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Scientific article

Design and experimental study of a low-temperature Stirling engine model

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Abstract. This paper aims to study the physical principles of a low-temperature Stirling engine and develop a working model. Both ideal and realistic cycle parameters are considered. Actual energy losses occurring during engine operation are analyzed, and approaches for accounting for them in modeling are proposed, facilitating theoretical research on low-temperature heat engines. Various Stirling engine modifications are also considered, and their potential efficiency is analyzed as a function of temperature, material properties, and operating conditions. The construction of an experimental engine model contributes to a deeper understanding of the heat transfer and energy conversion mechanisms in closed cycles, which is important for the development of heat engine theory. Experimental research also contributes to the development of a domestic scientific base in the field of alternative energy. The study makes an educational and methodological contribution: a model has been proposed that can clearly demonstrate the operation of a Stirling engine and conduct basic experiments, making it a useful tool in educational practice.
Keywords: heat engine, Stirling engine, thermodynamic processes, heat transfer, heat exchange element.

Introduction

The Stirling engine originated in the early 1800s when Scottish clergyman and inventor Robert Stirling (1790-1878) developed an alternative to the steam engines that dominated that era. His 1816 patent described an initial prototype operating on a closed thermodynamic cycle with external thermal input. Safety considerations drove this invention, as steam engines frequently exploded due to excessive pressure and inadequate temperature regulation. Stirling aimed to create a more reliable and safer thermal machine [1, p.42].

His original device, termed an "air engine," featured a basic design utilizing air as the working fluid. A critical component was the regenerator – a heat exchange element that enhanced efficiency through thermal energy recycling. Although the regenerator reached full effectiveness later, Robert Stirling pioneered this concept.

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Subsequently, his brother James Stirling, a professional engineer, joined the development effort. Together, they produced more powerful variants, including a unit constructed in 1843 that powered pumps at a foundry facility. Despite their efforts, the Stirling engine couldn't compete with advancing steam engine technology. Its power output and reliability were constrained by available materials, particularly metals lacking sufficient thermal resistance, which limited operating temperatures. The Stirling engine found applications in smaller mechanisms and pumping systems, but interest gradually declined with the widespread adoption of internal combustion engines and electric machinery [2, p.2134].

Interest in Stirling engines resurged significantly during the latter half of the 20th century. This revival stemmed from advances in materials science, especially heat-resistant alloys that improved engine thermal tolerance, alongside growing demand for alternative, environmentally cleaner energy sources [11, p.48].

During the 1930s-1950s, Philips Corporation (Netherlands) conducted extensive Stirling engine research and modernization. The initial objective was to create silent electrical generators for radio receivers in remote areas without electricity. Philips engineers developed compact, reliable units, including models employing helium as the working fluid. Despite successful demonstrations, commercial adoption remained limited due to competing technologies, particularly batteries and gasoline generators [3, p.395].

In the late 20th and early 21st centuries, the Stirling engine has experienced renewed interest among researchers and engineers for several reasons:

- High theoretical efficiency approaching the Carnot cycle
- Versatility in thermal sources: renewable energy sources (solar, biomass combustion, geothermal heat) and low-temperature sources, including body heat
- Minimal noise and vibration, making it attractive for medical equipment and underwater vessels
- Environmental friendliness, as the engine itself produces no combustion products; all processes occur externally to the working chamber

Applications in space technology, micro-generators, autonomous power systems, and experimental vehicles [5, p.56].

Current Applications

Contemporary Stirling engine applications include:

- Solar power stations (e.g., Dish-Stirling systems)
- Space technology (NASA and ESA projects as energy sources for extended missions)
- Military applications (submarines, where silence and autonomy are critical)
- Small-scale energy generation (cogeneration units for residences and farms)
- Engineering education, as instructional models and laboratory setups

Low-temperature Stirling engine variants are also under development, operating on temperature gradients such as between human body temperature surfaces and cold surfaces, or between warm water and ambient air. These serve to demonstrate thermodynamic processes and educational purposes [11, p.67].

The methodology

The Stirling engine is a thermal machine with an external heat supply, operating on a closed thermodynamic cycle. Its operation is based on the Stirling cycle, consisting of four idealized processes: two isothermal and two isochoric (constant volume) transformations [10, p. 44].

The schematic diagram shows the primary Stirling engine components: working piston and displacer, heater, cooler, and regenerator, along with expansion and compression volumes [4, p.23].

Essential engine elements include:

· Working and displacement pistons, with a phase regulator ensuring synchronized operation,
· Heater and cooler,
· Regenerator-heat exchange element that stores and releases thermal energy,
· Heat rejection system-radiators or heat exchangers [12, p. 103].

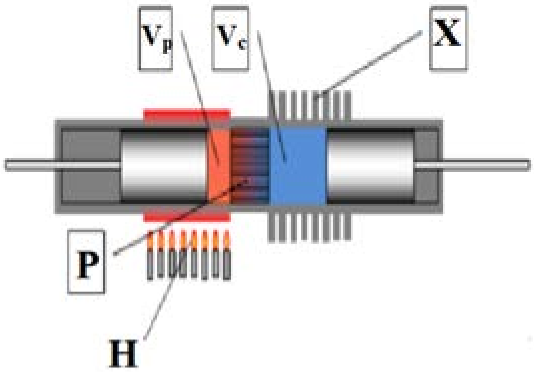

Figure 1. Stirling engine schematic

The Stirling cycle is a reversible thermodynamic process utilizing compressible working gas in a closed volume. It consists of two isotherms and two isochores, forming a closed cycle in p-V and T-S coordinates. The Stirling machine can operate in direct cycle (as an engine) or reverse cycle (as a refrigeration machine).In the p-V and T-S diagrams, Q_1 represents heat absorbed from the heater, Q_2 represents heat rejected to the cooler, q_1 represents heat returned from the regenerator to the working fluid during isochoric heating, and q_2 represents heat extracted from the working fluid by the regenerator during isochoric cooling. The enclosed area in p-V coordinates represents useful work per cycle, while the area in T-S coordinates equals heat converted to work per cycle [7, p.186].

Figure 2 illustrates the heat interactions within the Stirling cycle. Q_1 denotes the heat supplied by the heater (J), while Q_2 represents the heat transferred to the cooler (J). The quantities q_1 and q_2 describe the heat exchange with the regenerator: q_1 is the heat delivered back to the working fluid during isochoric heating, and q_2 is the heat absorbed by the regenerator during isochoric cooling (J).

The enclosed area of the cycle in the P-V diagram corresponds to the net work produced per cycle. In the T-S diagram, the enclosed area represents the portion of heat converted into mechanical work [8, p.35].

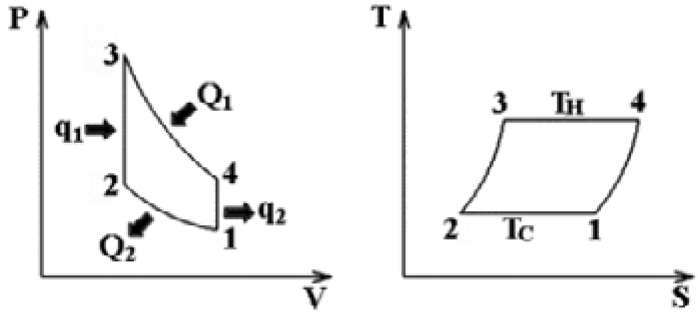

Figure 2. Thermodynamic representation of the Stirling cycle

Stirling engines are categorized based on their structural design, which is determined by the arrangement of cylinders, pistons, and displacers. The three principal configurations - alpha (α), beta (β), and gamma (γ) - are depicted in Figure 3. Each configuration exhibits distinct design characteristics and is suitable for specific applications. Figure 3 visually highlights the structural differences among these Stirling engine types.

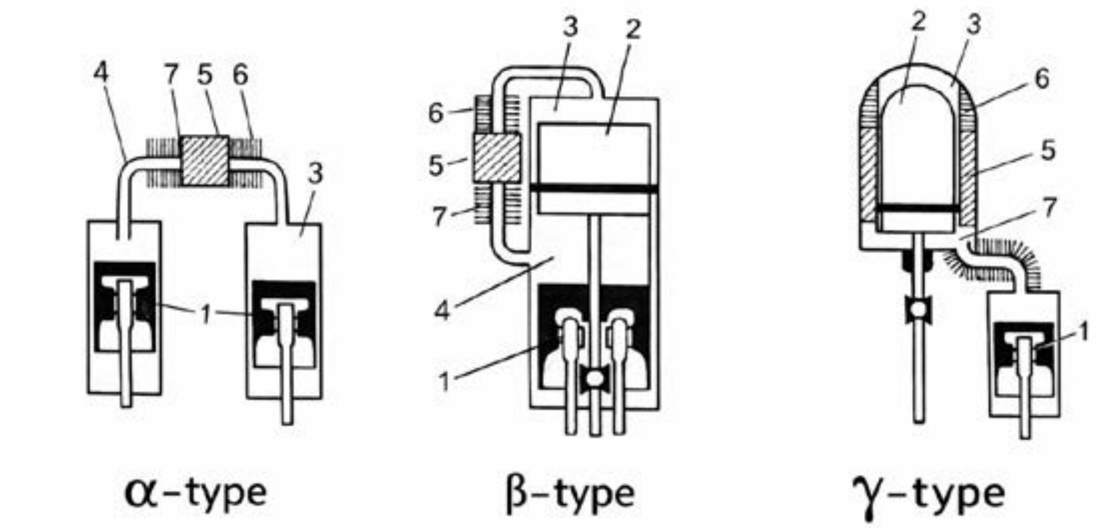

Figure 3. Three main Stirling engine configurations based on the cylinder connection arrangement. 1 – power piston,2 – displacer,3 – expansion space,4 – compression space, 5 – regenerator, 6 – heater, 7 – cooler

Stirling engines are classified by construction type based on cylinder, piston, and displacer configuration. Three main configurations exist: alpha (α), beta (β), and gamma (γ), each with distinct characteristics and application areas.

Alpha Configuration (α-type): The alpha engine consists of two separate pistons in two separate cylinders. One cylinder is continuously heated, the other cooled. Pistons connect to the crankshaft through a connecting rod mechanism. Working gas moves between hot and cold zones, expanding and contracting in different pistons [6, p.134-138].

Beta Configuration (β-type): The beta engine has one cylinder containing both the working piston and displacer. Pistons are coaxial but non-contacting. The displacer moves gas between hot and cold cylinder sections, while the working piston converts pressure into mechanical work [5, p. 52-59].

Gamma Configuration (γ-type): The gamma engine resembles the beta but has two separate cylinders: one for the displacer, another for the working piston. They connect through a common working volume. This arrangement simplifies construction, improving cooling and insulation [12, p. 88-93].

Configuration Selection and Justification. For this modeling effort, a gamma-type Stirling engine was selected. It is most suitable for low-temperature conditions due to its construction simplicity, ease of assembly, and stable operation at low temperature gradients. The gamma configuration allows separation of working and displacement cylinders, simplifying visual inspection and operation demonstration [9, p.33].

Selection rationale:

- Construction and assembly simplicity
- High stability at low temperature differentials ($\Delta T=T_h-T_C$)
- Material availability
- Safety for educational purposes

Materials and Components.

The Stirling engine model was constructed using inexpensive and readily available materials, which are listed in Table 1.

Table 1. Parts and materials

Component	Material	Notes
Working cylinder	Glass flask	Transparent for process observation
Piston	Aluminum	Lightweight and easily machined
Displacement cylinder	Plastic	Heat-resistant and transparent
Membrane	Rubber	Flexible and sealed
Regulator	Wire	Motion transfer between cylinders
Base and frame	Aluminum	Rigidity and stability

Tools utilized during assembly: mini-drill, adhesive, soldering iron, jigsaw, files, caliper, ruler, thermometer.

Assembly Process

The model assembly consisted of several production stages:

– Base fabrication and cylinder mounting
– Installation of working and displacement pistons
– Crank mechanism assembly

– Regenerator connection (if present)
– Joint sealing and leak testing
– Testing and troubleshooting

Design Features for Low-Temperature Operation

– Large working volume utilization
– Minimizing heat losses through cold zone insulation
– Increasing heat exchange surface area in the hot zone
– Using lightweight components to reduce inertial losses
– Air as working agent, eliminating sealing requirements

Safety Measures

– Pre-startup seal verification
– Heater insulation from exposed elements
– Eye protection during testing (goggles recommended)
– Safe heat source usage (e.g., hot water cup)
– Electrical safety compliance when using a heater or soldering iron

Experimental Model Construction. Energy conversion from thermal to mechanical form represents one of the most significant processes in contemporary energy systems. The Stirling engine model provides a clear and effective demonstration of this transformation. This thermal machine type is characterized by its capability to operate across various temperature gradients, including relatively low differentials [13, p.25].

This work examines not only the theoretical operating principles of the Stirling engine but also presents a practical implementation of an experimental model. Particular emphasis is placed on assembly stages and experimentation demonstrating rotational frequency dependence on temperature differential (Figure 4) [14, p.56].

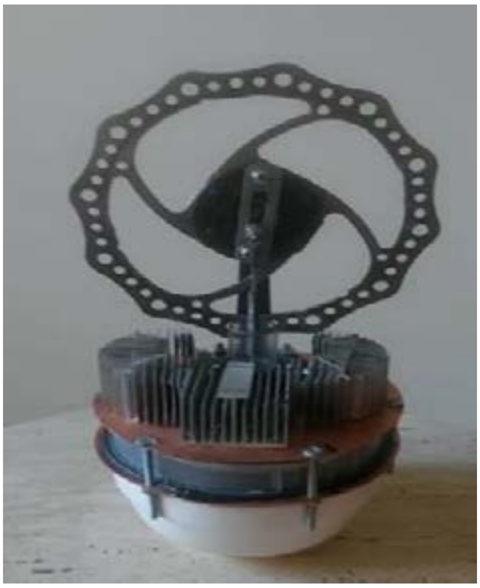

Figure 4. External view of the engine, together with a cup of hot water

The experimental Stirling engine model represents a functional low-temperature Stirling engine implementation with magnetic coupling. The engine base is a 160 mm diameter cylinder, closed on both sides by circular disks of 170 mm diameter. The cylinder body is plastic, a material with low thermal conductivity. Disks are metallic with high thermal conductivity (1 mm thick copper sheet). Disks seal the cylinder hermetically using rubber gaskets. The distance between disks (chamber height) is 40 mm. Lower and upper disks are fastened with screws, forming a cylinder containing the displacer. This cylinder volume constitutes the Stirling engine working volume. Thus, the model represents a two-plate construction where air volume is enclosed between two metal disks.

The lower disk, through which heat is supplied, is called the "hot" disk. The upper disk, through which heat is removed, is called the "cold" disk. For improved heat removal, radiators are installed on the upper ("cold") disk. At the center of the upper disk's external surface is an opening for working cylinder sleeve installation, plus a flywheel support. The flywheel support is a shaft with a disk at one end for attachment to the upper ("cold") disk. The shaft's opposite end has a head with an opening for flywheel shaft installation with a bearing. The flywheel is installed on the bearing assembly shaft of the upper head support. The 160 mm diameter flywheel is a thin steel with a plastic hub. An axle offset 12 mm from the flywheel axis is installed in the hub.

The glass sleeve-working cylinder is designated by position 9, in which the piston moves. The piston connects to the flywheel through a connecting rod bearing the working cylinder.

The distance from the flywheel axis to the connecting rod upper head axis determines the piston working stroke (20 mm). The glass sleeve is made from a 20 mm diameter medical syringe. For effective engine operation, the sleeve should ideally be fabricated from a metal with high thermal conductivity. The piston is manufactured from epoxy resin. An axle hole is drilled approximately midway through the piston, through which it connects to the connecting rod lower head.

The displacer is a circular disk of foam insulation board, 10 mm smaller in diameter than the cylinder (150 mm diameter), with 18 mm thickness. The displacer occupies half the engine working volume. Foam insulation board is a material with low thermal conductivity and low density (lightweight).

A 10 mm diameter neodymium magnet is bonded into the displacer center for magnetic coupling with the piston, which also has an attached magnet for displacer connection.

Heating the lower plate (in this case with a hot water cup) and cooling the upper plate creates a temperature gradient that causes air expansion and compression. Consequently, reciprocating motion arises, converted into rotational movement. This model serves educational purposes and visually demonstrates the operating principle of a thermal machine with external heat supply.

Figure 5 shows the main components of the Stirling engine model.

The experimental Stirling engine model consists of the following components:

1. Lower metal plate (heater) - The engine body contacts the hot surface (in this case, hot water in the vessel on which the lower plate is positioned).

2. Engine body wall - Cylindrical body made of transparent material (plastic) connecting upper and lower plates.

3. Flywheel (connecting rod) assembly - Used to convert reciprocating motion into continuous rotation.

4. Radiators - Used for effective upper chamber cooling, attached to the upper copper plate (cooler). Cooling is provided by an external source, air, or ice placed on the upper plate.

5. Piston with magnet - Responds to air pressure changes inside the chamber.

6. Flywheel with crankshaft - Converts piston reciprocating motion into rotation. Drive mechanism (crank, connecting rod) links two piston movements with ~90° phase shift.

7-8. Displacement piston with magnet - Moves up and down, transferring air between warm and cold zones.

9. Regulator.

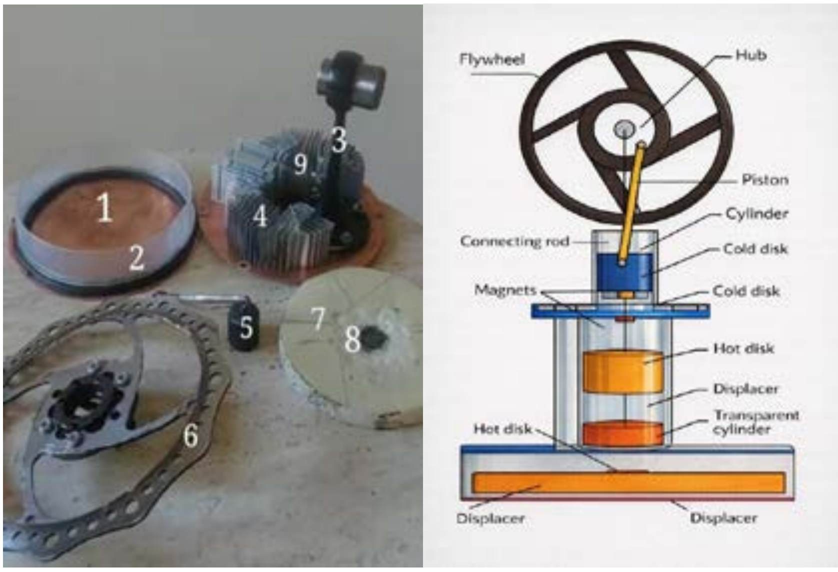

Figure 5. Components of the Stirling engine

All model elements are carefully aligned and sealed, ensuring effective engine operation and air leak resistance. Elements are connected to ensure precise motion transmission, guaranteeing stable operation at various temperatures.

Assembly Procedure

Model assembly occurs in several stages:

- Body installation and cylinder sealing
- Lower (heating) and upper (cooling) plate installation
- Piston mounting, connected to the connecting rod and flywheel
- Piston and connecting rod mechanism installation and balancing, with special attention to flywheel rotation axis alignment and free piston movement
- Flywheel connection with magnetic transmission
- Seal integrity and component mobility verification

- Assembly materials used:
- Copper and steel elements for strength and thermal conductivity
- Magnets for piston drive without direct contact
- Transparent plastic and silicone gaskets for sealing
- Standard laboratory containers for hot water and ice

Findings and discussion

Operating Principle. Stirling engine operation is based on cyclic heating and cooling of the working fluid. In this model, the working fluid is air enclosed in a sealed cylinder. When the lower displacer section is heated, air in the cylinder expands, pressure increases, and it pushes the working piston upward. Then the displacer moves air to the cold zone, where it cools and compresses, pressure drops, and the piston returns downward. This cyclic air movement between hot and cold zones creates periodic oscillations converted into flywheel rotational motion. Consequently, thermal energy transforms into mechanical energy, ensuring flywheel rotation. Thus, the Stirling engine operates through an external heat source and can effectively utilize even minimal temperature differentials.

Operating Conditions and Parameters

1. Heat source: For the developed model, the heat source is hot water in a cup (alternatively, a lamp or candle can be placed under the metal plate). Upper plate temperature: ~70-75°C, lower plate temperature: ~20-25°C. Minimum temperature gradient: $\Delta T \sim 20$°C.
2. Flywheel rotational speed: 0.6-1.4 rpm depending on temperature gradient ΔT.
3. Continuous operation time: Approximately 14 minutes per heat supply cycle.

Table 2 lists the dimensions of the Stirling engine model components.

Element	**Size**	**Comment**
Base diameter	160 mm	Heating plate
Displacer diameter	150 mm	Internal plastic body
Chamber height	40 mm	Distance between plates
Flywheel diameter	150 mm	Made from lightweight metal
Connecting rod length	30 mm	Connects the piston and crankshaft
Piston stroke	~20 mm	Reciprocating motion
Model weight	~300 g	Depending on the materials used

Experimental Procedure. The experiment consisted of two parts with different temperature conditions to study engine behavior at different temperature gradients.

First Experiment: The engine model is placed on a hot water cup at 74.8°C, while the upper plate is at room temperature (23°C), creating a temperature difference of approximately 52°C. The relationship between the temperature difference and the flywheel speed is shown in Table 3.

Table 3. Results of the first experiment

Lower Plate Temp (°C)	Upper Plate Temp (°C)	ΔT	Rotation Speed (rpm)
74.1	26.3	47.8	0.9
72.3	28.2	44.1	0.85
68.0	28.7	39.3	0.8
67.3	29.0	38.3	0.7
66.0	28.0	38.0	0.6

Results show rotational frequency gradually decreased as the temperature differential decreased. Rotation duration was 4 minutes.

Second Experiment: In the second experiment, the model was cooled to room temperature, then ice pieces (0°C) were placed on the upper plate while the lower section remained at room temperature (~20°C). This created a 20°C temperature difference, sufficient for engine startup.

Subsequently, the lower plate was reheated while the upper remained ice-cooled. The temperature differential reached over 65°C. The results of the second experiment are presented in Table 4.

Table 4. Results of the second experiment

Lower Plate Temp (°C)	Upper Plate Temp (°C)	ΔT	Rotation Speed (rpm)
74.8	6.8	68.0	1.4
73.3	6.6	66.7	1.3
72.0	6.0	64.4	1.2
71.2	5.8	62.0	1.1
68.6	5.5	59.1	1.0
67.6	5.4	57.2	0.9
61.0	5.3	55.7	0.8
58.7	5.2	53.5	0.7
56.4	4.8	52.6	0.6

During the second experiment, the engine operated for 14 minutes, demonstrating stable and clear operation at large temperature differentials.

The graphical relationship between rotation speed and temperature differential ΔT for both experimental modes clearly shows that rotation speed increases with growing temperature differential, confirming the engine's thermodynamic efficiency at larger temperature gradients.

- Air cooling (lower ΔT) – left curve;
- Ice cooling (higher ΔT) – right curve.

The right curve shows the relationship between the rotation speed and the temperature difference at a larger temperature gradient. In this case, the lower part was reheated to approximately 74°C, while the upper part was cooled with ice.

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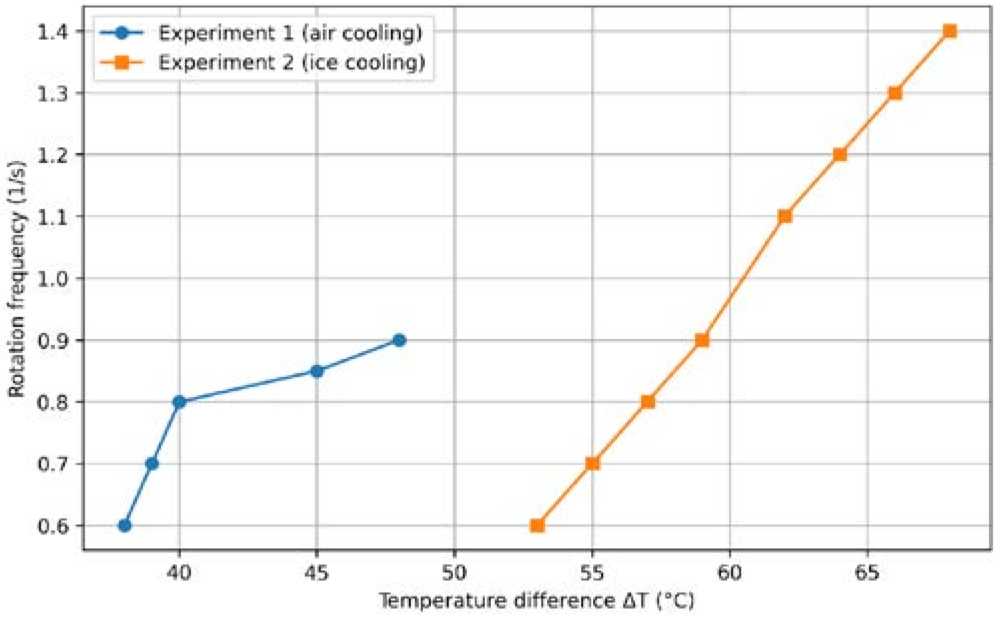

Figure 6. Dependence of the rotation frequency on the temperature difference

For the Stirling engine, maximum theoretical efficiency is determined by the Carnot formula:

$$\eta = 1 - \frac{T_c}{T_H} \quad (1)$$

First Experiment (air cooling):

$$T_H = 74{,}1^0C = 347{,}25K, T_C = 26{,}3^0C = 299{,}45K \quad (2)$$

$$\eta_{max} = 1 - \frac{299.45}{347.25} \approx 13{,}8\% \quad (3)$$

Second Experiment (highest efficiency): $T_H = 74{,}8^0C = 347{,}95K, T_c = 6{,}8^0C = 279{,}95K$

$$\eta_{2max} = 1 - \frac{279.95}{347.95} \approx 19{,}5\% \quad (4)$$

In reality, Stirling engine efficiency constitutes approximately 40% (maximum) of ideal efficiency. Thus:

First experiment: $\eta_{1real} = 0{,}4\eta_{1max} = 0{,}4 \cdot 13{,}8 \approx 5{,}5\%$

Second experiment: $\eta_{2real} = 0{,}4\eta_{2max} = 0{,}4 \cdot 19{,}5 \approx 7{,}8\%$

Actual Efficiency from Experimental Parameters. Useful work, knowing frequency f, flywheel mass m, and moment of inertia I, is determined from flywheel kinetic energy:

$$E_k = \frac{1}{2}Iw^2 = \frac{1}{2}I(2\pi f)^2 = 2\pi^2 f^2 I \tag{5}$$

For a disk flywheel:

$$I = \frac{1}{2}mR^2 = \frac{1}{8}mD^2 = \frac{1}{8}\rho V D^2 = \frac{1}{8}\rho\pi\left(\frac{D}{2}\right)^2 hD^2 = \frac{\pi}{32}\rho h D^4 \tag{6}$$

There fore:

$$E_k = 2\pi^2 f^2 I = 2\pi^2 f^2 \frac{\pi}{32}\rho h D^4 = f^2\frac{\pi^3}{16}\rho h D^4 \tag{7}$$

Substituting values $D = 15cm = 0{,}15m, h = 0{,}15cm = 0{,}0015m, f = 0{,}9(1{,}4)Hz$:

$$E_{k2} = f^2\frac{\pi^3}{16}\rho h D^4 = 0{,}9^2\frac{3{,}14^3}{16}4000\cdot 1{,}5\cdot 10^{-3}\cdot\left(15\cdot 10^{-2}\right)^4 \approx 4{,}9mJ$$

$$E_{k2} = f^2\frac{\pi^3}{16}\rho h D^4 = 1{,}4^2\frac{3{,}14^3}{16}4000\cdot 1{,}5\cdot 10^{-3}\cdot\left(15\cdot 10^{-2}\right)^4 \approx 11{,}6mJ$$

This represents minimal energy, natural for a desktop engine model, but clearly demonstrates heat-to-mechanical motion conversion. Thus, work equals approximately:

$W_1 \approx 22mJ$ (first experiment)

$W_1 \approx 52mJ$ (second experiment)

Heat Input Estimation:

Using the heat capacity equation:

$$Q = mc_V\Delta T \tag{8}$$

Here, m is the mass of the gas, $c_V = C_V\mu = \frac{i}{2}\frac{R}{M} = \frac{5}{2}\frac{8{,}31}{29\cdot 10^{-3}} \approx 716J/(kg\cdot K)$ is the specific heat capacity of air at constant volume (approximately), and ΔT is the temperature difference between the hot and cold sections of the engine.

Let us estimate the volume V of the working chamber. For a cylinder with diameter d and piston stroke h, the volume V of the working chamber is given by the expression:

$$V = \pi\frac{d^2}{4}h \tag{9}$$

The mass of air can be determined using the ideal gas equation

$$m = \frac{PV\mu}{RT} \tag{10}$$

Alternatively, considering the formula for the volume V of the working chamber, we obtain:

$$m = \frac{P\mu}{RT}\pi\frac{d^2}{4}h \tag{11}$$

Substituting the numerical values into the formula for the mass, we have: $d = 2{,}0cm = 0{,}020m, h = 2{,}0cm = 0{,}020m, P = 101325Pa$ (atmospheric pressure), $\mu = 0{,}029kg/mol, T \approx 300K$ (average temperature), $R = 8{,}31J/(mol \cdot K)$.

$$m = \frac{P\mu}{RT}\pi\frac{d^2}{4}h = \frac{101325 \cdot 29 \cdot 10^{-3}}{8{,}31 \cdot 300}3{,}14\frac{(20 \cdot 10^{-3})^2}{4}20 \cdot 10^{-3} \approx 7{,}4mg$$

By substituting the obtained mass value into the heat formula and using $\Delta T_1 \approx 40K$ for the first experiment and $\Delta T^2 \approx 60K$ for the second experiment, we obtain:

$$Q_{H1} = mc_V\Delta T_1 = 7{,}4 \cdot 10^{-6} \cdot 716 \cdot 40 \approx 0{,}22J$$

$$Q_{H2} = mc_V\Delta T_2 = 7{,}4 \cdot 10^{-6} \cdot 716 \cdot 60 \approx 0{,}32J = \frac{3}{2}Q_{H1}$$

These values for the heat obtained by the model (approximate upper estimate) were calculated under the assumption that the gas in the cylinder is heated by 40°C (and by 60°C in the second experiment) during each cycle.

In practice, the actual amount of heat per cycle will be lower, since not all heat is converted into work; some is lost due to heat dissipation and uneven heating.

Now, let us calculate the actual efficiency of the experimental Stirling engine model using its parameters, according to the formula:

$$\eta^*_{1real} = \frac{W_1}{Q_{H1}} = \frac{4{,}9 \cdot 10^{-3}}{0{,}22} \approx 2{,}2\%$$

$$\eta^*_{2real} = \frac{W_2}{Q_{H2}} = \frac{11{,}6 \cdot 10^{-3}}{0{,}32} \approx 3{,}6\%$$

The difference between the actual efficiency, calculated under the assumption that Stirling engines achieve 40% of the ideal (Carnot cycle) efficiency, and the efficiency of the Stirling engine calculated from its parameters, is:

first experiment $\frac{\eta_{1real}}{\eta^*_{1real}} = \frac{5{,}5}{2{,}2} \approx 2{,}5$

second experiment $\frac{\eta_{1real}}{\eta^*_{1real}} = \frac{7{,}8}{3{,}6} \approx 2{,}2$

In reality, our model's efficiency was 16-18% of ideal (maximum) efficiency, whereas many real Stirling engines achieve around 40%.

The obtained low efficiency (2,2% and 3,6%) is normal for a demonstration model. Friction losses, heat transfer, non-ideal cycle, and small gas mass significantly reduce efficiency. The theoretical limit (Carnot cycle efficiency) was ~13,8% and ~19,5%, but this is unattainable for a real model.

This Stirling engine model described in the work represents an accessible and clear method for demonstrating thermodynamic processes converting heat into mechanical work. Construction simplicity, use of inexpensive materials, and the capability to operate at temperature differentials of just ~20°C make it ideal for school and university laboratory work.

Conclusion

1. The experimental model effectively demonstrates thermal energy conversion to mechanical energy, with efficiency and rotation speed directly dependent on the temperature differential between heating and cooling plates.

2. Even a small temperature difference (20°C) suffices for engine startup and stable operation. This confirms the engine's capability to operate on low-temperature energy sources.

3. Increasing the temperature differential increases flywheel rotation speed.

4. Model assembly requires precision and accurate fitting, especially regarding sealing and moving parts balancing. Model assembly is possible from accessible materials.

5. Obtained data can be utilized in school and university practice for studying thermodynamics, alternative energy, and engineering design fundamentals. This setup represents significant educational value for thermodynamics, physics, and engineering instruction.

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There are no conflicts to declare.

The contribution of the authors

G. Baiman – Development of the research concept, formulation of the aims and objectives of the study, supervision of all stages of modeling and results analysis, and participation in writing the introduction and conclusion.

G. Baubekova – Collection and systematization of literature sources, preparation of materials for the methodology section, and critical revision of the manuscript text

D. Pazylova – Approval of the final version of the manuscript for publication.

Statement on the use of generative AI and AI-enabled technologies in the manuscript preparation process

During the preparation of this paper, the authors used AI tools for text style improvement, as well as for clarity of wording. After using this service, the authors have checked and edited the content as needed and are fully responsible for the content of the published article.

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Төмен температуралы Стирлинг қозғалтқышының моделін жобалау және эксперименттік зерттеу

Аңдатпа. Бұл мақаланың мақсаты – төмен температуралы Стирлинг қозғалтқышының физикалық принциптерін зерттеу және жұмыс моделін әзірлеу. Идеал және нақты циклдердің параметрлері қарастырылады. Қозғалтқыштың жұмысы кезінде пайда болатын нақты энергия шығындары талданады және оларды модельдеуде есепке алу тәсілдері ұсынылады, бұл төмен температуралы жылу қозғалтқыштары бойынша теориялық зерттеулерді жеңілдетеді. Стирлинг қозғалтқышының әртүрлі модификациялары да қарастырылады және олардың температураға, материалдық қасиеттерге және жұмыс жағдайларына байланысты әлеуетті тиімділігі талданады.

Тәжірибелік қозғалтқыш моделін құру тұйық циклдердегі жылу беру және энергияны түрлендіру механизмдерін тереңірек түсінуге ықпал етеді, бұл жылу қозғалтқышы теориясын дамыту үшін маңызды. Тәжірибелік зерттеулер баламалы энергия саласындағы отандық ғылыми базаны дамытуға да үлес қосады.

Зерттеу білім беру және әдістемелік салаға үлес қосады: Стирлинг қозғалтқышының жұмысын анық көрсету және негізгі тәжірибелер жүргізу үшін пайдалануға болатын модель ұсынылды, бұл оны білім беру тәжірибесінде пайдалы құралға айналдырады.

Түйін сөздер: жылу қозғалтқышы, Стирлинг қозғалтқышы, термодинамикалық процестер, жылу беру, жылуалмасу элементі.

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Проектирование и экспериментальное исследование модели низкотемпературного двигателя Стирлинга

Аннотация. Целью данной работы является изучение физических принципов работы низкотемпературного двигателя Стирлинга и создание его рабочей модели. В работе рассматриваются как идеальные, так и реальные параметры цикла. Анализируются реальные потери энергии, возникающие при работе двигателя, и предлагаются подходы к их учету при моделировании, что способствует теоретическим исследованиям низкотемпературных тепловых двигателей. Также рассматриваются различные модификации двигателя Стирлинга и анализируется их потенциальная эффективность в зависимости от температуры, особенностей материала и условий эксплуатации.

Построение экспериментальной модели двигателя способствует более глубокому пониманию механизмов теплопередачи и преобразования энергии в замкнутых циклах, что важно для развития теории тепловых двигателей. Экспериментальные исследования также способствуют развитию отечественной научной базы в области альтернативной энергетики.

Исследование вносит образовательный и методический вклад: предложена модель, с помощью которой можно наглядно продемонстрировать работу двигателя Стирлинга и провести основные эксперименты, что делает ее полезным инструментом в образовательной практике.

Ключевые слова: тепловой двигатель, двигатель Стирлинга, термодинамические процессы, теплопередача, теплообменный элемент

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