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DEVELOPMENT OF TWIN PISTON EXPANDER WITH SOLENOID VALVE FOR ORGANIC RANKINE CYCLE

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ABSTRACT

This paper presents the progress of development of a new twin-type piston expander, (TPE) to be used as an expansion unit for a low temperature organic Rankine cycle (ORC). The lack of suitably suitable available expanders and most of the available expander are commonly limited to a certain range of operation. As an initiative to introduce a suitable expander, and the available type of expanders operation commonly limited for a certain range of operation. Therefore, in this study, an existing unused twin piston compressor has been converted into a TPE, with a few modifications on the compressor on by replacing the compressor valves with a solenoid valve and its ports conditions. The newly developed TPE behavior, functionality and performance are were tested at different inlet temperature and pressure. The preliminary results observed showed that the power produced by the TPE is was proportionally changed to the inlet temperature and pressure, and it is was recorded that the highest power of 3.4 kW achieved when TPE operated at 7 bars with 153 °C inlet temperature. Meanwhile, it was also observed that the rotational speed variation depends on the inlet pressure stronger than it does on the inlet temperature. The results also revealed that the TPE is feasible to be used as an expander for the ORC system with several improvements before it is adapted into the system.

Keywords: twin piston expander compressed air solenoid valve reciprocating piston organic rankine cycle.

INTRODUCTION

Recent progress in industrial development and the expansion growth of human population globally are among the trigger factors that urge for the higher and higher energy production to satisfy these demands. Although the energy demand can be fulfilled by means of presently available energy conversion systems, most of the systems, particularly those operate on fossil fuels generate relatively low efficiency of approximately within 20% to 45%. Meanwhile, the environment issues such as global warming, air pollution and climate change due to massive consumption of the fossil fuel, have drawn the world's attention to investigate and utilize the renewable energy resources in order to solve those problems (Liu *et al.,* 2015) and (Hua *et al.,* 2016).

Current renewable energy resources, such as heat from solar thermal, geothermal, biomass, solid waste, industrial and automobile waste heat are the potential methods to be adapted to meet the energy demand globally (Saadatfar *et al.,* 2013). However, the amounts of heat produced from the mentioned sources are generally low in average, and these low grade heat cannot be converted efficiently to the useful energy by conventional power generation methods (Wang *et al.,* 2013) and (Öhman and Lundqvist, 2013).

The interest in recovering low grade heat into a useful energy receives great attention around the world, and several important methods have been proposed to convert the heat into electricity (Quoilin *et al.,* 2010). Among the proposed solutions, Organic Rankine Cycle (ORC) system offers an interesting alternative to recover the low grade heat due to its simplicity, sizing, and flexibility to fit with various heat sources, with little modifications making this system more adapted to the energy conversion of the low grade heat, compared to conventional energy conversion systems (Quoilin *et al.,* 2013).

The heart of any ORC systems is the expander, which is a critical component limiting the cycle efficiency as it impacts the amount of mechanical power output produced by the ORC. In order to improve the cycle efficiency, the selection of expanders is of considerable importance to the development of ORC systems. There are many types of the expanders have been investigated and proposed by researchers i.e., turbo-machinery expander, scroll expander, screw expander, rotor expander, reciprocating expander, etc. Among these expanders, reciprocating piston expander (RPE) could work under high pressure ratio, having relatively good isentropic efficiency across a range of operating conditions and good performance over the size ratio, making the expander a suitable candidate for small scale power conversion system (Zhang *et al.* 2015) and (Bao and Zhao, 2013).

Due to the lack of suitably available expanders and the attractive features disclosed for the RPE, a new RPE need to be developed for an ORC in order to discover the real potential of the expander in ORC system especially in heat recovery applications. Therefore, this paper presents about the development progress and the result of preliminary performance test on a single unit twin-type piston expander (TPE).

DEVELOPMENT OF TWIN-TYPE PISTON EXPANDER (TPE)

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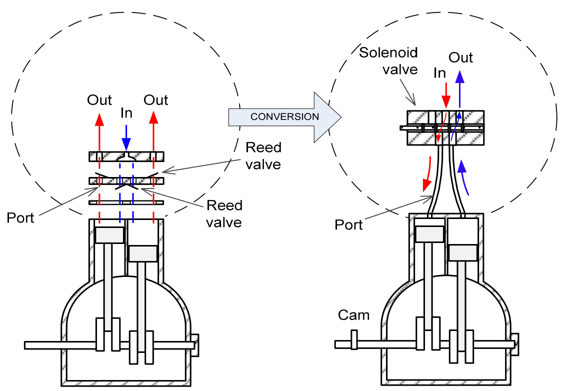
Conversion of twin piston compressor into TPE

The conversion of twin compressor into an expander was done by modifying the valve mechanism i.e., replacing the reed valves of the compressor with a 5/2 way solenoid valve, and change the two separate (inlet and outlet) ports into a single port for each cylinder. With this modification, the fluid enters and leaves each cylinder alternatingly through a common port and this action is determined by the valve position. The conversion of the twin compressor into TPE is shown in Figure-1.

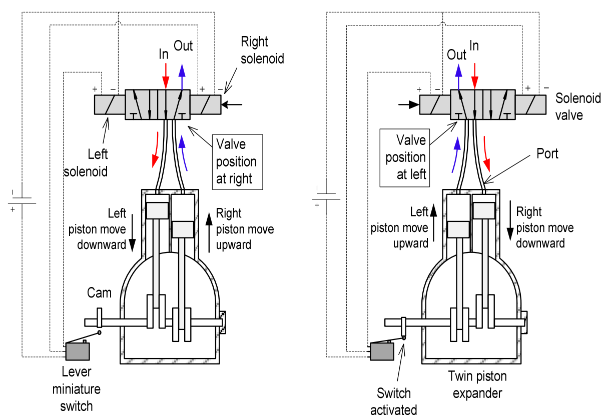


(a) Compressor mode (with reed valves) (b) Expander mode (with solenoid valve)

Figure-1. Conversion of the twin compressor into TPE.

The operational of TPE with electric activated solenoid valve

The valve position mechanism is triggered by a pair of 24-Volt electric solenoids attached at both end (left and right side) of the valve. These solenoids are operated when a lever switch is activated, i.e., the switch contacts to the cam that is installed on the expander shaft. The basic valve circuit and the expander operation are shown in Figure-2.



(a) Valve position at right (solenoid pushing the valve the left) (b) Valve position at left (solenoid pushing the valve the right)

Figure-2. Valve position controlling the fluid inlet and outlet of the expander.

EXPERIMANTAEXPERIMENTA L SETUP

In this study, the functionality of the TPE and its performance test has been carried out preliminarily by a simple experiment on the TPE using compress air as a working fluid. The schematic diagram of the test system is shown in the Figure-3. The compressed air initially supplied by a compressor has been regulated to a selected pressure, i.e., within 3 – 7 bars, using a pressure regulator.

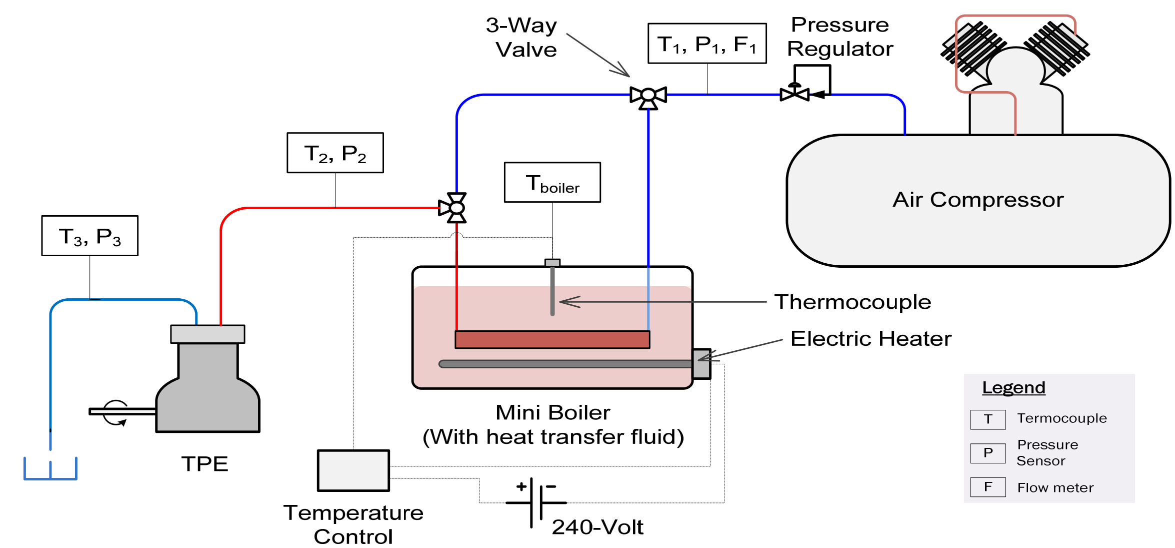


Figure-3. The schematic diagram of the TPE test system.

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Two test conditions have been decided for this study studied, i.e., the first experiment conducted when with the fluid at room temperature (as a reference condition), and the second is when the fluid being heated to higher temperature according based on to boiler temperature of 100 °C, 150 °C and 200 °C. The second condition is important for this study since it imitates the actual the real applications of the expander is for ORC systems which are always involved with the heated fluid.

To meet these test conditions, two units of 3-way valves have been installed before and after the boiler to direct the fluid either through the boiler or directly to the expander. In order to determine the thermodynamics properties of the fluid, the air temperature and pressure have been measured before and after the boiler, and after the TPE unit. The air mass flow rate was measured from the speed of the air flow inside the piping after the regulator (and before the boiler). At these specified conditions, air can be was treated as an ideal gas, and the specific volume of the air is obtained from the ideal gas equation of state as

$$v = \frac{RT_1}{P_1} \tag{1}$$

where, R is was an ideal gas constant of air, 0.287 kJ/kg K, T_1 and are the temperature and pressure measured after the pressure regulator. The mass flow rate of the air, is then calculated as

$$\dot{m} = \frac{\dot{V}}{v} \tag{2}$$

Here, $\dot{V}$ was the volume flow rate of the air at the measured position (position 1). The important properties in this study such as the enthalpies and entropies were calculated from the measured pressure and temperature using REFPROP software version 9.0 (Lemmon *et al*., 2010). The mechanical power produced by the expander, during the expansion process is expressed as

$$\dot{W}_{exp} = \dot{m}(h_2 - h_3) \tag{3}$$

This theoretical power determined from the difference of enthalpy at the expander inlet, h_2 and at the expander outlet, h_3.

RESULTS AND DISCUSSIONS

The measurement results of the air velocity together with the mass flow rate at different pressure are shown in Figure-4. It shown that the air velocity and mass flow rate were increased proportional to the increase of the air pressure. It is observed in this study that, for the specific system sizing and the increase in system pressure, the fluid velocity and mass flow rate were also increased.

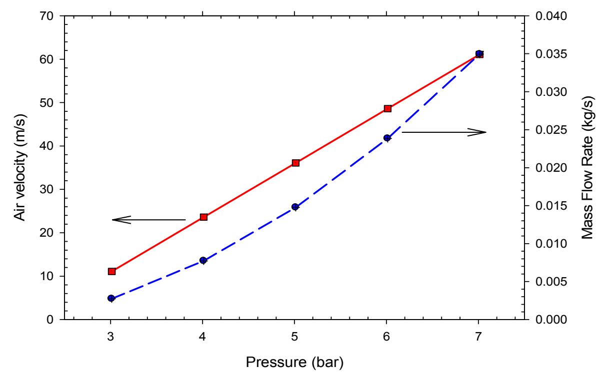

Figure-4. Air velocity and mass flow rate.

Since the air flow through the boiler, its temperature changed according to the boiler temperature. The fluid temperature also deviated from the initial condition after going through the expansion process in the expander. Figure-5 shows the temperature variations before and after passing through the expander (TPE), at a different boiler temperature and the expander inlet pressure.

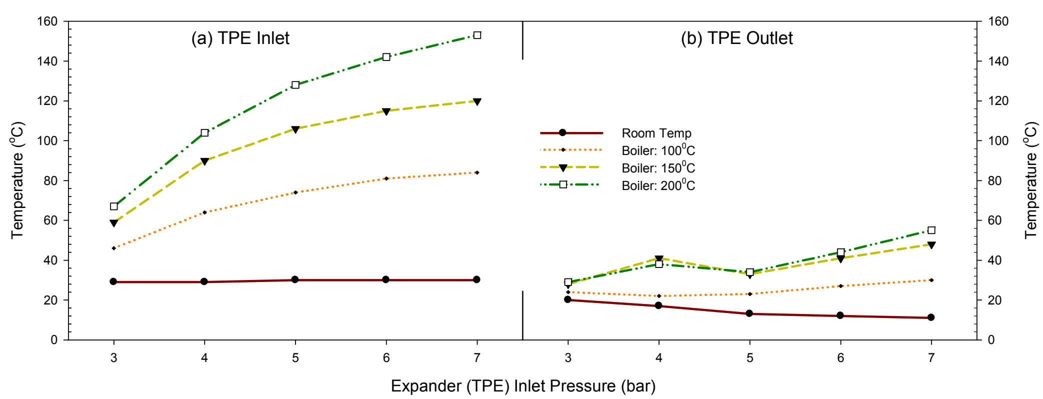

Figure-5. The variation of air temperature at boiler temperature and pressure: (a) At expander inlet, and (b) at the expander outlet.

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It is was obviously shown in Figure-5 (a) that, with the increase in boiler temperature, the air temperature at the expander inlet raised also increased and almost directly proportional when both boiler and operating pressure increased. It is however, when the supplied pressure increased for a constant boiler temperature, the temperature slowly increased, due to the dependent effect of the temperature and pressure.

Observation on the Figure-5 (b) revealed that the expansion process in the TPE has significantly reduce the air temperature at the TPE outlet. The noticeable reduction of the air temperature with approximately from 10 °C – to 100 °C recorded for different boiler temperature and this occurred due to rapid reduction of kinetic energy of air molecules during the expansion in a large TPE expansion volume inside the TPE.

In order to clearly understand the change of temperature during the experiment, Figure-6 shows the variation of air temperature and its entropy, at different boiler temperature, pressure, and state positions, (i.e., at compressor outlet, boiler outlet, and expander outlet). According to the temperature-entropy (T–s) diagram shown, the air temperature reached its maximum level of 153 °C when the boiler temperature set to 200 °C and at 7 bars. The least temperature recorded (except the air at room temperature) occurred when the air heated at lowest boiler temperature, i.e., 100 °C.

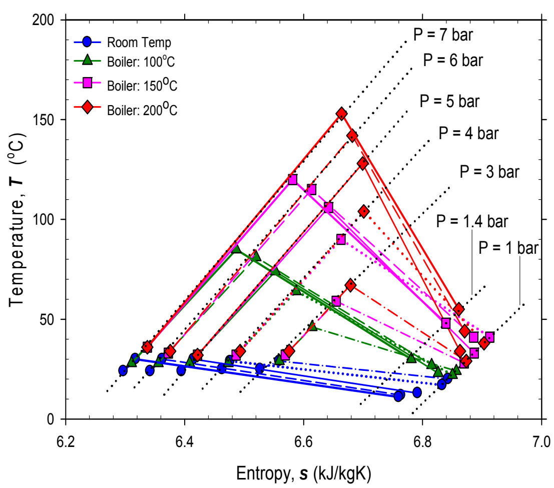

Figure-6. Air temperature and entropy change at different boiler temperature and supplied pressure.

From the ***T–s*** diagram, it was observed that the increase in the air temperature after the boiler was significant when the air is heated at higher temperature and pressure. The opposite phenomena faced by the same air after it was expanded in the TPE, as its temperature drops quickly compared to the air that enter the TPE at lower temperature and pressure.

Although this condition seems favorable for ORC applications as it reduces the fluid vapor temperature at the expander outlet to ease the transformation of the fluid back into its liquid state, excessive reduction in fluid temperature causing the phase of the fluid fall into a two-phase condition at the end of the expansion process inside the expander, and this limits most of the expander operations including TPE.

Beside the change in the fluid temperature, the interesting discovery observed during the expansion process was the pressure ratio of the expander inlet to the outlet is quite big, as it ranges from 3 to 5 bars for the entire supplied pressure within 3 – 7 bars. The observation of the TPE pressure ratio was critical as it determined whether the TPE fit or not to the behavior of displacement type reciprocating expander.

The important results i.e., the power and rotational speed produced by the TPE are given in the Figure-7 and Figure-8, respectively. Figure-7 reveals that the TPE power produced were proportional to the inlet temperature and pressure. For the supplied pressure less than 5 bars, the TPE power recorded was less than 1 kW (i.e., approximately within 100W – 500W). The highest power produced by the TPE is 3.4 kW occurred when the inlet conditions at 7 bars and 153 °C.

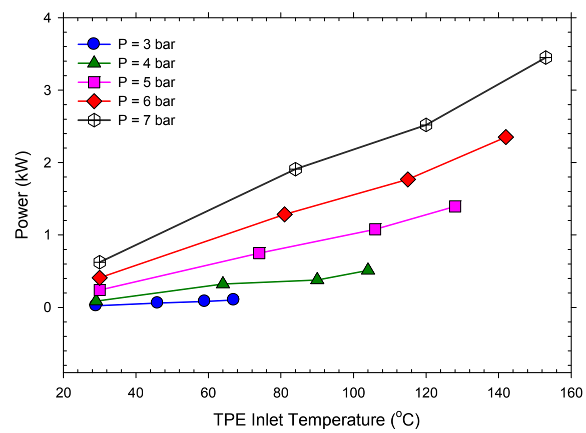

Figure-7. The power produced by the TPE over the inlet temperature at different pressure.

Figure-8 observes that the rotational speed varied with the given pressure and temperature. The speed achieved its maximum reading of 263 rpm when the TPE operated at 7 bars with the boiler temperature of 100 °C. Although both of the inlet pressure and temperature influenced the TPE speed, the pressure showed a strong effect on the speed than the inlet temperature did.

It was shown that, at the higher pressure condition, the rotational speed fluctuated at higher value compared to the conditions at higher inlet temperature. When the inlet pressure reached 7 bars, the rotational speed varied at higher average speed of 260 rpm, the speed variations however laid at lower ranges within 195 – 210 rpm when the inlet pressure reduced to 3 bars although the inlet temperature increased up to 200 °C of boiler temperature.

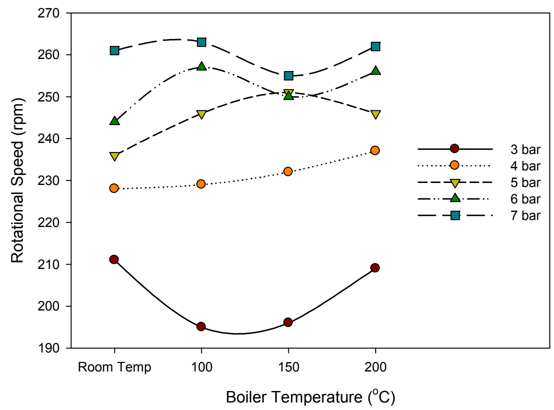

Figure-8. The rotational speed of TPE over the boiler temperature at different pressure.

CONCLUSIONS

This newly developed TPE showed a good functionality with an acceptable performance, and it behaved like most of the reciprocating expanders. In this study, the application of a solenoid valve had simplified the development process of the TPE by eliminating a few components that are most of the reciprocating expanders have.

The study observed that the power produced by the TPE were proportional to the inlet temperature and pressure. Although both of the inlet pressure and temperature influenced the TPE power and speed, the pressure showed a strong response on the power and speed compared to the inlet temperature effect. The preliminary result observed that the maximum power delivered by the TPE was 3.4 kW occurred when it operated at 7 bars with 153 °C inlet temperature, i.e., when the boiler operated at 200 °C. The rotational speed showed it varied with the average 260 rpm speed at input pressure of 7 bars regardless of the inlet temperature.

In the future work, the study should be carried out by measuring the actual power produced by the TPE, in order to determine the TPE isentropic efficiency. The next stage is to install the TPE into the ORC system and carried out the related test to determine the effectiveness of the TPE operates on the real ORC system. Several improvements should be carried out on the TPE head construction, and the valve system.

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REFERENCES

[1] Bao, Junjiang, and Li Zhao. 2013. "A Review of Working Fluid and Expander Selections for Organic Rankine Cycle." Renewable and Sustainable Energy Reviews 24: 325–42.

[2] Hua, Yaping, Monica Oliphant, and Eric Jing Hu. 2016. "Development of Renewable Energy in Australia and China: A Comparison of Policies and Status." Renewable Energy 85: 1044–51.

[3] Lemmon, E., M. Huber, and M. McLinden. 2010. "NIST Standard Reference Database 23: Reference Fluid Thermodynamic and Transport Properties (REFPROP 9.0)." Gaithersburg.

[4] Liu, Jizhen *et al*. 2015. "A Novel MPPT Method for Enhancing Energy Conversion Efficiency Taking Power Smoothing into Account." Energy Conversion and Management 101: 738–48.

[5] Öhman, Henrik, and Per Lundqvist. 2013. "Comparison and Analysis of Performance Using Low Temperature Power Cycles." Applied Thermal Engineering 52(1): 160–69.

[6] Quoilin, Sylvain *et al*. 2013. "Techno-Economic Survey of Organic Rankine Cycle (ORC) Systems." Renewable and Sustainable Energy Reviews 22: 168–86.

[7] Quoilin, Sylvain, Vincent Lemort, and Jean Lebrun. 2010. "Experimental Study and Modeling of an Organic Rankine Cycle Using Scroll Expander." Applied Energy 87(4): 1260–68.

[8] Saadatfar, Bahram, Reza Fakhrai, and Torsten Fransson. 2013. "Waste Heat Recovery Organic Rankine Cycles in Sustainable Energy Conversion: A State-of-the-Art Review." The Journal of MacroTrends in Energy and Sustainability 1(1): 161–88.

[9] Wang, Dongxiang *et al*. 2013. "Efficiency and Optimal Performance Evaluation of Organic Rankine Cycle for Low Grade Waste Heat Power Generation." Energy 50: 343–52.

[10] Zhang, Xinjing *et al*. 2015. "Study of a Single-Valve Reciprocating Expander." Journal of the Energy Institute.