# More Discussions about the Application of Stirling Engine on the Power Generating

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## ABSTRACT

This article makes more discussions toward the paper which has been presented at the 18th International Stirling Engine Conference to improve the completeness of the statement. The presented paper addressed the requirement of the application of Stirling Engine in Submarines, reviewed relevant submarines of different countries to analyze the power required to drive submarines underwater, and pointed out the requirement of specific equipment such as heating device and heat exchanger to keep submarines navigating at proper speed when underwater navigation. It presented if the traditional basic design of Stirling engine was modified, its fuel economy should be increased. However, it does not provide any evidence to support its argument. This article collects more related researches in the world, and further verifies the above arguments especially about the power output after make more analyses and comparisons.

**Keywords:** fuel economy, power generating, regenerator, combustion hood

# 史特靈引擎應用於動力輸出的進一步探討

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## 摘　要

本論文對已發表於第十八屆國際史特靈引擎研討會之論文做進一步探討，以使評論更為完整；該論文討論史特靈引擎應用於潛艦之水下潛航所需條件，並回顧國際間各相關潛艦，針對潛艦水下潛航所需動力予以分析，其結果指出如果要以適當速度於水下潛航，則需要特別的加熱裝置與熱交換器等，且該論文提出可藉由修改傳統的史特靈引擎基礎設計，以提升其燃油效率。然該論點並未提供相關事證，而本論文蒐集更多國內外相關研究，尤其經由比較分析其動力輸出之後，以佐證上述評論。

**關鍵詞**：燃油效率、動力輸出、再生器、加熱罩

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# I. INTRODUCTION

It is known that Stirling engine is an external combustion engine, different from the internal combustion engine, which usually combusts petrochemical fuel. The Stirling engine does not combust petrochemical fuel inside the engine head, instead it heats engine head externally and can use diversified heating resources (such as solar energy, biomass energy, geothermal heat, various waste heat, etc.). The Stirling engine can not only be categorized as green energy engine but also be used as the power source for the Air-Independent Propulsion (AIP) of submarine.

Taiwan, R.O.C government has announced the Indigenous Defence Submarine Project in 2016. To support the government policy, Chang's research group have studied the Air-Independent Propulsion (AIP) on the submarine since 2016, and have presented one paper [1] which discusses the requirement for the power output of Stirling engine on the underwater navigation of the submarine. In that paper, authors reviewed some famous submarines made by different countries, also mentioned the required power for underwater navigation. They found that if the submarine needs the underwater navigation with proper speed, the specific heating and heat exchanger etc. is required, and if the traditional basic design of Stirling engine was modified, its fuel economy should be increased. However, in that paper authors did not provide enough evidences to support their argument. In this article we will show more related researches in the world, and make more analyses and comparisons to further verify the above arguments.

For example, in 2011, Angkee Sripakagorn et al. [2] developed a beta-type Stirling engine and controlled the temperature of the electric heater to 350-500°C to simulate the high temperature which results from the parabolic solar collector's heating. Their evaluations were carried out under different heating temperature and different cylinder pressure parameters. Their experimental results showed that when the electric heater temperature and pressure were up to 500°C and 7bar, respectively, the engine's maximum output power was up to 95.4W and the ratio of the output power to the electric power input to the electric heater (defined as thermal efficiency) was 9.35%. In the same year, Solar Junction of San Jose, USA, used a solar concentrator (CPV; Concentrated Photovoltaic) combined with a Stirling engine to drive generators to produce electricity, which created a world record for the concentrating solar system corresponding fuel economy of 43.5% [3], and got the United States certification by the National Energy Research Laboratory.

It is interesting to note that even the engine thermal efficiency in the research of Angkee Sripakagorn et al. [2] is only 9.35%, it is much more than those of the research [1]. We will make more discussions in the following sections to explore the methods to increase the thermal efficiency and fuel economy of the Stirling engine.

# II. EXPERIMENTAL SYSTEM

For the convenience of readers, the mentioned experimental system in the presented paper [1] is shown as figure 1 and described again as follows: the $\gamma$ type Stirling engine (5) model M14-03-S is made by CCID Consulting Company Limited. The WindLab$^{tm}$ Wind Turbine (2) were combined and set on a test rig. To understand the effects of different way of heating and cooling on fuel economy, we used an alcohol lamp or heat gun (6), respectively, as heat sources, and used a ceramic cover or metal insulation cover (8), respectively, to maintain the heat at the hot side. We used water or air cooler (11), respectively, at the cold side to explore the effect of temperature difference between the hot and cold sides. Nine different resistors (820, 680, 390, 220, 150, 115, 82, 51, 39ohms) were used as the load (3).

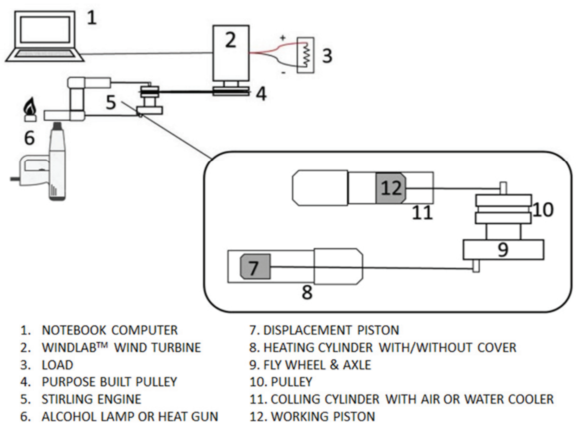


Fig. 1 Schematic diagram of the experimental system.

Authors used a three-phase alternator to generate "commercial grade" power by a WindLab[tm] wind turbine (2). By using different resistors (3) to study the effects of each load on the alternator. The graphical computer display of the WindLab[tm] wind turbine (2) shows the voltage, current and power along with the speed of the purpose built pulley (4) rotation in revolutions per minute (RPM). When the Stirling engine has a resistive load, the pulley rotation speed, voltage, power and current change immediately. Normally graphical computer display shows the speed of pulley rotation (upper black curve), the voltage (green curve), the power (lower red curve) and the current (lowest blue curve) (see Fig. 2). However, the unit of speed is single digits (already divided by one hundred), the voltage unit is single digit, and the current and output power are in one thousandth (mW). The four curves are displayed on the same window, but if we want to see the curves on the same window, we can only select either showing the rotation and voltage or the power and current simultaneously. However for easy analysis, the data is saved (shown in Table 1) in the notebook computer (1 in Fig. 1) and analyzed by excel (Fig. 3). It should be mentioned that the measured powers are reasonable though they are quite low. The M14-03-S Stirling engine is a purpose-built engine to drive a generator and to light up an LED (light-emitting diode) whose rated power is about 0.06 watts.

As mentioned in the previous paper [1], the real quantity of heat from the heating source should be taken. However, for the alcohol lamp case, the quantity of heat from the heating source can only be estimated based on the chemical reaction heat and the fuel consumption. We apply the heat gun as the heating source in the test (6 in Fig.1). The heat gun model 1001 is made by Maddish. The specifications as follows: versatility of 2 temperature, ranges 1000°F, 10 amps or 4 amps, 1200 watts. For comparison, the estimation of the real quantity of heat from the heat gun is based on the temperature data and specific heat of water by heating 100 gram water for 30 seconds. The fuel economy is estimated following the formula: [(the measured power output, Watt)/ (the real quantity of heat from the heat gun, Watt)]×100%. The heat gun has two different heating temperatures, 538°C and 316°C, respectively. When heating 100 gram water with the heat gun in high grade temperature (538°C) for 30 seconds, the water temperature can rise up about 4.36 Celsius degree, which means 14.53 calories per second (i.e. 60.8 joules per second = 60.8W) of heating rate provided by the heat gun, and for the low grade temperature (316°C), the heating rate is 31.3 W.

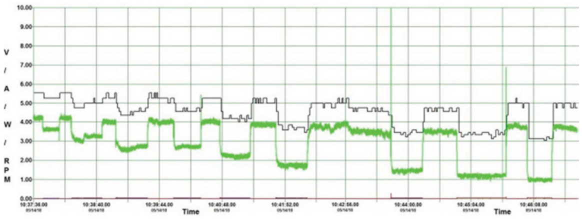

Fig. 2 The typical graphical computer display of the WindLab[tm] Wind Turbine.

Table 1 Power and current with different loads.

| | 820Ohm | 680Ohm | 390Ohm | 220Ohm | 150Ohm | 115Ohm | 82Ohm | 51Ohm | 39Ohm |
|---|---|---|---|---|---|---|---|---|---|
| Average power(W) | 0.01608 | 0.02019 | 0.0399 | 0.05267 | 0.05821 | 0.05969 | 0.06152 | 0.06057 | 0.04906 |
| Average current(A) | 0.00401 | 0.00508 | 0.00989 | 0.01523 | 0.01972 | 0.02291 | 0.0274 | 0.03442 | 0.03555 |

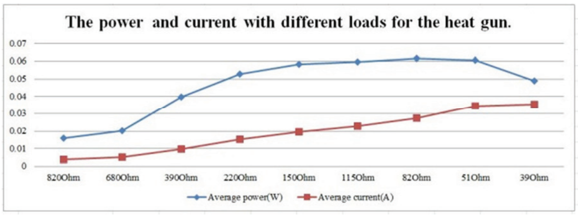


Fig. 3 The power and current with different loads for the heat gun.

## III. MORE DISCUSSIONS

As mentioned in the previous paper [1], China modified the Sweden 4V-275R MkIII Stirling engine to build up the 039B submarine power system with AIP. The MkIII Stirling engine can provide 162.75kW power output each. The 039B submarine with four Stirling engines can provide 651kW (885.11hp) power output totally [4]. It should be mentioned that the Japan そうりゅう(Soryu-class) submarine with AIP using four Sweden 4V-275R MkIII Stirling engines can only provide 300kw power output totally [5]. Therefore it cannot make submarine underwater navigation with proper speed and charge the battery simultaneously, in other words, it can only charge the battery when underwater navigation. According to the above literature survey, the power requirement of traditional submarine with AIP ranges from 300kW to 651kW. Jy-Cheng Chang et al. [1]

based on the schematic of そうりゅう (Soryu-class) submarine [4], they estimated the space of its fuel tank about 380kl. If using their purchased engine with its largest power output 0.0797W, we needs about 3,800 thousand units engines for the power required (300kW / 0.0797W= 3,764,115). The power engine totally occupies about 760kl space. The fuel tank with 380kl space can only provide 1.74 hour endurance. At this point about fuel economy, it is unfeasible for using the design concept of the commercial small γ type Stirling engine to submarine AIP. However Japan and China have already used Stirling engine as submarine AIP. We will make more discussions about the methods to increase the endurance and fuel economy in the following sections.

### 3.1 Effect of the cooling and heating temperature ratio

It is known that the Stirling ideal power cycle can be described in four processes (Fig. 4), consisting of two isometric and two isothermal processes, briefly described as follows:

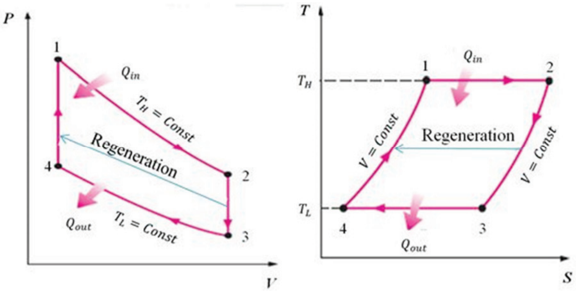


Fig. 4 The Stirling engine ideal power cycle.

(I) Isometric and heat-addition process (4→1)：The working fluid flows from the engine's cold side to the hot side due to the pushing of the displacer. During this process, the cold working fluid passes though the regenerator and absorbs the heat which is stored in the regenerator (or the displacer) and not from the engine's hot side (see the green arrow in Fig4.). During the heat-addition process, even the working fluid absorbs heat but the volume does not change, therefore the working fluid does not carry out any work. It is worth mentioning that the entropy and temperature of working fluid increase.

(II) Isothermal expansion process (1→2)：The working fluid is at the engine's hot side, therefore the supplied heat ($Q_{in}$) is added to working fluid from the hot side of the engine and the working fluid expands, and pushes the piston carrying out the mechanical work. The working fluid temperature does not change, but the entropy increases. The working system consists of the connecting rod, crank, flywheel, pulley and belt, and electrical generator (see no. 4 and 5 in Fig. 1). The rotation of the flywheel can overcome working system dead point obstacles and push the displacer.

(III) Isometric heat-removed process (2→3): The working fluid flows from the engine's hot side to the cold side passing through the regenerator (or the displacer) due to the pushing of the displacer. During this process, the hot working fluid passes though the regenerator and the heat is removed from working fluid to regenerator (or the displacer) and not to the engine's cold side (see the green arrow in Fig4.). During the heat-removed process, even the working fluid rejects heat but the volume does not change, therefore the working fluid does not perform any work. It is worth mentioning that the entropy and temperature of working fluid decrease.

(IV) Isothermal compression process (3→4): The working fluid is at the engine's cold side, therefore the rejected heat ($Q_{out}$) is removed to the cold side of the engine and the working fluid shrinks, and pulls the piston carrying out the mechanical work. The working fluid temperature does not change, but the entropy decreases, finally complete the power cycle.

According to the above description, if the quantity of the heat-addition in the process (4→1) and the quantity of the heat-removed process (2→3) is equal, then the thermal efficiency of Stirling power cycle will be equivalent to that of Carnot cycle [12], as follows:

$$\eta_{th} = 1 - \frac{T_L}{T_H} \tag{1}$$

Where $T_H$ is the temperature of the engine's hot side and $T_L$ is the temperature of the engine's cold side, respectively.

Based on equation (1), it is clear that decreasing the cooling and heating temperature ratio will improve the thermal efficiency of power cycle. Theoretically increasing thermal efficiency will improve power output of engine. Liu [6] used metal insulation cover (see no. 1 in Fig. 5) and water cooler (see no. 2 in Fig. 5) to increase the temperature difference between the hot and cold sides, but did not provide the enough information about the values of temperature. Figure 5 also shows the fly wheel and axle (no.3), pulley (no.4) and WindLab$^{tm}$ Wind Turbine (no. 5).

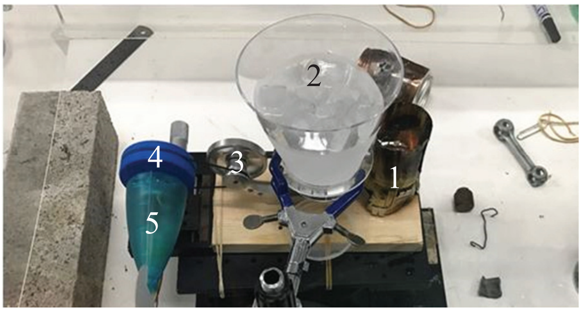


Fig. 5 The test engine with metal insulation cover and water cooler. [6]

It is interesting to note that the fuel economy in Liu's work is not proportionally improved with maximum power (see Table 2) since using the metal insulation cover unexpected increases the alcohol consumption.

Table 2 Maximum power and fuel economy for cases with/without cover. (data sorted out from references [1], [6])

| Cases \ Items | | Maximum Power | Improved | Fuel Economy | Improved | Endurance |
|---|---|---|---|---|---|---|
| Alcohol lamp (water cooler) | Without cover | 0.062W | +27% | 0.020% | +7% | 1.62 hour |
| | With metal insulation cover | 0.079W | | 0.021% | | 1.74 hour |
| Heat gun (air cooler) | Without cover | 0.013W | +377% | 0.021% | +376% | 1.74 hour |
| | With creamic cover | 0.062W | | 0.102% | | 8.45 hour |

In order to improve above fuel economy, the heat gun (see no. 1 in Fig. 6) was used instead of alcohol lamp as a heat source. In addition, the metal insulation cover was replaced by a ceramic cover (see no. 1 in Fig. 6), and the water cooler was replaced by air cooler (see no. 3 in Fig. 6). Figure 6 also shows the Stirling engine (no.4), fly wheel and axle (no.5), pulley (no.6) and WindLab$^{tm}$ Wind Turbine (no. 7).

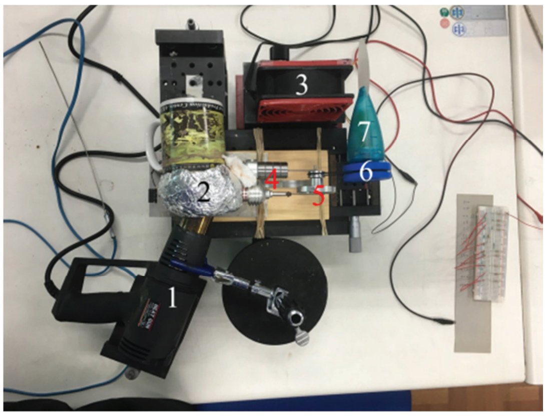


Fig. 6 The test engine with ceramic cover and air cooler.

It can be seen from Table 2 that using the alcohol lamp as heat source and insulation metal as cover can increase the maximum power from 0.062W up to 0.08W, but it takes more consumption of alcohol, result in increasing 7% of fuel economy only, compared with the ratio of maximum power improved (29%), which is not proportional. Fortunately, it can also be seen from Table 2 that using the heat gun as heat source and ceramic as cover can enormously increase the maximum power (377%), without increase the electricity consumption, result in the ratio of fuel economy (376%), so the fuel economy was proportional improved. It should be mentioned that, when using the heat gun as a heat source, the fuel economy was also increased because the heating wire inside the gun generated heat, the wind blown by the fan passes through the heating wire, and the hot air was blown into the ceramic cover to generate a heat source. It is now worth mentioning that the fuel economy of Chang's experiment [1] is improved from Liu's 0.02% to 0.102% (see Table 2) by using the heat gun as the heating source. It should be mentioned again that in the works of Liu, the alcohol lamp always contact with the air, resulting in heat lost in the air, so Liu cannot find the real effect of the temperature difference between the hot and cold sides on fuel economy. Chang's group [1] replaced the alcohol lamp with a heat gun in the experiment and used a ceramic cover to reduce heat loss; in addition, the ball of steel wire (Fig. 7) is placed in the ceramic cover to maintain the heat at the hot side. The mentioned fact can explain why the fuel economy can be improved up to 0.102%.

Fig. 7 The ball of steel wire.

Since in the works of Chang's research group [1] and Liu [6], the real thermal efficiency cannot be estimated, the effect of the cooling and heating temperature ratio cannot be evaluated as well. We reviewed one more relevant research carried out by Zhang Shengkai [7]. At first, Zhang used the computational fluid dynamics to simulate the power cycle of the gamma-type Stirling engine, analysed and compared the various parameters of engine, and sought to optimize the combined parameter design to improve the engine output power. Then Zhang designed combustion hood and insulation cotton, which can reduce the heat dissipation problem and maintain the heat inside the combustion hood; Zhang also used a water-cooled system to keep the temperature difference between the hot and cold sides. It should be mentioned that the above Zhang's improving methods were consistent with ours. In the experiment of Chang's group [1] the temperature difference between the hot and cold side was 478 °C, which is almost same with that of Zhang [7] (shown in table 3). Zhang's simulation results indicate that the maximum calculated thermal efficiency is 30.5% when the temperature difference between the hot and cold sides was 400°C (the cooling and heating temperature ratio is about 0.43). Based on equation (1), its ideal thermal efficiency should be about 57% and almost same with that of Chang's group since their cooling and heating temperature ratio is about 0.41. Therefore the calculated thermal efficiency of Chang's group should be in the same order (about 30%) with Zhang's. It is worthy to mention that Zhang only measured the output power and temperature difference between the hot and cold sides, and did not estimated the real quantity of heat from the alcohol lamp, so the real fuel economy of Zhang's experiment could not be found. It is obvious that the maximum powers are quite different between the Zhang's and Chang's group; the reason is that the dimensions of Zhang's engine is quite larger than that of Chang's group; the piston diameter ratio is 5.

Table 3 Temperatures of hot and cold sides, fuel economy, thermal efficiency and maximum power for cases of Zhang and Chang et al. (data sorted out from references [1], [7])

| Items / Authors | Hot Side Temperature | Cold Side Temperature | Temperature Difference Between Hot And Cold Side | Fuel Economy | Thermal Efficiency | Maximum Power |
|---|---|---|---|---|---|---|
| Zhang Shengkai | 700K (427°C) | 300K (27°C) | 400K (400°C) | - | 30.5% | 2.9W |
| Chang et al. | 811K (538°C) | 333K (60°C) | 478K (478°C) | 0.102% | - | 0.062W |

As already mentioned, fuel economy of Chang's experiment was improved up to 0.102%. However it is much lower than that 9.35% of Angkee Sripakagorn et al. [2] and the so called endurance is only about 35 hours. At this point about fuel economy, it is still unfeasible for using the design concept of the commercial small γ type Stirling engine to submarine AIP by modifying the heating method and decreasing the cooling and heating temperature ratio. In the following section we will discuss how the heating surface area and regenerator of Stirling engine to affect the fuel economy.

### 3.2 Effect of the heating surface area

As above section mentioned, for the requirement of submarine underwater navigation even increasing the thermal efficiency of Stirling engine, it cannot guarantee improving fuel economy. Similarly the endurance of underwater navigation cannot be increased as well. The reason is that the fuel consumption is not only depend on the ratio of cold and hot side temperatures.

The so called the fuel economy implies that the high fuel economy means high rate for transferring the chemical heat of fuel to the engine. Normally the working fluid of Stirling engine is air, therefore we can use Newton's law of cooling [8] to express the heat transfer from engine cylinder wall to working fluid:

$$q = hA\,(T_w - T_\infty) \tag{2}$$

Where $q$ is the heat transfer rate (W), $h$ is the convection heat-transfer coefficient ($W/m^2K$), $A$ is the surface area ($m^2$), $T_W$ is the temperature of the hot wall, and $T_\infty$ is the temperature of the working fluid. Based on equation (2), it is clear that the heat transfer rate is related to temperature between wall and working fluid, the convection heat-transfer coefficient and the surface area. We will discuss the effect of heating surface area on the Stirling engine fuel economy in this section.

It is worth to mention the research of NASA [9]. In their report the heating device can enormously improve the fuel economy. Their heating device consists of two heat exchangers, the heater head and the regenerator. The heater head was constructed of many fine tubes to increase the heat transfer area in the hot combustion to the hydrogen. The regenerator assembly consisted of the wire-mesh and partition wall. The wire-mesh was to pre-hot and pre-cold the working gas, and the partition wall separated the regenerator and cooler. Due to above design, the annular heating head and regenerator can make the Stirling engine fuel economy up to 38.5%.

Cheng et al. [10] used the same concept to develop a 300W beta-type Stirling engine to measure engine torque, speed and output power under different working fluids, working pressures, regenerator mesh numbers and temperatures. In order to increase the total heat transfer area and reduce the thermal resistance, the heating side is composed of 12 stainless steel tubes; the cooling side was made of a finned water jacket water cooling system made of aluminum alloy. The input heat transfer rate was 1.21kW, maximum output power was 390W, and the fuel economy was 32.2%.

Based on the researches of NASA [9] and Cheng et al. [10], the special design can increase the heat transfer area, and can achieve fuel economy up to 38.5% and 32.2%, respectively, which are higher than that of Chang et al. [1]. The reason for the difference fuel economy is the difference heat transfer area. Since NASA and Cheng et al. did not provide any information about the heat transfer area in detail, we estimate the heat transfer area of Stirling engines for the above two researches based on fuel economy and heat transfer area in the research of Chang et al.

It is worth to note that there are many separate tubes in the heater head of Stirling engine in NASA's research [9]; the tube's external surface is heated by the combustion gas. Cheng et al. [10] also used 12 stainless tubes on hot part of the engine to increase the total heat transfer area. It is clear that the cylindrical surface area of tube is larger than plane surface area. Therefore we conclude that if the heat transfer area can be improved much, such as hundred times, then we could achieve the same fuel economy as those (see Table 4). Then endurance of submarine underwater navigation using Stirling engine as power system could improve up to hundred times.

To further clarify the effect of appropriate design on the increasing heat transfer area, an example based on the geometric theory is described as follows:

For a heat transfer room (or space) constructed by a hollow parallelepiped with square cross-section, whose size is length ($l$) by width ($w$) by height ($w$), the surface area of the hollow parallelepiped is $4lw$ except both ends. If we install $n$ by $n$ numbers of pipe into the hollow space of parallelepiped mimicking the honeycomb structure, theoretically the heat transfer area will be increased up to $n\pi lw$, which means that we ideally get about $n\pi/4$ times surface area for transferring heat to or from the working fluid.

Table 4 Fuel economy and heat transfer area for cases of NASA, Cheng et al. and Chang et al. (data sorted out from references [1], [9] and [10])

| Authors \ Items | Fuel Economy | Improved | Heat Transfer Area | Heat Transfer Area Estimated By Authors |
|---|---|---|---|---|
| NASA | 38.5% | ~377 times | - | ~8068 cm² |
| Cheng et al. | 32.2% | ~316 times | - | ~6762 cm² |
| Chang et al. | 0.102% | - | 21.4cm² | - |

Since increasing the heat transfer area can make submarine underwater navigation feasible, but the fuel economy still related to other factors. For completeness, we will discuss other factors in the next section.

### 3.3 Effect of other factors and summary for feasibility

Based on the Stirling engine ideal power cycle in the section 3.1, during the heat-addition and heat-removed process, the working fluid passes through the regenerator and absorbs the heat from the regenerator or the regenerator removes the heat from the working fluid. It is worth to mention that a good regenerator could make the power cycle ideal and improve the fuel economy. It is worth to review the paper about the regenerator. Ramla Gheith et al. [11] optimized the gamma-type Stirling engine regenerator. They carried out two experiments. In the first experiment they used different materials (stainless steel, copper, aluminum and nickel-copper alloy) for the regenerator and examined the engine performance and the state of each material after 15 hours. The use of the stainless steel regenerator produced the best power output 308W, and the aluminum regenerator generated the worst power output 203W. The results show that stainless steel is the most suitable material due to its high heat capacity and low thermal conductivity. Then the different porosity (ratio of pore volume to total material volume) of stainless steel regenerator (75-95%) was tested at different working pressures and heat source temperatures. The data shows that the porosity of 85% stainless steel regenerators can minimize thermal and friction losses and maximize output power was 320W, and the fuel economy was 26% (see Table 5).

Table 5 Effect of different regenerator's materials. (data sorted out from references [11])

| Items / Regenerator Materials | Temperature Difference Between Hot And Cold Side | Input Power (Estimated) | Output Power | Fuel Economy | Improved |
|---|---|---|---|---|---|
| Stainless Steel | 500°C | 1230W | 320W | 26% | +57.5% |
| Stainless Steel | 400°C | | 308W | 25% (Estimated) | +51.5% |
| Aluminum | 400°C | | 203W | 16.5% (Estimated) | 0% |

Based on Ramla Gheith et al. [11], it is clear that the Stirling engine with a good regenerator can get better fuel economy (improving up to 16.5% ~25%). It is worth to note that the hydrogen was used as the working fluid by NASA [9], and Cheng et al. [9] [10] used air as the working fluid. Considering different working fluids have different characteristics, therefore different working fluids alter the maximum output power and fuel economy.

Based on equation (2), the heat transfer rate also related to the convection heat-transfer coefficient, according to Holman [8], the approximate values of air convection heat-transfer coefficient ranges from 4.5 to 180 ($W/m^2K$). However there are at least three main types of working fluids applied on the Stirling engine: hydrogen, air, and helium. We will refer some papers discussion the effect of different working fluid on maximum power.

Yu-Feng Chang [12] explored the effects of the above three working fluids on engine output power, resulting in different engine output power. Since the hydrogen specific heat is only one-fifteenth of air and one-half of helium, when helium or hydrogen are used as the working fluid under the same pressure, more output power is available during operation, improving up to about 158% and 196%, respectively (See Table 6).

Table 6 Heat conductivity, density and power output for air, helium and hydrogen. (data sorted out from reference [12])

| Items / Gases | Specific Heat ($kJ/kg \cdot K$) | Heat Conductivity ($Cal/m \cdot s \cdot K$) | Density ($kg/m^3$) | Power Output ($W$) | Improved |
|---|---|---|---|---|---|
| Air | 1.03 | $5.8\times10^{-3}$ | 1.293 | 37.79 | - |
| Helium | 5.19 | $3.43\times10^{-2}$ | 0.1785 | 59.81 | 158% |
| Hydrogen | 14 | $4.19\times10^{-2}$ | 0.089 | 74.15 | 196% |

Can et al. [13] tested the alpha-type Stirling engine using different working fluids (air and helium, respectively) and under different working pressures. In their experiments, the hot side surface temperature and working pressure were set as variable parameters, and the engine speed and torque were measured. The experiment was carried out under the pressure of 1.5 to 3 bars, and the result showed that air and helium had maximum output power were 18.13W and 27.33 W at 3 bar, respectively (Fig. 8).

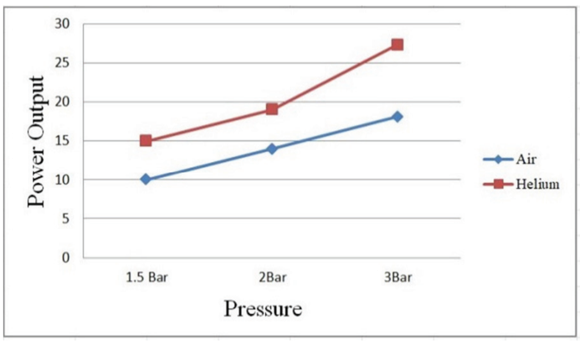


Fig. 8 The power output of different pressure. (data sorted out from references [13])

Figure 8 shows that the maximum power can be improved by using helium as working fluid instead of air. The reason is that if the working fluid in the cylinder with same quality, since the specific volume (reciprocal of density) of helium and hydrogen is 7.24 times and 14.52 times of air, respectively, the expansion and contraction of helium and hydrogen are more distinct, resulting in larger output power than air.

By the way, when the mechanical power converts into the generator power, the output power will be little bit less than the input mechanical power. Compensation will be considered when we interpret the WindLabtm wind turbine power, based on Roger A. Hinrichs and Merlin H. Kleinbach [14]. Table 7 [14] shows the average conversion efficiency of the generator is about 70~99%. The compensation is estimated following the formula: (measured value / 0.99 ~ measured value / 0.7).

Table 7 Efficiencies of some energy conversion devices and systems. (data sorted out from reference [14])

| Device | Efficiency |
|---|---|
| Electric generators(mechanical → electrical) | 70–99% |
| Electric motor(electrical → mechanical) | 50–90% |
| Others (For the detail see ref. 12) | 5–95% |

Finally we summarize methods, fuel economy, endurance and feasibility for cases in this article as Table 8. As the Table shows, one of the methods for improving fuel economy of the engine is to increase the heating transfer area on the engine hot and cold sides such as NASA's research, whose endurance of underwater navigation of submarine is estimated about 131 days. After this study, Chang [15] installed heat transfer fins on the hot side of the Stirling engine and investigated the effect of improvement. His experimental results show that the engine power can be increased up to 3.7 times by increasing 5.4 times heating surface area.

For completeness, the other methods for improve fuel economy are such as using appropriate regenerator and working fluid with high conductivity characteristic. Finally, the insulation between the heating and cooling zones of engine should be considered as well.

Table 8 Methods, fuel economy, endurance and feasibility for cases in this article.

| Items / Authors | Methods | | | Fuel Economy | Endurance | Feasibility |
|---|---|---|---|---|---|---|
| | Cooling And Heating Temperature Ratio | Heating Surface Area | Other factors | | | |
| Angkee Sripakagorn et al. | ◎ | | ◎ | 9.35% | 768hr(~32days) | ○ |
| Solar Junction | | | | 43.5% | 3577hr(~149days) | ○ |
| Zhang Shengkai | ◎ | | | 30.5% | 2508hr(~104days) | ○ |
| Can et al. | ◎ | | ◎ | - | - | - |
| NASA | | ◎ | | 38.5% | 3166hr(~131days) | ○ |
| Cheng Chin-Hsiang | | ◎ | | 32.2% | 2647hr(~110days) | ○ |
| Ramla Gheith et al. | | ◎ | | 26% | 2154hr(~89days) | ○ |
| Yu-Feng Chang | | | ◎ | - | - | - |
| Jy-Cheng Chang et al. | ◎ | | | 0.1% | 8hr | × |
| Jin-Rung Liu | ◎ | | | 0.02% | 2hr | × |

# Ⅳ. CONCLUSIONS

We have discussed related papers and made analysis and comparison about the feasibility of Stirling engine for the underwater navigation of the submarine. At first, we find that it is still unfeasible for using the normal design concept of the commercial small γ type Stirling engine to submarine underwater navigation by only decreasing the cooling and heating temperature ratio. Secondary, we find that if the heat transfer area on the hot and cold sides of the engine can be increased, fuel economy and endurance of submarine underwater navigation will be tremendously improved to same order. Third, a good regenerators can minimize thermal and friction losses and maximize output power and improve fuel economy up to about 25%. Fourth, we find that the maximum power can be improved by using helium or hydrogen as working fluid instead of air.

Finally we conclude that some smart methods for improving fuel economy of the engine can be used. If specific components such as fins or honeycomb structures can be used on the hot and cold side spaces of Stirling engine, the good regenerator and working fluid under appropriate pressed condition can be selected, and the insulation for against the heat loss can be considered, the fuel economy can be tremendously improved and make the endurance meet requirements, which is feasible for underwater navigation of Submarine.

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