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Battery Charger with Stirling Engine

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Abstract -

Current work is a key issue in design and development. The purpose of optimizing the Stirling engine is to establish an accurate thermodynamic model to predict output power, thermal efficiency, and detailed performance characteristics, and to provide useful information for further improvement. In this study, a thermodynamic model called an improved simple analysis model was proposed, while carefully considering the heat and power loss of the Stirling engine. A 100 W β type Stirling engine was built and tested with helium and nitrogen under pressure and speed of 1.6 MPa to 3 MPa and 260 r/min or 1380 r/min. Experimental information about performance, such as PV charts and heater and cooler temperatures, are very detailed. The increase in rotation speed brings about a "thin" PV curve because it makes the compression and expansion process more imperfect, indicating that the compression and expansion chambers in high-speed Stirling engines must enhance heat transfer. In the case of rotation speeds of 1000 r/min and 650 r/min, the shaft power of helium reaches the upper limit rate of 30.1W and 21.0W of nitrogen. Improving the average pressure of the gas will increase the indicated power, cycle efficiency, shaft power and electrical power. Under the same working conditions of 2.96MPa and 1120r/min, the maximum indicated power and cycle efficiency of helium are 165W and 16.5%, respectively, and nitrogen is 139W and 12.2%. The improved simple analysis model is in good agreement with the experimental data. The deviation of helium gas is 4.3-13.4%, and the deviation of nitrogen gas is 1-7.1%. The analysis of energy loss with an improved simple analysis model shows that under the same working conditions, helium has greater reciprocating and sealing leakage losses than nitrogen, and the flow resistance and heat transfer losses of the regenerator are smaller. With the surge of speed and pressure, the heat transfer loss of the flow resistance and the heat storage body is much faster than the heat transfer loss of the sealed connecting rod or the shuttle type, which plays an important role and causes the performance of the two working gases to be different. This study provides a comprehensive understanding of the mechanism of influence of heat/power loss on Stirling engine performance and suggests that more work should be done (for example, the mechanism of heat and power loss and PV chart). To improve the accuracy of the second-order model.

***Key Words*:** Stirling Engine, Power Piston, Displacer, Compression, Expansion, Regenerator, Heat Flux

1. INTRODUCTION

The Stirling engine circulates continuously by repeatedly heating and cooling the gas sealed inside the engine. When the gas is heated, it expands to push out the piston. After cooling, shrink to pull in the same piston. Once the piston is fully pulled back, the heating of the gas will restart. Therefore, the piston continuously moves back and forth. The movement of the piston speed [1] usually rotates the flywheel through a linkage mechanism that connects the two components. The rotating flywheel is the power generated by heating and cooling gas. The Stirling hot air engine was originally developed for pumping water in mines. It is a safe alternative to steam engines. Development has led to the widespread use of small Stirling engines to pump water from household wells. Today, Stirling engines are used to generate electricity from renewable energy sources such as solar energy. When a silent method is needed, it can be used in submarines as a backup for its main diesel engine. It is increasingly used to provide supplementary heat and power to the house. The Stirling engine replaces the traditional central heating boiler. This engine can not only heat the house, but also generate 1kW of electricity.

2. STIRLING ENGINE PRINCIPLE OF OPERATION

If the air is cooled, it will cause the air to shrink. This contraction causes the pressure in the engine cylinder to drop. As shown in Figure 1, this increase and decrease in pressure can be used to move the piston back and forth due to heating and cooling. It must also be noted that if the pressure decreases, the pressure and temperature are proportional, and the temperature will decrease on average.

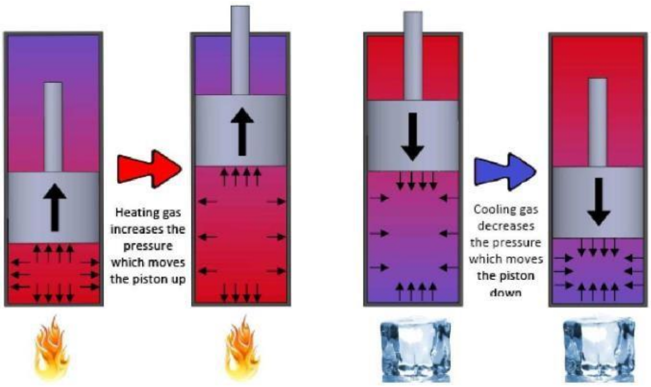


Figure-1: **Heating and cooling of a gas changes pressure which moves a piston**

If the piston shown in Figure 1 is connected to a disk called a flywheel, the heating and cooling that cause the linear movement of the piston will cause the flywheel to rotate. The flywheel is mechanical energy. Due to the heating and cooling of the gas, the Stirling engine has converted it from a temperature difference to mechanical energy.

The process of heating the air to increase the pressure to turn the flywheel is the basis for the operation of the heat engine. Therefore, the Stirling engine is a heat engine. As shown in Figure 2, the term heat engine applies to any engine that uses thermal energy to produce mechanical work.

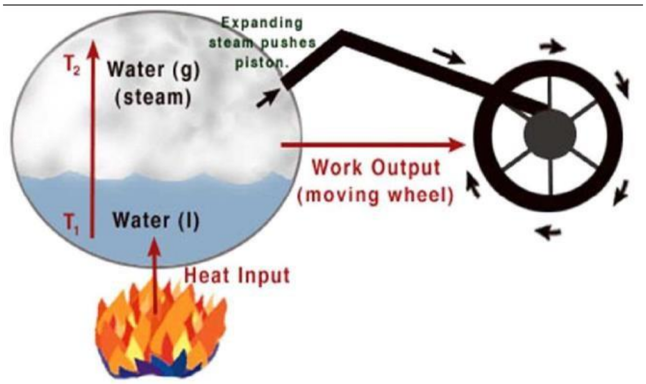


Figure-2: **Principle of heat engine**

The Stirling engine repeatedly heats and cools the air or other gases in the engine to generate useful power that can drive the machine, thereby running in a continuous cycle. The air is sealed inside the engine and moves back and forth when heating and cooling occurs, so it is called a closed-loop heat engine. This gives the advantage of the Stirling engine a lot of simplification because it does not require the intake and exhaust valves used in diesel and gasoline engines. In order to m aintain continuous operation, the Stirling engine needs a flywheel [2]. The flywheel is usually a disc made of stee l that can store energy. When the gas expands, the Stirling engine generates power for only a portion of the entire cycle. Energy needs to be input when compressing gas. Part of the flywheel momentum obtained from the gas expansion is used to overcome the compression of the gas and keep the engine running smoothly.

3. The Parts of the Stirling Engine

The Stirling engine is an external combustion engine, which means that the engine gets heat from the outside rather than from inside the working cylinder, which is different from internal combustion engines such as diesel or gasoline engines. The gas powered motor is delicate to its fuel type, which gives the Stirling motor the benefit of having the option to create power from any hotness source as long as the temperature is sufficiently high.

- The **power piston** is connected to the flywheel through the crankshaft to provide the output power of the engine.
- The **displacer** is unique to the Stirling engine. The functi on of the displacer is to move air from one end of the cylinder to the other.
- The **heat accumulator**, also known as the heat exchanger, is unique to the Stirling engine. It reduces the waste heat in the engine cycle and improves the efficiency of the engine.

The Stirling engine has only three basic layouts; as shown in **Figure-3**, the layout of the Alpha, Beta and Gamma engines also illustrates the main components of the Stirling engine. Gamma (the first Stirling design) and Beta engine are associat ed with Robert Stirling, and the Alpha engine design was carri ed out after Stirling's work was completed.

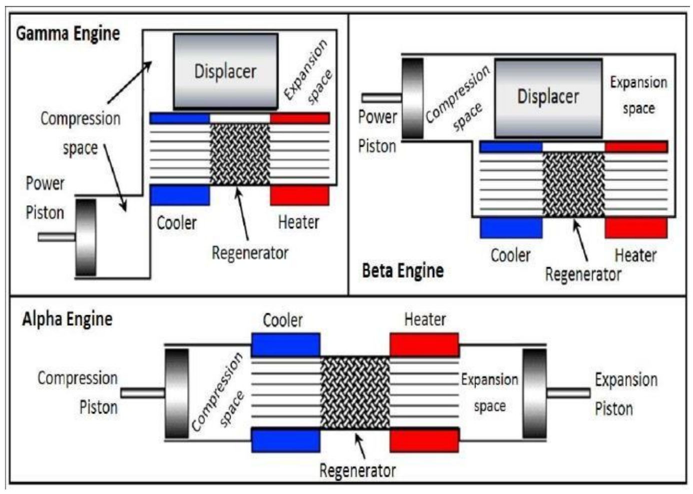


Figure-3: **Three Basic Mechanical Configurations for Stirling Engines**

The encased space of the Stirling motor is two chambers, one of which contains the displacer and the other contains the power cylinder, which is totally fixed. Preferably, no gas can enter or leave.

The displacer is unique to the Stirling engine design. Heat is applied to one end of the displacement cylinder and discharged at the other end. The function of the displacer. It transfers air from a heated place to a cool place. The displacer is a cylinder inside the cylinder. Its function is similar to a plunger. It is not a piston because it does not affect the pressure but can control the position of the gas. The displacer is a loose fit of 60-70% of the cylinder length, and the displacer is moved by a connecting rod connected to the crankshaft through a connecting rod mechanism. When the displacer moves from one end of the cylinder to the other end, the air must move around the displacer to reach the other end of the cylinder, as shown in **Figure-4**.

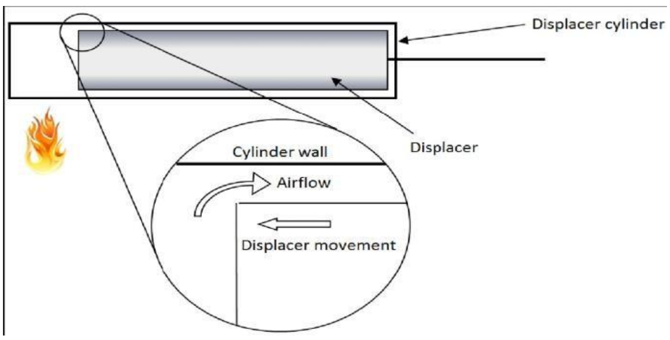


Figure-4: Displacer Principle

When the displacer is on the cold end and the gas is on the hot end, the temperature and pressure will rise, and this pressure rise will push the power piston forward. When the displacer is moved from the cold end to the hot end, the pressurised gas is forced to move to the cold end, pushing the power piston forward and causing it to expand. When the displacer is on the hot end, however, air is forced into the cold end. As a result, the air condenses and pulls the piston back, as illustrated in Figure 5. To make the Stirling engine work, the displacer must first move the air, then the air first heats up and then expands to move the power piston. The displacer moves first, followed by the piston stroke, so both the displacer and the power piston are called "out of phase." Since both are connected to the same flywheel, a phase difference is required, usually 90 degrees is sufficient. The design of the connecting rod system makes the piston and the piston move with each other, but with a phase difference of 90°. For example when the power piston is in the middle of the piston cylinder, the piston is at the end of the piston cylinder.

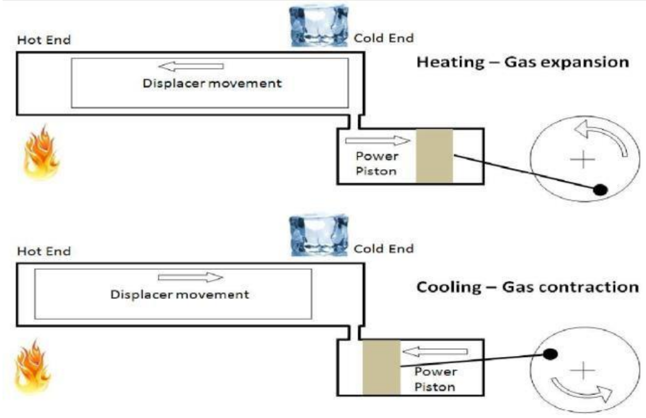


Figure-5: Displacer and Power Piston Position During Heating and Cooling

4. The Regenerator

When observed on a Stirling engine for the first time, it seems that the purpose of the hot end of the displacement cylinder is to increase heat, which will be lost to the cold end, and the cold end absorbs the heat added by the hot end, but this is not the case. The main unique function is to include a heat accumulator called a heat accumulator in the air passage between the hot end and the cold end of the displacement cylinder. The purpose of the regenerator [4]. Is to remove heat from the gas as it moves from the hot end to the cold end; the heat accumulator stores heat and returns it to the gas as it moves from the cold end to the hot end, as described earlier. The regenerator is usually composed of wire mesh, be cause the wire mesh can easily absorb heat, but it can also all ow air to pass freely. Generally, the gap between the displace r and its cylinder will increase to accommodate. The benefit of the regenerator is that it reduces waste heat through the heat sink, thereby reducing the need for fuel. Similarly, for the same power output, less cooling and heating are required, so the engine is more efficient.

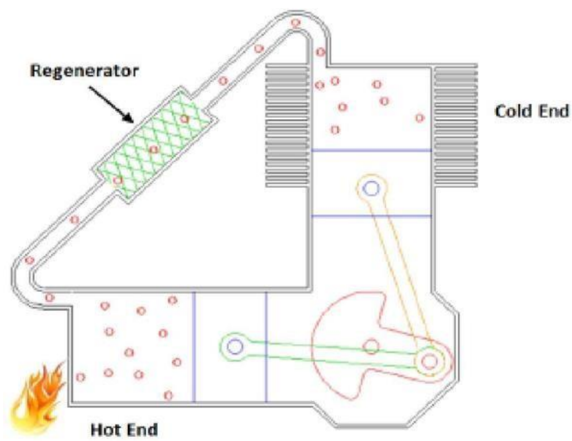


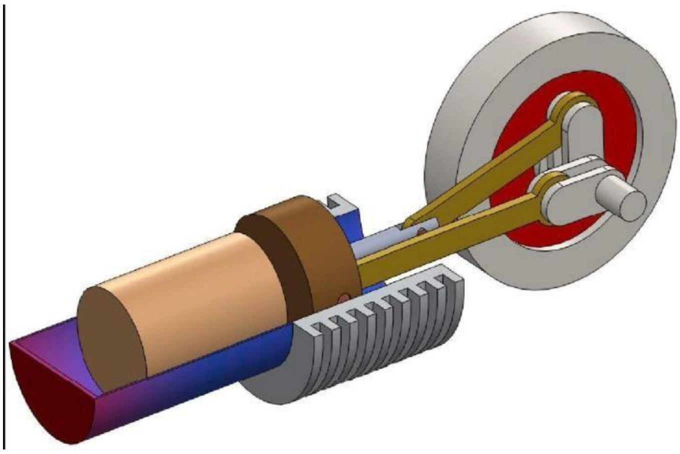
Figure-6: Beta Type Stirling Engine with Regenerator

5. The Beta Stirling Engine Cycle

The following illustration shows the complete cycle of the Beta Stirling engine in four stages. The difference between the beta engine and the gamma engine is that the displacer and power piston are both in the same cylinder. The power in the form of a rotating flywheel is only generated in a part of the cycle, and the momentum of the flywheel completes the entire cycle. The 90° phase difference between the displacer and the piston is also shown.

Stage 1 – Expansion (Heating)

The displacer is in the middle position. The power piston is at the top of the stroke. Most of the air in the system has just been driven to the hot end of the cylinder. The air heats and expands, pushing the piston outward. This is the beginning of the power generation phase of the cycle.



Note: arrows indicate movement of components from stage 1 to 2

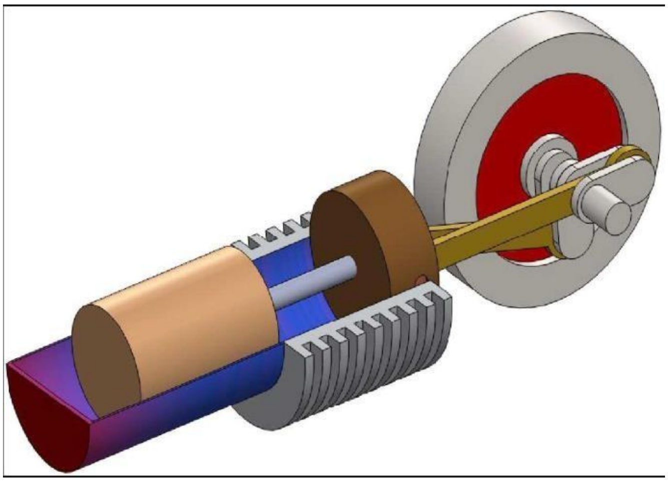
Stage 2 – Transfer

The displacer has reached the cold end. The power piston is in the middle of its travel. The air has expanded. Most of the air is still located in the hot end of the cylinder. Flywheel momentum carries the crankshaft the next quarter turn. Most of the air is moved around the displacer to the cool end of the cylinder.

Note: arrows point to operation of components from stage 2 to 3

Stage 3 – Reduction (Cooling)

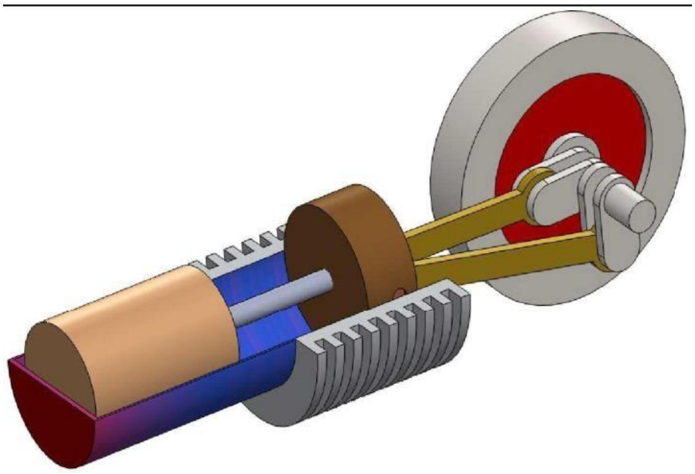
Displacer is mid position. Power piston is at bottom of stroke. Most of the expanded air has moved to the cold end. The air cools and contracts, pulling the piston inward.



Note: arrows indicate movement of components from stage 3 to 4

Stage 4 – Transfer

The displacer is at the hot end. The power piston is in the middle position. The air is completely cooled at the cold end of the cylinder. The momentum of the flywheel causes the crank to turn another quarter turn, moving the displacer and transferring air back to the hot end of the cylinder to start the cycle again.



Note: arrows indicate movement of components from stage 4 to 1

6. Beta type Stirling Engine Cycle

The Stirling engine cycle described in 5 and 6 can be plotted on a graph to illustrate the power output of the engine. In **Figure-7**, the four rows show the four stages of the cycle discussed earlier: heating, expansion, cooling, and contraction. The area enclosed by the four lines is used to measure the power output of the Stirling engine.

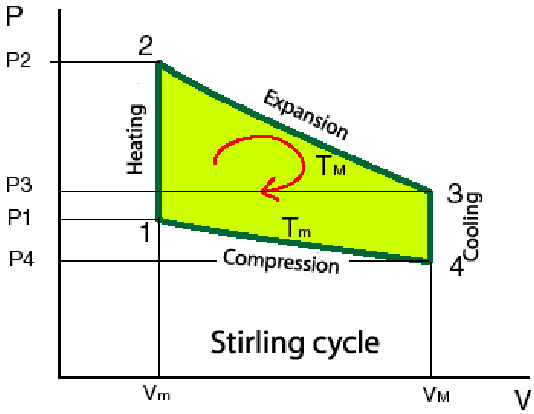


Figure-7: P-V diagram representing the power output of a Stirling engine

The volume in the diagram is the volume of gas in the power piston cylinder. It can be calculated based on the diameter of the piston and the position of the piston.

$$Volume\ of\ a\ cylinder = (\pi \times r^2) \times height$$

The change in volume during the expansion process can be calculated as:

$$Change\ in\ volume = (\pi \times r^2) \times distance\ moved\ by\ the\ power\ pisto$$

The pressure can be determined from the temperature of the gas; they are directly related to each other.

Note: The temperature must be in Kelvin.
Kelvin = Degree Celsius + 273

The performance of any heat engine is defined by its efficiency. The performance, or efficiency, is expressed as a ratio of the output of the engine divided by the input required for the engine:

$$\text{Stirling engine efficiency} = \frac{\text{Desired output of the engine}}{\text{Required input of the engine}} \times \frac{100}{1}$$

However, a theoretical maximum efficiency for the Stirling engine can be calculated based on the temperatures of the hot end (Thot) and cold end (TCold). The previous formula can be written as:

Example:

If the room temperature in which the Stirling engine is operati ng is 20°C.

Cold = 20 + 273 =293K

Butane is to be used as the fuel source. If the temperature of a butane flame is 600°C.

Thot = 600 + 273 =873K

$$\text{The maximum efficiency of the Stirling engine} = \frac{873 - 293}{873} \times \frac{100}{1} = 66.4\%$$

Based on this formula, increasing the hot end temperature, or decreasing the cold end temperature will improve the efficiency. The higher the efficiency, the greater the power output from the engine. Increasing the pressure in the engine also increases the power output.

This ideal efficiency for a Stirling engine is the highest possible efficiency of any heat engine. The car engine is approx. 25% efficient, less than half the possible efficiency of the Stirling engine.

7. Solar Power Generation

Stirling engines can operate using heat from the sun, providing a renewable form of energy to power homes. The so lar power is generated using a dome (parabolic) shaped mirror and a Stirling engine positioned at the focus of the mirror. Th e sunlight is focused on the hot side of the engine. This heat expands a gas to drive a piston and crankshaft. An alternator c onverts the power generated by the engine into electricity.

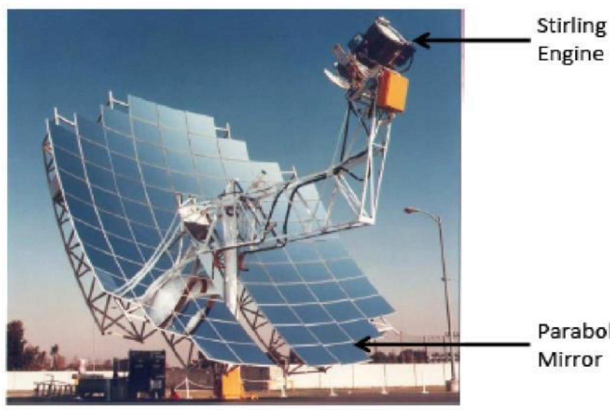


Figure-8: Solar Power Stirling engines

Currently, the most significant development of Stirling engine technology is in the micro combined heat and power (**CHP**). I n the micro cogeneration system, Stirling heat engine is used to generate electricity for households. In the Stirling CHP device,

$$\text{Stirling engine maximum efficiency} = \frac{T^{hot} - T^{cold}}{T^{hot}} \times \frac{100}{1}$$

fuel is used to drive the Stirling engine to generate mecha nical power [5]. Used to generate electricity. However, th e waste heat from the engine is used to provide heat to th e house instead of being discarded.

The miniature CHP Stirling engine device can generate up to 5 kilowatts of heat and 1 kilowatt of electricity by driving the displacer and magnetic piston up and down between the gen erators. Other applications include reversing the Stirling engi ne for use as a refrigeration system. At normal refrigeration temperature. (As low as 20°C) Stirling cooler is not as efficient as other refrigeration devices. However, below -40°C, Stirling coolers are competitive with other coolers. Stirling coolers that operate at temperatu es as low as -200°C are called dry coolers.

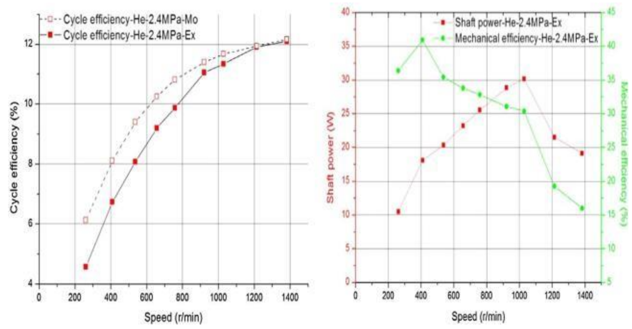


Figure-9: Efficiency and shaft power at differentRotary Speeds (Helium at 2.4 Mpa)

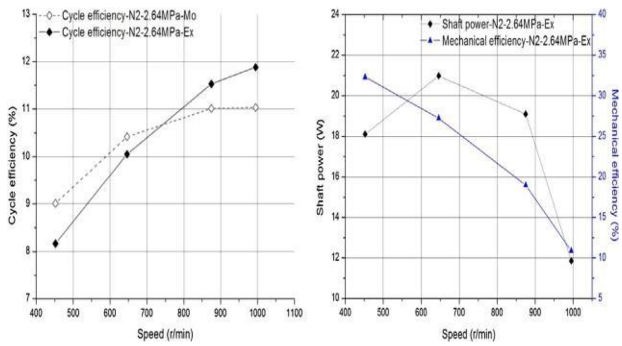


Figure-10: Efficiency and Shaft Power at different Rotary Speeds (Nitrogen 2.64 M Pa)

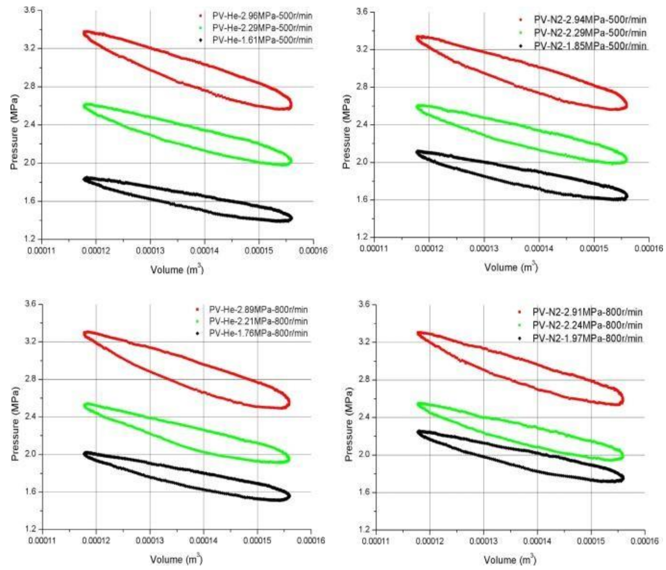


Figure-11: PV Diagram of Helium and Nitrogen at Different Mean Pressures

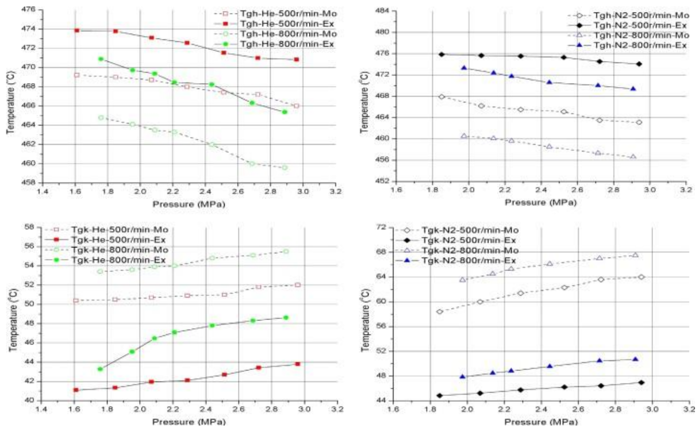


Fig.12: Working gas temperatures in the hot and cold end at different pressures

Figure-9 and Figure-10 shows the efficiency and shaft power at different rotary speeds. Cycle efficiency incre ases with increase in rotary speed, a result that coincides wel l with the results of the model. The increase in cycle efficien cy [6] slowed down when the engine worked at a high rotary speed.

We believe that if the engine speed increases too much due to the increase in speed, the cycle efficiency will eventually drop, because the flow resistance and the transmission loss heard by the generator increase rapidly. The results also show that the cycle efficiency may reach its maximum value at the optimal engine speed. As the speed increases, themechanical efficiency gradually decreases. The f luctuation of the mechanical efficiency and shaft power curve may be caused by the low efficiency and poor stability of the mechanical structure. At the same time, the shaft power first increased and then decreased.

This result is consistent with the results of previous similar studies. When the speed of helium reachesabout 1000 r/min a nd the speed of nitrogen reaches 650 r/minthe shaft power wil l increase to the maximum. All these results show that the speed is an important parameter, which should be optimized in the design in order to obtain the best efficiency and output power of the Stirling engine.

Fig.11 and Fig.12 shows PV diagrams of helium and nitrogen at different mean pressures. The pressure difference increased rapidly under a given volume ratio as the mean pressure increased; hence, the area of the PV diagram was enlarged. Helium exhibited a slightly larger pressure difference and larger output power than nitrogen in the same working conditions. The total heat input and the indicated power increase with the increase of pressure [7]. Heat conduction, shuttle heat and flow resistance loss slightly change. For helium at a speed of 800 r/min, when the pressure changes from 1.76 MPa to 2.89 MPa, the heat loss and seal leakage loss of the accumulator increase from 18.3W to 36.4 W (about 2 times) and from 23W to 41.5 W (about 1.8 times). (About 1.6 times); At the same time, heat conduction, shuttle heat and flow resistance loss were changed from 391.6W to 391W, 61.2W to 60.8W, and 5W to 5.3W. The results show that the leakage loss of the regenerator and the seal is sensitive to the average pressure, because the physical parameters of the working gas relative to the reciprocating motion and the flow resistance loss are little affected by pressure changes. High pressure means to absorb more gas and significantly increase more heat transfer losses. High pressure also brings more gas leakage.

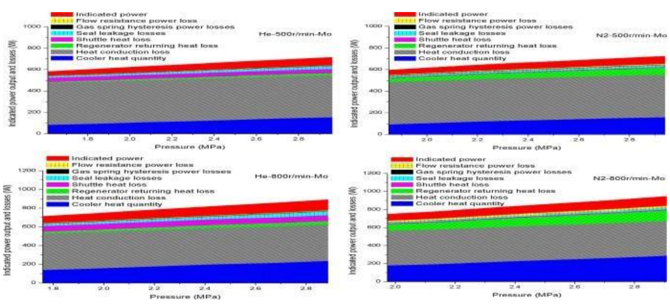


Figure-13: PV diagram of helium and nitrogen in the same working conditions (2.07 MPa, 500 ± 20 r/min)

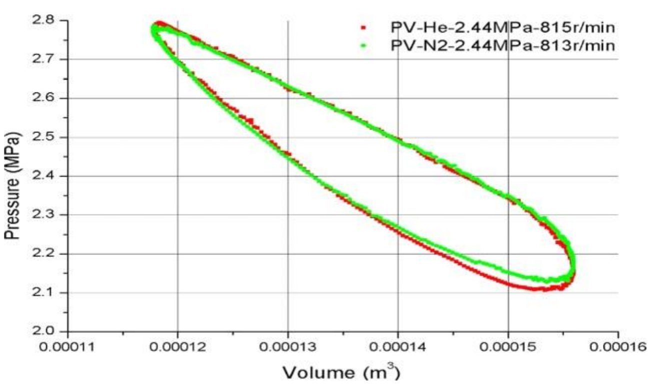


Figure-14: PV diagram of helium and nitrogen in the same working conditions (2.44 MPa, 800 ± 20 r/min)

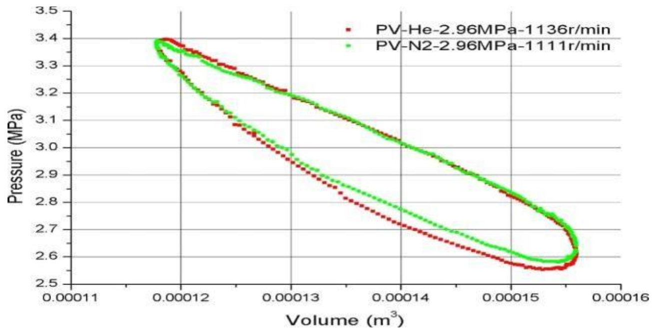


Figure-15: PV diagrams of helium and nitrogen in the same working conditions (2.96 MPa, 1120 ± 20 r/min)

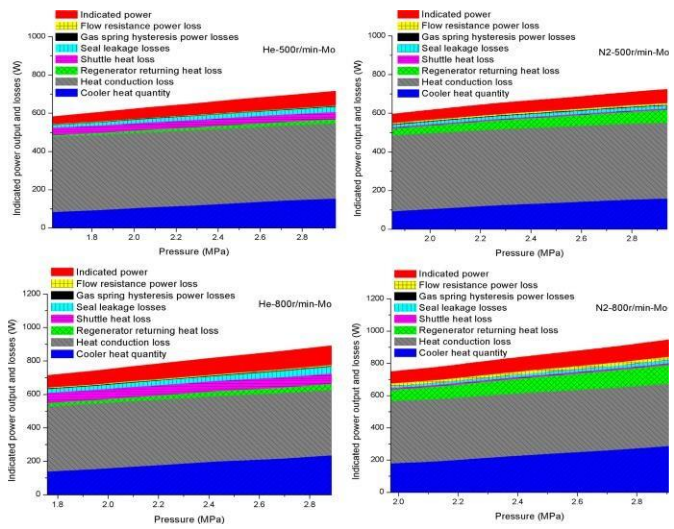


Figure-16: Indicated Power output and energy loss analysis with ISAM at different pressure values

Fig. 13 to 16 shows PV diagrams of helium and nitrogen under the same working conditions. At low mean pressure and low speed, the PV diagrams of helium and nitrogen almost overlap; the difference in output power is rather small. On the one hand, helium has higher heat conductivity and lower viscosity than nitrogen; these characteristics lead to greater gas leakage through the piston rings and heat waste with the displacer moving from the hot end to the cold one. This condition causes large seal leakage and shuttle heat losses.

On the other hand, the high heat conductivity and low viscosity of helium results in a high heat transfer coefficient and low pressure drop, which in turn lead to small regenerator heat transfer loss and flow resistance loss, respectively. In addition, the high heat transfer coefficient results in a large temperature difference between hot end and the cold end and high thermal-to-power efficiency. Flow resistance and regenerator heat transfer losses increased much more rapidly with the increase in rotary speed. Pressure also has a little influence on regenerator heat and seal leakage losses exerted the most influence when pressure and rotary speed increased; they also resulted in different performances of increasingly sensitivity to pressure at high rotary speeds. The difference between theoretical and experimental temperatures suggests that the heat transfer characteristics of oscillating flows should be considered to improve the precision of thermodynamic analytical models.

CONCLUSIONS

In this paper, a β-type Stirling engine was built and studied and the influence of rotary speed, pressure and working gase s were investigated.

The heat flux of the heater increased and caused a large heat transfer temperature difference between the hot and cold end with the increase in pressure and rotary speed.

Indicated power and cycle efficiency increased and mechanic al efficiency decreased with the increase in rotary speed. Shaft power reached the maximum value of 30.1 W for heliu m and 21.0 W for nitrogen when the rotary speed was 1000 a nd 650 r/min, respectively.

Analysis of the energy losses with improved Simple Analytical Model (ISAM) indicated that helium has larger shuttle and seal leakage losses and smaller flow resistance an d regenerator heat transfer losses than nitrogen in the same w orking condition.

The flow resistance and regenerator heat transfer losses, which increased much more rapidly than the seal leakage or shuttle heat losses with the increase in rotary speed and pressure, play an important role and result in different perf ormances of the two working gases.

The study provides incredibly detailed information about PV diagrams, indicated work which is extremely helpful to analy ze the performance of Stirling engine. Besides, the experimen tal data also indicated that the designed rotary speed should be optimized to obtain a preferred efficiency and output pow er of Stirling engine

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