Simscape [11]. The Simscape programming environment provides the following advantages for current application:

- Physical connections (data sharing manipulation across models in minimum)
- Multi-physics (models blocks of various domains already available)
- Parametrization (allows model re-configuration from libraries with ease)
- Equations are represented as acausal, implicit, differential algebraic equations (DAEs)
- Re-usable models
- Refrigerant properties can be acquired if linked with a fluid properties database like NIST Refprop [12]

The overall model was composed of various submodels and different parametrization of the same model primarily acquired from the gas library of Simscape. Fig 6 presents how a translational mechanical converter (already available in simscape gas library) was adapted to act as a bounce chamber of the machine. The model was parametrised and all parameters for the model are stored in a separate .m file for ease of reconfiguration.



Mechanical orientation: Positive
Interface cross-sectional area: Area_trv mm^2
Interface initial displacement: trv_init_pos m
Dead volume: bounce_dead_volume mm^3
Cross-sectional area at port A: A_port mm^2

Figure 6. Translational mechanical converter model configured for bounce chamber

The mechanical converter model is connected to other components which include, valves, piping volumes, and heat transfer components, and can be masked as transfer chamber volume (TRV) submodel, as presented in Fig 7. The transfer chamber volume model interacts in a similar way to the main chamber model and appears as a submodel if observed from the thermo-fluid model as presented in Fig 8.

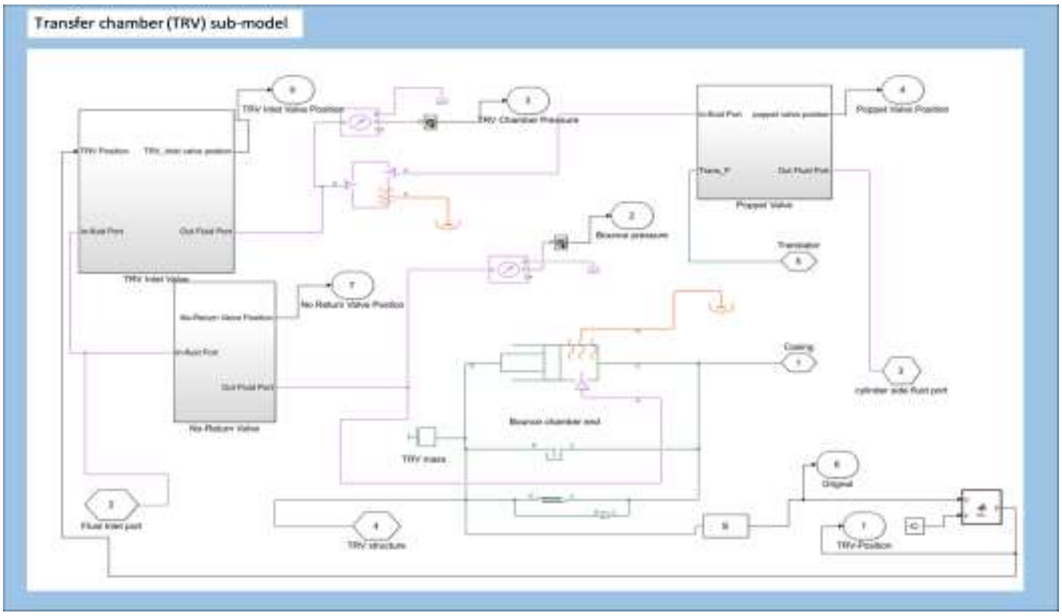


Figure 7. Transfer chamber volume (TRV) sub-model

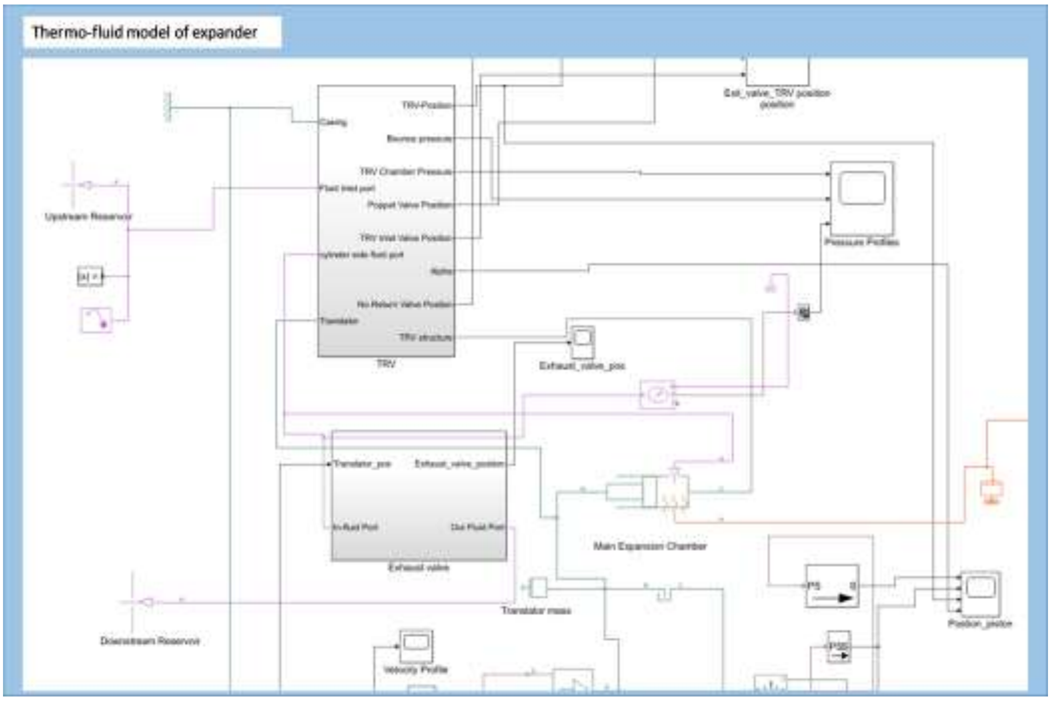


Figure 8. Thermo-fluid model of the expander

3. Results and conclusions

The model was parameterized against a pre-existing expansion machine at Libertine FPE. The machine was experimentally tested using air as the working fluid. The motion profile along with the pressure profiles of the main chamber, bounce chamber and transfer chamber were obtained, which supported the calibration of the thermo-fluid model. The model was fine-tuned and re-run to generate the model simulated pressure profiles presented in Fig 9, which were in agreement with experimental data.

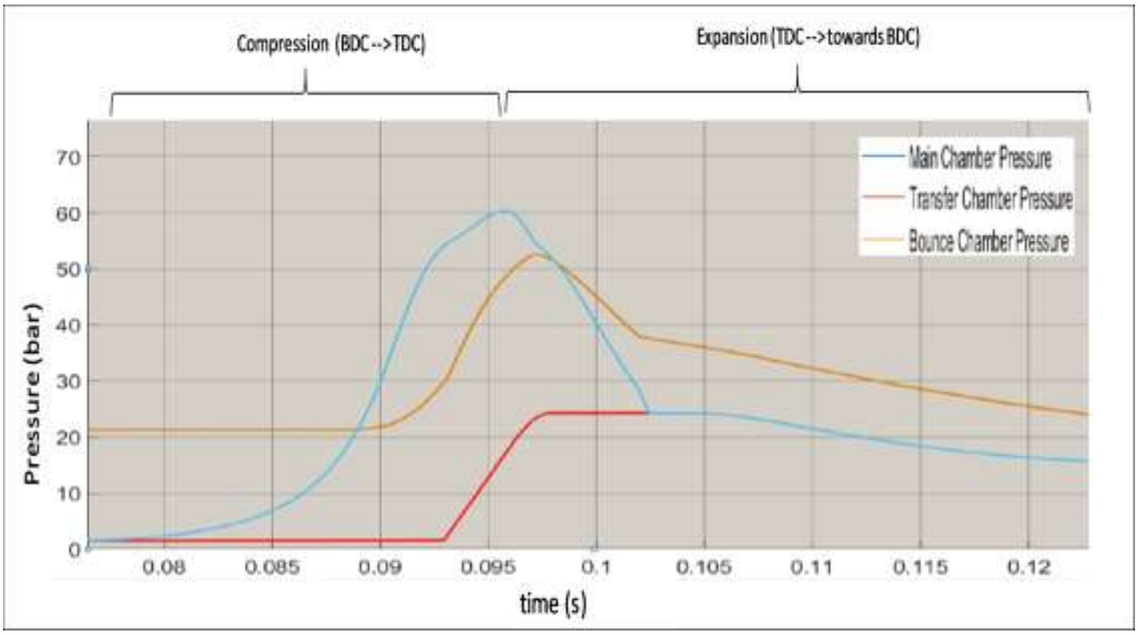


Figure 9. Pressure Profile against time for single compression and expansion event at one end of expander

The pressure profiles in Fig 9 were used to acquire the force values required which can be fed into the electric machine model to support the tuning of the controller, which acts to maintain the motion profile of the translator to achieve the optimal expansion. The model acts as a very useful tool to acquire the power output values based on different operating frequencies and boundary conditions, and study the impact of changing the geometry of the machine. The initial calibration with experimental data based on air as the working fluid has provided confidence to match with the basic physics of the system. The future work on the model is focussed on its ability to be adapted for an organic working fluid. The next phase of the modelling effort is focussed on the implementation of fluid properties for R1233zde working fluid to simulate the performance of an organic working fluid. After simulations, a complete prototype is scheduled to be tested at Brunel University London.

Nomenclature

$\dot{m}$	Mass flowrate
HTF	Heat transfer fluid
wf	Working fluid
cf	Cooling fluid
T	Temperature
s	Entropy

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