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Research Paper

Low grade waste heat recovery using diethyl ether thermo-fluid diaphragm engine

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HIGHLIGHTS

- A novel two-phase thermo-fluid diaphragm engine with single chamber was developed.
- The engine utilizes low grade heat using diethyl ether as working fluid.
- The engine was tested experimentally in wide temperature and pressure ranges.
- Maximum indicated power and efficiency were 70 W and 10.3%, respectively.

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ABSTRACT

The recovery of low grade waste heat for power generation is getting more attention due to its large magnitude in the industrial sector. Commonly proposed solutions include Organic Rankine Cycle (ORC), transcritical carbon dioxide (T-CO_2) cycle and Kalina cycle but with complex architectures. Special type Stirling liquid piston engines such as the Fluidyne and thermo-fluid oscillator can also recover low grade waste heat below 150 °C with simple construction. In this study, a novel two-phase thermo-fluid engine with single chamber and diaphragm was developed and tested experimentally. The engine was characterized at different heat source temperatures ranging from 50 °C up to 100 °C and maximum pressure in the range of 1.2–2 bar. Highest indicated efficiency was 10.3% compared to 25.5% Carnot efficiency with maximum indicated power of 70 W at 10 RPM engine speed. A crankshaft mechanism was installed with flywheel and rope brake dynamometer to measure engine brake power. Maximum brake power measured was about 0.4 W at 8 RPM due to the high friction losses in the power delivery mechanism.

1. Introduction

The industrial sector consumes large quantities of energy especially in thermal energy and therefore contributes most of the greenhouse emissions. The industrial sector has accounted for about 52% of the world energy consumption in 2012 [1]. The exact amounts of industrial energy loses in the form of hot exhaust gases, cooling water and hot equipment surfaces heat lost are poorly quantified but estimated to be in the range of 20–50% [2]. Some of the common technologies to recover medium (230–650 °C) and high grade (>650 °C) waste heat into electrical power are: steam Rankine cycle, thermoelectric generator and Striling engine [2,3]. On the other hand, low temperature or low grade waste heat below 230 °C presents a big challenge since it cannot be used directly for power generation using the conventional electrical generation methods, despite its significant magnitude that exceeds the other waste heat sources [2]. Therefore, large scale recovery for this type is currently limited to thermal applications such as air and water preheat in boilers and domestic water and space heating applications.

Many non-conventional technologies such as organic Rankine cycle (ORC), transcritical carbon dioxide (T-CO_2) cycle [4], Kaline cycle [5–7] and special types of Striling engines [8] have been proposed for electricity production from low grade industrial waste heat. Although some of these technologies have been investigated for many decades, none of them has been commercially enrolled in industry due to many technical and feasibility constraints.

ORC has been extensively investigated in the last two decades and it can deal with low temperature sources by utilizing low boiling temperature working fluids. Although, steam Rankine cycle technology and cycle components are well established, using conventional rotary expanders for low scale power generation will

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result in a significant drop in cycle efficiency. Thus, other types of volumetric expanders such as scroll [9–11], vane [12], and screw [13] types have been widely investigated with ORC. These power cycles include multiple components such as the expander and several heat exchangers which increase the economic risk and make them less attractive from operation and maintenance points of view.

Another option is Sirling engine based on moving pistons or diaphragms. These engines commonly utilize medium grade heat (230–650 °C) and operate with air or helium as the working fluid [8]. A special type of Stirling engine is the Fluidyne engine introduced back in 1969 [8]. It was commonly used for water pumping and utilizes moving water as the pistons or in a hybrid metallic and liquid piston manner. Fluidyne pumps can utilize low grade waste heat with source temperature below 100 °C [8]. Another special type of Stirling engine introduced in 2004 [14] was the two-phase liquid piston thermo-fluid oscillator. This type is similar to the Fluidyne in terms of using liquid pistons and utilizing low grade heat, although, the movement is not dependant on the fluid inertia but rather on the partial vaporization of the fluid. The engine consists of two vertical (power and displacer) cylinders connected from top and bottom by horizontal pipes with a feedback valve located on the bottom pipe. Displacer pipe contains two vertical hot and cold heat exchanger blocks, and evaporation occurs when liquid comes in contact with the hot block during liquid piston movement. Feedback valve is opened to allow liquid level to drop for condensation process and control the oscillation frequency [15–17].

All the aforementioned technologies suffer from complexity and elaboration in system components that increases technical and economic risk. Thus, this study aims at investigating experimentally a simple solution for low grade heat utilization. The proposed engine is based on pressure increment utilization from boiling process such as in steam piston engine. However, unlike the steam engine with continuous heating in open cycle, periodic heating/cooling process is performed in a single control volume in closed cycle. Also, to avoid complexity, the dedicated compression and expansion equipment were replaced with a single diaphragm. The engine follows partially the Stirling thermodynamic cycle and main key elements for this new concept are:

- Single chamber with one moving part (diaphragm).
- No liquid oscillating movement and the diaphragm movement depends on the vapor pressure change inside the chamber.
- External flow control valves, with no internal valve inside the engine.
- Periodic heat addition and removal for more efficient operation.

2. Engine concept

The engine is based on a thermodynamic cycle similar to Stirling cycle with two isothermal processes and two isochoric processes. However, the engine does not operate at the common Stirling cycle condition which is the superheated vapor or gas zone, but rather in the two-phase vapor zone. Thus, processes 2 and 4 as shown in Fig. 1 go through isothermal heat transfer while maintaining constant pressure during the process. The second difference between this cycle and Stirling cycle is that all processes in the latter allow fluid flow through the boundaries. However, in this cycle, all processes occur in a closed system with no flow through the boundaries. Processes 1 and 3 occur at constant volume heat transfer with no moving boundaries while processes 2 and 4 present moving boundary isobaric/isothermal heat transfer. The third difference between this cycle and Stirling cycle is that there is no mechanical compression and expansion caused by piston movement. Instead, pressure elevation and reduction are achieved by heat addition and removal in the non-moving boundary manner.

Low boiling temperature (34.6 °C) diethyl ether was used for thermal waste recovery below 100 °C. Water can be used for the applications in the range of (100–200 °C). However, due to the higher specific volume and higher latent heat, the engine will be larger and requires intensive heat addition and removal, thus the engine tends to be slower. In general, engine speed depends on the rate of heat addition and heat rejection. This engine can also use low boiling point refrigerants such as R134a, and the engine can replace the heat exchanger commonly used in refrigerators between condenser outlet (to sub-cool the refrigerant) and evaporator outlet (to overheat the refrigerant). Refrigerator condenser can be used as thermal source and evaporator can be used as cooling source. The engine can absorb thermal power causing sub cooling effect at condenser outlet while rejecting thermal power to the evaporator causing the overheating effect. Fig. 1 also shows a schematic drawing of the engine that comprises: engine chamber with diaphragm, hot and cold heat exchanger coils, ice bath cold reservoir, hot water reservoir and hot and cold flow control valves. The thermodynamic processes are:

- First, heat addition at constant volume: in this process hot water valve is opened and heat is added through the heat exchanger coil when the diaphragm is still located at the bottom dead center (BDC). Since the process is closed, pressure starts to elevate and the piston does not start to move until the pressure is high enough to overcome the engine load and friction resistance.
- Second, heat addition at constant pressure and temperature: in this closed process, piston starts to move preventing pressure from further elevation while heat is still added in the evaporation process.
- Third, heat removal at constant volume: in this closed process, hot water valve is closed whilst the cold water valve is opened. Heat is removed through the cold heat exchanger coil forcing the pressure to drop while the diaphragm is located at the Top dead center (TDC).
- Forth, heat removal at constant pressure and temperature: in this closed process, piston starts to move preventing pressure from further dropping while heat is still removed in the condensation process.

This study demonstrates a proof of concept thermal engine operated between a hot reservoir with temperature range of 50–100 °C, and a cold reservoir with fixed temperature of 5 °C. The experimental results for this operating temperature range can be applicable for refrigeration cycle enhancement or other applications with low heat sink temperature. Exergy and economic feasibility analysis are not in the scope of this work.

3. Methods

3.1. Engine design and materials

A small lab-scale engine was designed and developed to test the engine concept. Diethyl ether with normal boiling point of 34.6 °C was used as the working fluid. This material is commonly used as a solvent and it has resulted in silicon and rubber deterioration when used as diaphragms, thus, a 5 mm thick nylon diaphragm was used instead. The engine was designed to operate at low temperature levels with moderate pressure difference of 0.7 bar. At steady-state operation, the engine will fluctuate between 0.5 bar (48.36 °C) and 1.2 bar (60.98 °C).