Effects of Working Fluids on the Performance of Stirling Engine

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Abstract: The purpose of this study is to investigate the effects of working fluids on the performance of the Stirling engine. The gamma-type Stirling engine was constructed from a displacer piston and a power piston. Various working fluids for the Stirling engine used in this study were air, air-ethanol mixture, and nano-fluids. Preparing nano-fluids were based on the immersing ZnO nanoparticles into the air-ethanol mixture. ZnO nanoparticles were produced by the method of flame assisted spray pyrolysis (FASP) and their size was examined by scanning electron microscopy (SEM). The working fluid of air-ethanol mixture had the volume ratio of 1%, 5%, and 10%. Meanwhile, the volume ratio of nano fluids used in this study was 1×10^{-3}, 2.5×10^{-3}, and 5×10^{-3}. For working fluids of air-ethanol mixture, the best performance of the engine was achieved at volume ratio about 5% where the engine torque, power, and efficiency were 0.29 Nm, 10.6 W, and 3.9%, respectively. By using the nano-fluids, the engine performance increased with ZnO nanoparticles. The respective engine torque, power, and efficiency featured with nano-working fluid at volume ratio of 5×10^{-3} were 0.43 Nm, 16.67 W, and 5.95%. Moreover, nano-fluids have a big challenge to study further as working fluids to enhance the performance of the bigger size of Stirling engine.

Keywords: Stirling engine, Gamma-type, Ethanol, ZnO nanoparticles, Nano-fluids.

1. Introduction

For many years, Stirling engine becomes one of interesting heat engines since it can use flexible types of energy, especially from renewable ones and result in low pollution. This engine operates by alternating motion of pistons due to the compression and expansion of working fluids caused by different temperatures between power and displacer pistons. Moreover, enhancing the performance of Stirling engine by means of reducing losses and increasing power output using suitable working fluids are still challenging [1]. The physical and thermal properties of working fluids for Stirling engines should comply high thermal conductivity, high heat capacity, and low viscosity [2]. The working fluids with high thermal conductivity may produce a high temperature difference with a small amount of heat input. The low viscosity of working fluids is also selected to reduce pumping losses.

Three common working fluids used in Stirling engine are air, hydrogen, and helium. To best of our knowledge, efforts in the developing of working fluids for Stirling engines have been conducted in many ways including 3He component of 3He-4He mixture to provide cooling at low temperature below 2 K [3], hydrogen [4], atmospheric air [5], pressurized air [6, 7], helium [7], strong real gas effects, such as CO_2, HFC-125, HFC-23, and ethane [8], and sodium [9]. The most recommended working fluid is helium since the output shaft power of the engine is much higher than that of using air [10]. Meanwhile, helium and hydrogen with low viscosity are easily flow through the regenerator. However, using hydrogen has some drawbacks since it easily infiltrates through common metals, causes brittle for some metals, and tends flammable.

Interestingly, there is a new type of fluid developed intensively called as nano-fluids. Nano-fluids are innovative heat transfer fluids used in energy systems because of their superior thermo physical properties with respect to conventional fluids [11, 12]. Nano-fluids refer to biphasic suspensions of nanoparticles below 100 nm in conventional base fluids and they are coined to improve the thermal conductivity and the convective heat transfer coefficient [11, 13]. In addition, thermal conductivity, heat capacity, density, and viscosity are highly dependent on the concentration of nanoparticles in nano-fluids. All these properties affect significantly to the convective heat transfer coefficient [14]. Meanwhile, the drawback of nanoparticles in suspension stability can be avoided by using the proper method of stirring [15]. Despite the many advantages of nano-fluids but they have not been widely studied as working fluids for the Stirling engine. Furthermore, this paper presents an investigation of the effects of various working fluids including nano-fluids on the performance of the Stirling engine.

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2. Materials and Methods

2.1 *Materials preparation and characterization*

Various working fluids investigated to examine their effects on the performance of the Stirling engine are air, air-ethanol mixture, and air-ethanol-ZnO nanoparticles mixture (nano-fluids). Ethanol (96%) was received from Merck (Germany), while ZnO nanoparticles was synthesized from zinc nitrate tetra hydrate ($Zn(NO_3)_2$*$4H_2O$, Merck, Germany) by the method of flame assisted spray pyrolysis (FASP). Working fluids of air-ethanol mixture had several volume ratios, which were 1%, 5%, and 10%. The working fluid of air-ethanol mixture producing the best performance of the Stirling engine was then added ZnO particles at volume ratios of 1×10^{-3}, 2.5×10^{-3}, and 5×10^{-3}.

To produce ZnO nanoparticles, zinc nitrate tetra hydrate was first dissolved in H_2O at 0.1 M and stirred by magnetic stirrer for about 30 minutes. The solution was then put in the ultrasonic nebulizer (NE-U17, Omron). The atmospheric air is delivered into the ultrasonic nebulizer at a flow rate of 5 L/min to produce and to carry the droplets into the FASP reactor. The premixed flame in the FASP reactor generated by burning LPG (liquefied petroleum gas) was used to oxidize the solution and produce ZnO. ZnO particles were then examined their crystallinity by X-ray diffraction (XRD: Bruker, AXS D8 Advance, 40 kV, 40 mA) at 2θ (Cu-Kα) = 20–70°, and step size = 0.05°. The crystal diameter was calculated from the full width at half maximum (FWHM) of the (101) peak using Scherrer's equation [16].

$$d_{XRD} = 0.9\lambda/(\beta - \beta')cos\theta \tag{1}$$

Where λ is a wavelength of the X-ray (0.14506 nm). Meanwhile, β, β' and θ represent the measured FWHM, the broadening of a peak caused by the equipment and the diffraction angle, respectively. Moreover, the diameter and the morphology of ZnO nanoparticles were examined by scanning electron microscopy (SEM, JEOL JSM-6360LA).

2.1 *Stirling engine*

The scheme of gamma-type Stirling engine used in this study is shown in Fig. 1. The Stirling engine specification is included in Table 1. The power piston was mounted in the separate cylinder alongside the displacer of the piston cylinder and it was still connected to the same flywheel as shown in **Figure 1**. The electric heater was used to heat the power piston and the temperature was kept constant at 450 °C. The electric energy delivered to the power piston was measured as an electric energy input (W_{in}).

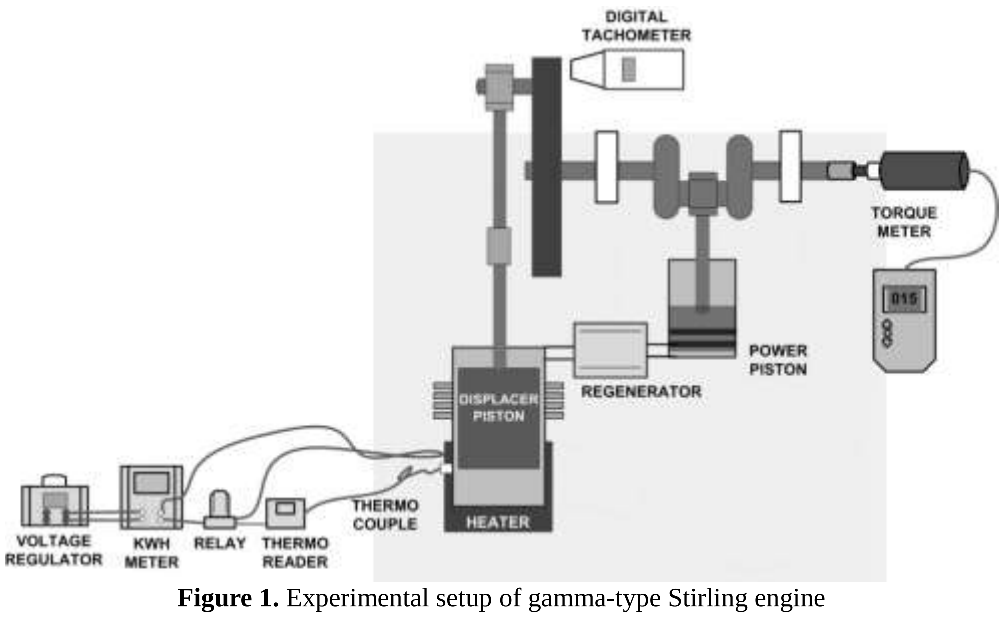

Figure 1. Experimental setup of gamma-type Stirling engine

The performance of the Stirling engine was expressed by torque, power, and efficiency. The engine torque (T) was measured with a torque meter (Lutron TQ-8800) while the speed (N) was measured with a digital tachometer (Lutron DT-2239A). The engine power (P) is formulated as follows

$$P = \frac{2 \times \pi \times N \times T}{60} \tag{2}$$

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Where T is the engine torque (Nm) measured by a torque meter. N is the engine speed (rpm). The efficiency of engine (η) is calculated with

$$\eta = \frac{P \times t}{W_{in}} \quad (3)$$

Where t is time.

Table 1. Specification of the Stirling engine

Mechanical configuration	Specification
Type	Gamma
Power piston:	
Bore x stroke (cm)	4 x 4
Swept volume (cm^3)	62.8
Displacer	
Bore x stroke (cm)	4 x 6
Swept volume (cm^3)	75.4
Compression ratio	7
Phase angle	90°

3. Results and Discussion

3.1 *Engine performance of the Stirling engine using working fluids of air-ethanol mixture*

Figure 2 shows the torque and power of the Stirling engine with working fluids of the air and the air-ethanol mixtures. The engine torque and power gradually increased with the volume ratio of ethanol up to 5%. The volume ratio of air-ethanol mixture at 5% featured the engine torque, power, and efficiency about 0.29 Nm, 10.6 W, and 3.9%, respectively. Mixing ethanol into air up to 5% by volume might improve the rate of heat transfer from cylinder wall to working fluids because of increasing the thermal conductivity. Therefore, the energy transferred to the working-piston increases since the heat transfer to the working fluids becomes more effective with increasing content of ethanol up to 5%. For the same volume of cylinder, additional ethanol leading to higher pressure might enhance the thrust of the power piston.

In contrast, increasing volume ratio of air-ethanol mixture at 10% significantly reduced the engine torque and power by 6.9% and 20.8%, respectively. Very high content of ethanol increasing the density and pressure of the working fluid is a drawback for the Stirling engine because it may increase the aerodynamic forces exceeding the heat transfer rate, thereby reducing the work done by the piston. This condition occurs at higher volume ratio of ethanol than 5%.

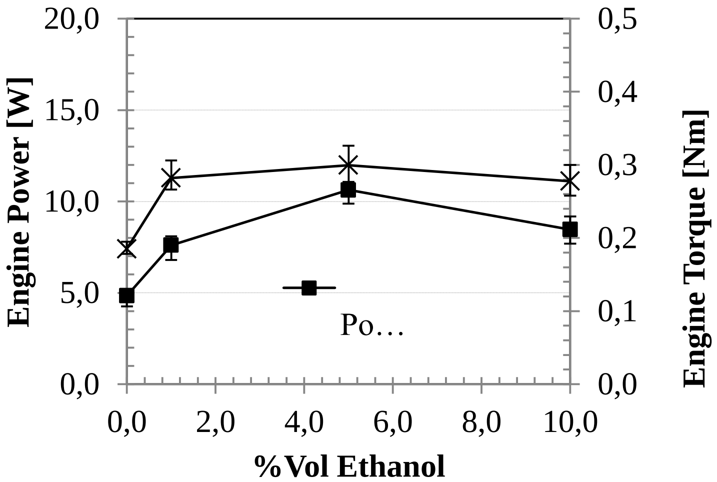

Figure 2. Power and torque of Stirling engine with working fluids of air-ethanol mixture

3.1 *Engine performance of the Stirling engine using working fluids of nano-fluids*

Next idea in this study is to develop nano-fluids as a working fluid for the Stirling engine. ZnO nanoparticles were immersed in the working fluids of air-ethanol mixture that featured the best efficiency. ZnO particles shown in Figure 3 have an average size of 80 nm. Figure 4 shows the XRD patterns of ZnO nanoparticles which have hexagonal zincite-crystalline. The crystal size of ZnO is about 30.62 nm.

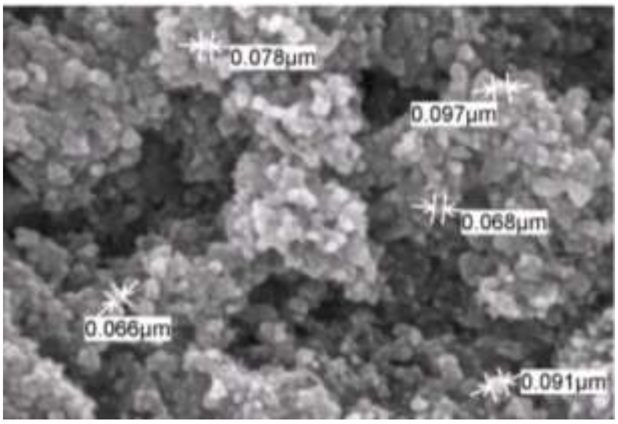

Figure 3. SEM image of ZnO particles produced by FASP method

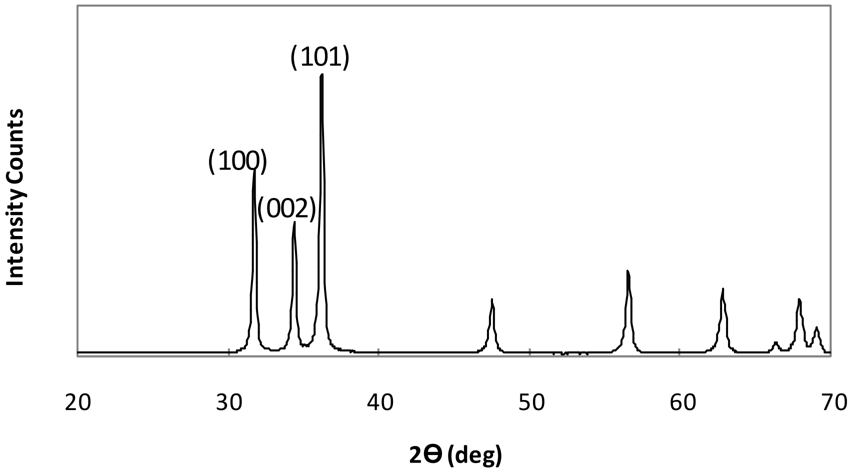

Figure 4. XRD pattern of ZnO nanoparticle

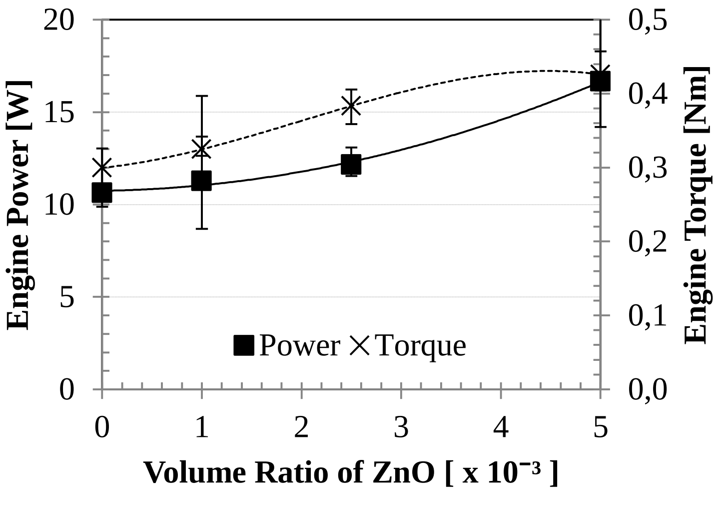

Figure 5. Stirling engine power and torque for the working fluid with nanofluid

Various volume ratios of ZnO nanoparticles ranging from 1 x 10^{-3} to 5 x 10^{-3} were immersed in the base-fluid of air–5% ethanol. The engine torque and power are shown in Figure 5. The higher the volume ratio of the nano-fluids, the higher the engine efficiency was achieved as shown in Figure 6.

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The nano-fluids with volume ratio of 5 x 10^{-3} featured the engine efficiency of 5.95%. Therefore, the engine efficiency with the nano-fluids is 3.4 times compared with that of the air. The increasing engine efficiency with working fluids of nano-fluids is higher than that of with working fluids of air-ethanol mixture. The working fluids with air-ethanol mixture above volume ratio of 5% potentially reduce the engine efficiency. In contrast, the addition of ZnO nanoparticles into air-ethanol mixture can further increase the engine efficiency as shown in Figure 6. The efficiency of the gamma-type Stirling engine investigated with ZnO nanoparticles is higher than that of found in previous studies as mentioned in Table 2.

Table 2. Some previous studies in gamma-type Stirling engines

Nr	Results	Notes	Literature
1	– Maximum efficiency of 2.9%	– Speed : 412 rpm – Working fluid: unpressurized air	[17]
2	– Maximum efficiency 0.65%	– Two power pistons – Speed: 52.1-133 rpm – Working fluid: atmospheric air	[18, 19]
3	– Maximum efficiency 0.809%	– Four power pistons – Speed: 20-42.1 rpm – Working fluid: atmospheric air	[18, 20]
4	– Power = 0.464 W. – The use of helium more than doubled the power output of the engine.	– Working fluid: air and helium with pressure from 1 to 4 bars. – Swept volume = 276 cc	[21]

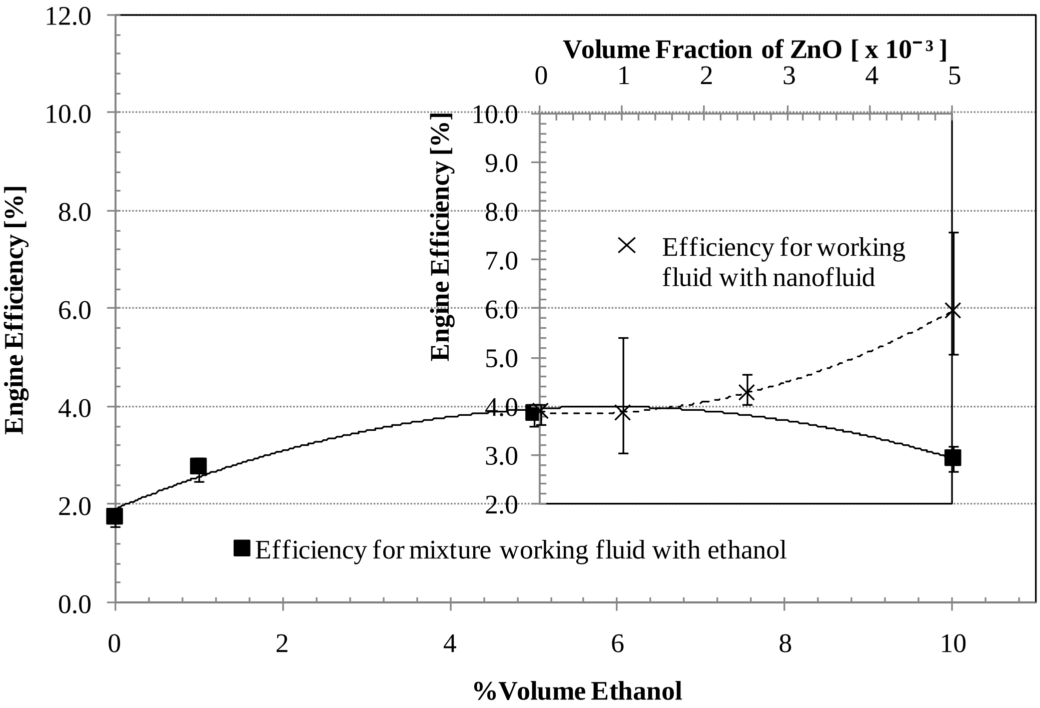

Figure 6. Stirling engine efficiency with working fluids of the air-ethanol mixtures and the nano-fluids

As exist in other solid particles, ZnO nanoparticles have higher thermal conductivity and higher density than that of ethanol and air. The thermal conductivity of nano-fluids increases nonlinearly up to 7.2-10.5% depending on the solution when the volume fraction of nanoparticles increases to 3 x 10^{-2} by volume [22]. Another study found that nano-fluids using the nanoparticles synthesized with plasma arcs can improve the thermal conductivity about 25% [23]. Meanwhile, the addition of 3 x 10^{-2} nanoparticles can enhance about 3.8% of the heat transfer [24]. Therefore, the engine power and torque show an increase with increasing content of ZnO particles in the nano-fluids as shown in Figure 6. In the ZnO-nanofluid with a volume ratio of 5 x 10^{-3}, the engine torque and power are 0.43 Nm and 16.7 W, respectively and it was significantly higher than that of in the working fluids of air-ethanol mixture with a volume ratio of 5%.

3. Conclusion

The effects of working fluids including nano-fluids on the performance of the Stirling engine were investigated. Among the seven working fluids, nano-fluids were found to be more effective than the air-ethanol mixture for improving the performance of the Stirling engine. The maximum of torque, power, and efficiency of the engine operated with the ethanol-air mixture with volume ratio of 5% was 0.29 Nm, 10.6 W, and 3.9%, respectively. Increasing volume ratio of air-ethanol mixture at 10% significantly has reduced the engine torque and power by 6.9% and 20.8%, respectively. In contrast, the addition of nano particles up to 5×10^{-3} has been able to produce the engine torque, power, and efficiency of 0.43 Nm, 16.67 W, and 5.95%, respectively. Moreover, these nano-fluids may be applicable to enhance the performance of the bigger Stirling.

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