







## Experimental Investigation of Waste Energy Recovery of Exhaust gases of an Internal Combustion Engine for Cooling Production Using the Combined Cycle of the Stirling Engine

Ezatollah Hassnzadeh<sup>1\*</sup>, Arash Mohammadi<sup>2</sup>, Mostafa Akbari<sup>3</sup>, Hossein Rahimi Asiabaraki<sup>4</sup>, Hamed Savaripour<sup>5</sup>

<sup>1,3,4,5</sup>Department of Mechanical Engineering, National University of Skills (NUS), Tehran, Iran

<sup>2</sup>Department of Mechanical Engineering, Shahid Rajaee Teacher Training University, Tehran, Iran.

### ARTICLE INFO

### ABSTRACT

#### Article Type:

Original Research

**Received:** 08.30.2024

**Revised:** 10.05.2024

**Accepted:** 10.20.2024

#### Keyword:

Stirling Gamma Engine  
Energy Recovery  
Gasoline Engine  
Exhaust Gases  
Cooling

#### \*Corresponding Author:

Ezatollah Hassnzadeh

#### Email:

[e.hassanzadeh1352@gmail.com](mailto:e.hassanzadeh1352@gmail.com)

This research explored the utilization of the combined cycle of the Stirling Gamma engine and internal combustion to recover waste energy from exhaust gases in internal combustion engines. Integrating the Stirling Gamma engine into the exhaust gas path aimed to generate cooling and reduce the reliance on the engine's output power for the air conditioning system, ultimately enhancing engine efficiency. The study demonstrated that the kinetic energy present in the exhaust gases resulted in power dissipation ranging from 10 to 77 kW. By incorporating the heating component of the Stirling engine in the exhaust gas path, it became feasible to recover this wasted heat and employ it for cooling purposes. Optimal operating conditions were achieved when the hot source fluid was at a pressure of 8 bar, and the average pressure of the cold source was 1 bar, leading to the attainment of the lowest cooling temperature. Specifically, the temperature of the hot source reached 580 degrees Celsius, while the temperature of the cold part was approximately -16 degrees Celsius.



## Introduction

One long-term solution to reduce air pollution is using renewable energies to prevent the emissions caused by fossil fuels [1-3]. Therefore, industrialized countries have seriously put the use of other sources of energy production (clean and renewable energy sources) on their agenda [4]. Nowadays, using renewable energy is one of the world's most critical topics, considering the pollution problem and the limitation of fossil energy resources. Renewable energies such as biomass fuel and solar energy are considered one of the most important renewable resources of the future [5-7]. One of the most suitable renewable energy sources is biomass, which, in addition to being renewable, is also environmentally friendly [4; 8].

Many countries are trying to expand and develop renewable energies to replace fossil fuels [9; 10]. Today, various technologies are being developed to use renewable energy. One of these technologies that has received much attention is the use of a heat engine called a Stirling engine [11-13]. The Stirling engine is an external combustion engine with high flexibility in using different energy sources and can convert thermal energy from renewable sources into mechanical and electrical energy [14; 15].

Stirling engines have progressed over many years, and various designs of this engine have been developed. Stirling engines are known as Alpha, Beta, Gamma, and free pistons [16; 17]. The thermodynamic principles are the same for each type of Stirling engine, and the main difference between them is in terms of how the various components of this engine are placed next to each other [18]. All Stirling engines have five control volumes: compression chamber, cooler, regenerator, heater, and expansion chamber [19; 20]. These engines have low noise because, unlike internal combustion engines, they can use any heat source as an energy source [21; 22].

In conventional passenger cars, approximately 30% of the energy produced by the combustion engine is rejected by exhaust gases to the environment [23]. Therefore, the energy of the exhaust gases is a suitable source for use as the high-temperature source in the Stirling engine to recover energy. The air conditioning system (A.C) is commonly used in automobiles to cool car cabins [24; 25]. Considering that the A.C. system takes its power from the engine, this reduces the power of the engine. The A.C. system consumes approximately 4 to 10 horsepower of the engine's useful power. Using the heat of the exhaust gases as an energy source in the A.C. system increases engine efficiency on the one hand and reduces fuel consumption as a result of not using engine power for the A.C. system [26].

The Stirling engine has been used to recover the exhaust gas heat of the internal combustion engine. Various factors such as the effects of working pressure and operating temperature of the Stirling engine on the efficiency and output power of the internal combustion engine have been investigated by researchers. Aladayleh and Allah Mehr [27] analyzed using a Stirling engine to recover exhaust gas heat on an air-cooled engine with direct injection. They found that by installing a Stirling engine in the exhaust manifold, fuel consumption is reduced by approximately 15%. Additionally, the power recovered from the Stirling engine can be used to charge the car battery or to operate accessories such as the oil pump, water pump, cooler compressor and steering pump. Batooei et al. [28] performed a thermal analysis of the alpha-type Otto-Stirling combined cycle to recover exhaust gas energy. They observed a 2-3% increase in efficiency compared to internal combustion engines. In the Batooei study, a single Stirling motor was utilized, and an electric power supply was employed for its initial start-up. However, in this particular research, a novel approach was undertaken by incorporating two Stirling engines. These engines operated at varying temperatures, revolutions, and conditions, and their operation involved harnessing the heat derived from natural gas and engine exhaust gases.

Amarlo et al. [29] conducted a thermodynamic analysis of the functional parameters of the new three-cylinder Stirling engine structure using GT-SUITE software. The analysis showed that increasing the rotational speed was unsuitable for increasing the engine performance and reduced the engine efficiency. Hasanpour Omam [30] recovered the exhaust heat dissipation of a gasoline engine using the Stirling cycle. They showed that the power of the Otto-Stirling-TEG combined cycle increases by approximately 7% and efficiency by about 2.5%. Furthermore, the reduction in fuel consumption in the Otto-Stirling-TEG combined cycle was 8%. Güven et al. [13] used Stirling engines for waste heat recovery (WHR) from exhaust gases of a heavy-duty truck diesel engine. They showed that the WHR system provides more than 1.3% of ICE power output and approximately 1% reduction in fuel consumption, which offers the Stirling engine a reasonable option for WHR on heavy-duty truck engines.

In this research, using the combined cycle of the Stirling Gamma engine and the internal combustion engine, the wasted energy of exhaust gases was recovered to produce refrigeration. Experimental results have shown that the temperature of exhaust gases changes from 450 to 776 degrees Celsius with gasoline fuel and from 430 to 731 degrees Celsius with CNG fuel according to the operating conditions of the gasoline engine. The engine can convert this wasted energy into useful work. This research proposes a new structure by connecting

two Stirling Gamma engines. By using this structure, the energy of the engine exhaust gases is used as a heat source for the high-temperature source of the first Stirling engine. The output work of the first Stirling engine drives the second Stirling engine to produce cooling.

### **Experimental method**

In this research, to recover the energy of the exhaust gases and use this energy as an A.C. system energy source, a Stirling engine with the specifications in Table 1 was used [31].

**Table 1.** Nominal specifications of the Stirling engine.ST500 -IPCO.

No.	Engine Technical Specifications	Value
1	Type	Gama
2	Output Power	500W
3	Thermal efficiency	8.5%
4	Standard Charge Pressure	8 bars
5	Working Fluid	Helium, Air
6	Operating Frequency	14Hz
7	Fuel	Natural gas, Biomass, Solar Energy
8	Cooling substance	Water
9	Power Piston Stroke	0.075 m
10	Displacer Stroke	0.075 m
11	Phase Angle	90 deg.
12	Heater Type	Tube (6mm dia.) × 20
13	Cooler Type	Duct (13mm <sup>2</sup> Section Area) × 144
14	Regenerator Material	Steel Matrix (.96 porosity)
15	Heat absorption Temperature	350-420° C
16	Heat excretion Temperature	30-50° C
17	Maximum Volume	1.79e-3m <sup>3</sup>
18	Minimum Volume	1.37e-3m <sup>3</sup>
19	Compression Ratio	1.3:1

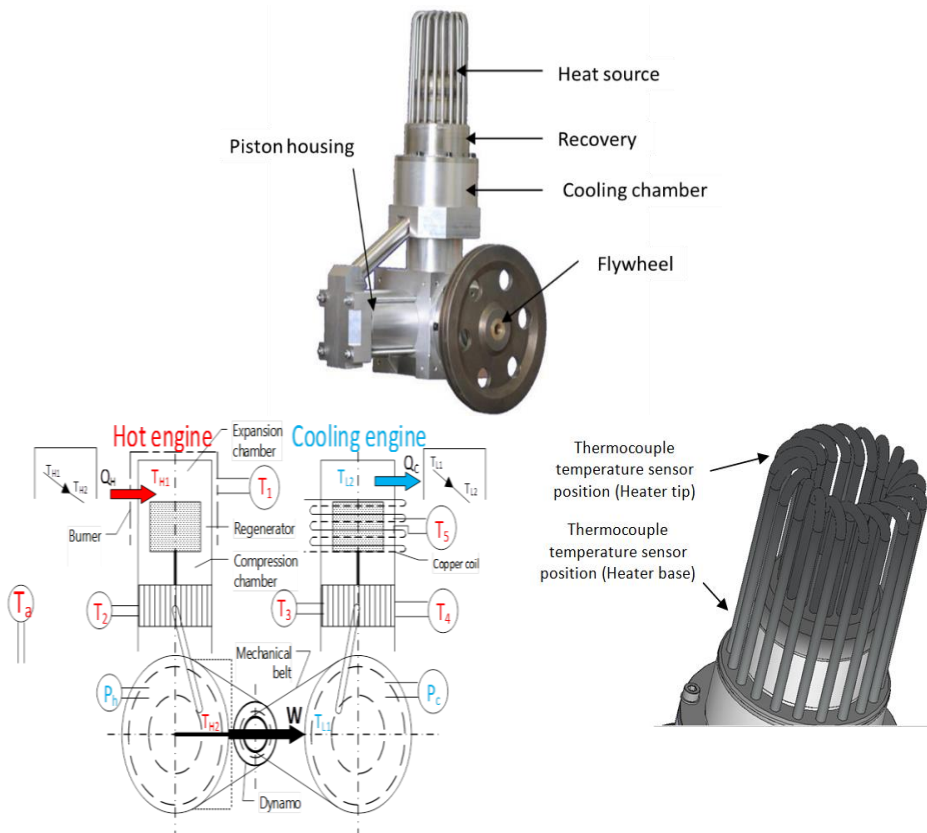
In the present research, experiments using biogas were first performed to check the capability of the developed structure with the use of biogas. In addition, some system parameters were obtained using biogas as a heat source. Table 2 presents the composition of the biogas used in this research. As it is clear from Table 2, the major part of the biogas used consisted of methane gas and reached a temperature of approximately 500 degrees Celsius.

**Table 2.** Biogas components were used in this research.

The percentage of biogas constituents (%)	Name of the ingredient
87.7	CH <sub>4</sub>
4.7	C <sub>2</sub> H <sub>6</sub>
4.7	N <sub>2</sub>
.2	H <sub>2</sub> S

The percentage of biogas constituents (%)	Name of the ingredient
.05	CO <sub>2</sub>
2.65	Other mixed gases

Figure 1 illustrates the view of the Stirling engine coupling used in this investigation. On the left is the named hot engine that operates by receiving thermal energy from a heat source such as biomass. On the right is another Stirling engine that is named the cold engine. The cold engine produces cooling using the power received from the hot engine. In the hot engine, an external power source is used for the initial start-up, which is connected to the flywheel of the hot engine. After a few seconds of starting the system, the power supply can be cut off so the system continues working. After starting the hot engine, the belt drives the cold engine. The rotation of the cold engine, according to the Stirling engine cycle, produces cooling. In order to prevent the waste of cooling energy in the heating part of the cooling engine, a special insulator is used for insulation. Each of the two engines is filled with helium gas.



**Figure 1.** Coupling Stirling refrigerator for cold generation and experimental setup-ST500 -IPCO.

After tests were conducted by biogas and Stirling engine parameters such as fluid pressure in Stirling engines were estimated, the developed system was coupled with an internal combustion engine to recover exhaust gas energy and use this energy for vehicle cooling. This research used the naturally aspirated engine in the combined cycle. This engine is designed based on CNG fuel and can simultaneously work with gasoline (Figure 2). Table 3 presents the technical specifications of the mentioned engine. The output power of the natural breathing engine changed in the range of 11 to 85 kW, according to the laboratory results.

**Table 3.** Geometric and functional characteristics of the natural breathing engine.

Engine type	Spark ignition
Engine volume (lit)	1.65
Number and arrangement of cylinders	4 linear cylinders
Engine compression ratio	11.2:1
Cylinder diameter (mm)	78.6
Piston stroke (mm)	86
Maximum engine power (kW)	85 at 6000 rpm
<b>Maximum engine torque (N.m)</b>	<b>155 in 3250 rounds</b>



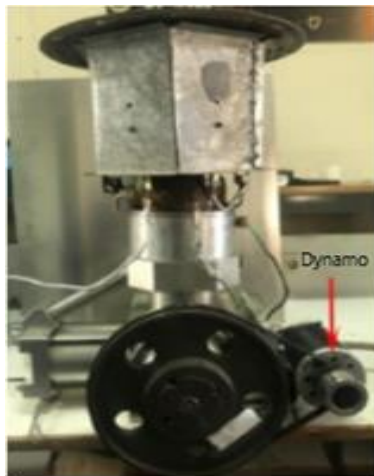
**Figure 2.** Laboratory engine. EF7 IPCO.

The engine tests were carried out at full load and sea level pressure under three different conditions:

- **TEAC1°C:** Air temperature: 25-40 Coolant Temperature: 90°C
- **TEAC2°C:** Air temperature: 50 Coolant Temperature: 90°C
- **TEAC3°C:** Air temperature: 50 Coolant Temperature: 105°

In order to calculate the starting power of the Stirling engine, these engines were started using an external power source (Figure 3). In this case, the amount of current and voltage consumed by the engine was 4.6 amps and 31 volts, respectively; so, the power consumption of a single motor can be obtained as

142.6 W. As it is common knowledge, compared to the compressor used in the car, the starting power of this engine is very low.

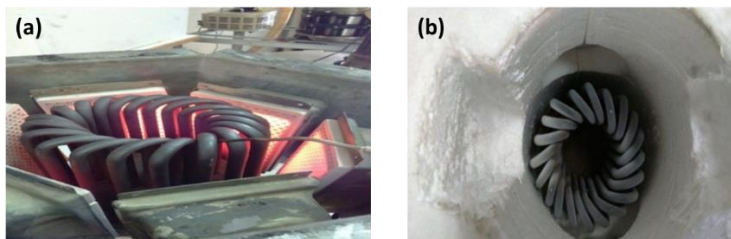


**Figure 3.** Dynamo and heat chamber in Stirling engine ST500- IPCO.

To estimate the parameters of the system first, the experiments were conducted under different conditions using biogas (Figure 4).

### **Result and discussion**

Table 4 provides the initial conditions for five tests conducted on the Sterling engine to produce cooling using helium gas. All experiments were carried out for 2 to 4 minutes. The water discharge from the copper coils was considered constant and equal for all five tests. The ambient temperature in all five tests was constant and equal to 25 degrees Celsius, and a temperature reader measured the cooling temperature. These tests were carried out to estimate fluid pressure in hot and cold engines. The power supply fixed the input power for a better comparison of the results.



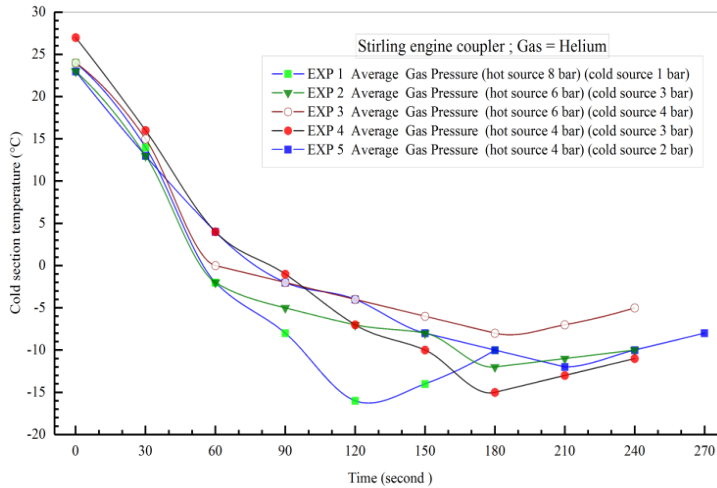
**Figure 4. a)** Stirling engine heating torch and hot engine temperature sensor, b) Cooling generation at the output of the Stirling Gamma engine.

**Table 4.** Different laboratory conditions for cooling production.

Test number	1	2	3	4 5
Power supply on time (minutes)	2	3	3	3 4
The medium gas pressure of the hot source (bar)	8	6	6	4 4
The medium gas pressure of the cold source (bar)	1	3	4	3 2
Working fluid	Helium	Helium	Helium	Helium

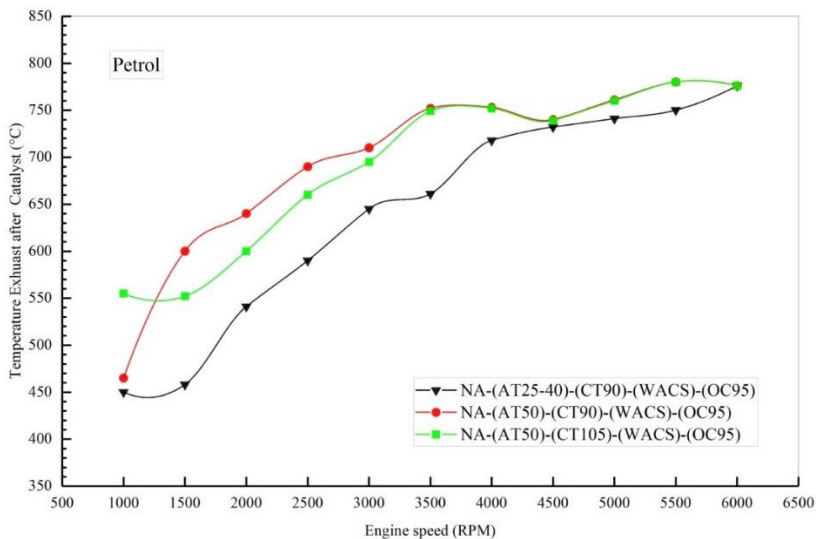
Figure 5 illustrates the temperature-time diagram for five experiments. The aforementioned findings were obtained through a series of experimental repetitions involving the coupling of Stirling engines. In this setup, one engine served as the hot source, while the other engine acted as the output and cold source. As can be observed, Experiment 1 achieved the lowest operating cooling temperature. The experimental results consistently demonstrated that increasing the average gas pressure in the hot source of the first engine, by up to 8 bars, and reducing the average gas pressure in the cold source of the second engine down to 1 bar (Experiment 1) had a significant impact. Under this condition, the temperature of the hot source reached 580 degrees Celsius, and the temperature of the cold part reached almost -16 degrees Celsius.

It was observed that factors such as the high temperature of the hot source and the utilization of a lightweight working fluid like helium played a crucial role in generating the desired cooling effect. These findings highlight the potential effectiveness of optimizing the gas pressure differentials and employing suitable working fluids to achieve efficient output cooling in Stirling engine applications.



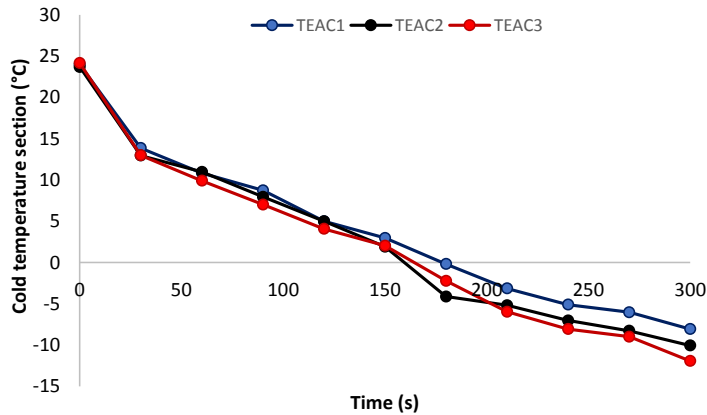
**Figure 5.** Temperature-time diagram for five experiments performed with helium gas at different pressures and motor Stirling coupling mode to produce cooling.

In the current research, using two Stirling engines, exhaust gas energy recovery for cabin cooling was presented as another solution. For this purpose, first, the temperature of the exhaust gases under different conditions was obtained. The results were obtained after installing the sensors at different points of the exhaust gases, i.e., before the catalyst, inside, and after the catalyst, according to the test conditions. Figure 6 depicts the temperature of exhaust gas in three gasoline fuel conditions.



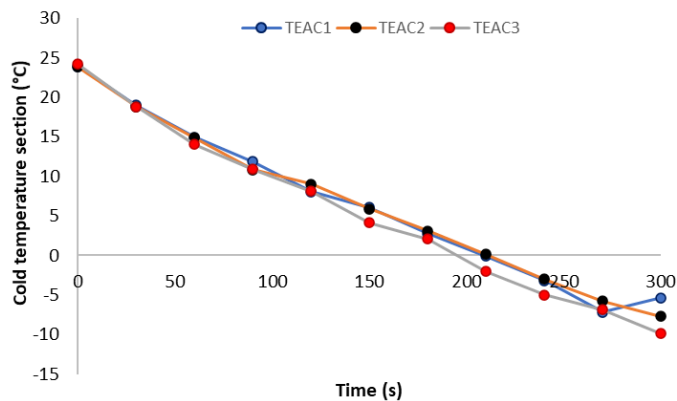
**Figure 6.** The temperature of the exhaust gases after the catalyst at different times of the engine with gasoline fuel.

Figure 7 demonstrates the cooling temperature under three tested conditions. As shown, the temperature of the minimum cooling fluid was in the range of -8 to -12 degrees Celsius after 300 seconds under different conditions. These results showed that cooling the car cabin can be ensured by using the developed system.



**Figure 7.** Temperature-time diagram for three conditions performed with gasoline engine

The results of the experiments conducted with CNG fuel under different conditions can be observed in Figure 8. As illustrated, the performance of the system designed with CNG gas was the same as that of gasoline fuel. The minimum coolant temperature ranged between -7 to -10 degrees under different conditions.



**Figure 8.** Temperature-time diagram for three conditions performed with CNG engine.

## Conclusion

In this research, using the combined cycle of the Stirling Gamma engine and the internal combustion engine, the heat loss of the exhaust gases was recovered to produce refrigerant. In cars, air conditioners are often used to cool the cabin and considering that the air conditioning system takes its power from the engine, it reduces the engine's efficiency. The air conditioning system consumes approximately 4 to 10 kilowatts of useful engine power in modern cars. Due to the high energy of exhaust gases, installing the heating part of the Stirling engine on the path of exhaust gases can turn this wasted energy into useful power to produce cooling. In summary, the following results were obtained from the present study.

- The starting power of the Stirling engine was approximately 142.6 W
- When the pressure of the hot source fluid is 8 bars, and the average pressure of the cold source is 1 bar, the lowest operating cooling temperature is achieved. Under this condition, the temperature of the hot source reached 580 degrees Celsius, and the temperature of the cold part reached approximately -16 degrees Celsius. These working pressures were used in subsequent tests performed by the internal combustion engine.
- The temperature of the exhaust gases in the engine under different conditions was in the range of 450 to 800 degrees Celsius, which showed that a large part of the loss in the engine was due to the heat dissipated by these gases.
- The results demonstrated that the use of the developed system in the path of the exhaust gases produces the desired cooling of the car. This system is a suitable replacement for the A.C. system.

## Disclosure statement and funding

The authors declare no potential conflicts of interest. The present study received no financial support from any organization or institution.

## Acknowledgment

We hereby express our gratitude and appreciation for the sincere cooperation of the management and experts of IPCO who cooperated in conducting tests and equipment and provided us with valuable information.

## References

- [1] Olabi, A. G., & Abdelkareem, M. A. (2022). Renewable energy and climate change. *Renewable and Sustainable Energy Reviews*, 158, 112111. <https://doi.org/10.1016/j.rser.2022.112111>

- [2] Fareed, Z., & Pata, U. K. (2022). Renewable, non-renewable energy consumption and income in top ten renewable energy-consuming countries: Advanced Fourier based panel data approaches. *Renewable Energy*, 194(4), 805-821. <https://doi.org/10.1016/j.renene.2022.05.156>
- [3] Shang, Y., Han, D., Gozgor, G., Mahalik, M. K., & Sahoo, B. K. (2022). The impact of climate policy uncertainty on renewable and non-renewable energy demand in the United States. *Renewable Energy*, 197, 654-667. <https://doi.org/10.1016/j.renene.2022.07.159>
- [4] Etghani, M. M., Shojaeefard, M. H., Khalkhali, A., & Akbari, M. (2013). A hybrid method of modified NSGA-II and TOPSIS to optimize performance and emissions of a diesel engine using biodiesel. *Applied Thermal Engineering*, 59(1-2), 309-315. <https://doi.org/10.1016/j.applthermaleng.2013.05.041>
- [5] Shojaeefard, M. H., Etghani, M. M., Akbari, M., Khalkhali, A., & Ghobadian, B. (2012). Artificial neural networks based prediction of performance and exhaust emissions in direct injection engine using castor oil biodiesel-diesel blends. *Journal of Renewable and Sustainable Energy*, 4(6), 063130. <https://doi.org/10.1063/1.4769200>
- [6] Rodionova, M. V., Poudyal, R. S., Tiwari, I., Voloshin, R. A., Zharmukhamedov, S. K., Nam, H. G., Zayadan, B. K., Bruce, B. D., Hou, H. J. M., & Allakhverdiev, S. I. (2017). Biofuel production: Challenges and opportunities. *International Journal of Hydrogen Energy*, 42(12), 8450-8461. <https://doi.org/10.1016/j.ijhydene.2016.11.125>
- [7] Joshi, G., Pandey, J. K., Rana, S., & Rawat, D. S. (2017). Challenges and opportunities for the application of biofuel. *Renewable and Sustainable Energy Reviews*, 79, 850-866. <https://doi.org/10.1016/j.rser.2017.05.185>
- [8] Hoang, A. T., Sirohi, R., Pandey, A., Nižetić, S., Lam, S. S., Chen, W-H., Luque, R., Thomas, S., Arici, M., & Pham, V. V. (2023). Biofuel production from microalgae: challenges and chances. *Phytochemistry Reviews*, 22(4), 1089-1126. <https://doi.org/10.1007/s11101-022-09819-y>
- [9] Babamiri, A., Gharib, M., & Ebrahimi, M. (2022). Multi-criteria evaluation of a novel micro-trigeneration cycle based on  $\alpha$ -type Stirling engine, organic Rankine cycle, and adsorption chiller. *Energy Conversion and Management*, 253, 115162. <https://doi.org/10.1016/j.enconman.2021.115162>
- [10] Katooli, M. H., Askari Moghadam, R., & Mehrpooya, M. (2022). Design optimization of a heat-to-cool Stirling cycle using artificial neural network. *International Journal of Energy Research*, 46(8), 10894-10906. <https://doi.org/10.1002/er.7890>
- [11] Wang, K., Sanders, S. R., Dubey, S., Choo, F. H., & Duan, F. (2016). Stirling cycle engines for recovering low and moderate temperature heat: A review. *Renewable and Sustainable Energy Reviews*, 62(2), 89-108. <https://doi.org/10.1016/j.rser.2016.04.031>
- [12] Saadon, S. (2018, December 11-14). *Possibility of Using Stirling Engine as Waste Heat Recovery – Preliminary Concept* [Conference session]. Institute of Physics Conference Series: Earth and Environmental Science, Kuala Lumpur, Malaysia. <https://dx.doi.org/10.1088/1755-1315/268/1/012095>
- [13] Güven, M., Bedir, H., & Anlaş, G. (2019). Optimization and application of Stirling engine for waste heat recovery from a heavy-duty truck engine. *Energy Conversion and Management*, 180, 411-424. <https://doi.org/10.1016/j.enconman.2018.10.096>
- [14] Sowale, A., Kolios, A. J., Fidalgo, B., Somorin, T., Parker, A., Williams, L., Collins, M., McAdam, E., & Tyrrel, S. (2018). Thermodynamic analysis of a gamma type Stirling

- engine in an energy recovery system. *Energy Conversion and Management*, 165, 528-540. <https://doi.org/10.1016/j.enconman.2018.03.085>
- [15] Durcansky, P., Nosek, R., & Jandacka, J. (2020). Use of Stirling Engine for Waste Heat Recovery. *Energies*, 13(16), 4133. <https://doi.org/10.3390/en13164133>
- [16] Romage, G., Jiménez, C., de Jesús Reyes, J., Zacarías, A., Carvajal, I., Jiménez, J. A., Pineda, J., & Venegas, M. (2020). Modeling and Simulation of a Hybrid Compression/Absorption Chiller Driven by Stirling Engine and Solar Dish Collector. *Applied Sciences*, 10(24), 9018. <https://doi.org/10.3390/app10249018>
- [17] Ramesh, U., & Kalyani, T. (2012). Improving the efficiency of marine power plant using Stirling engine in waste heat recovery systems. *International Journal of innovative research and development*, 1(10), 449-466. [https://www.internationaljournalcorner.com/index.php/ijird\\_ojs/article/view/132921](https://www.internationaljournalcorner.com/index.php/ijird_ojs/article/view/132921)
- [18] Laazaar, K., & Boutammachte, N. (2020). New approach of decision support method for Stirling engine type choice towards a better exploitation of renewable energies. *Energy Conversion and Management*, 223, 113326. <https://doi.org/10.1016/j.enconman.2020.113326>
- [19] Hachem, H., Gheith, R., Aloui, F., & Ben Nasrallah, S. (2018). Technological challenges and optimization efforts of the Stirling machine: A review. *Energy Conversion and Management*, 171(2), 1365-1387. <https://doi.org/10.1016/j.enconman.2018.06.042>
- [20] Snyman, H., Harms, T., & Strauss, J. (2008). Design analysis methods for Stirling engines. *Journal of Energy in Southern Africa*, 19(3), 4-19. <https://doi.org/10.17159/2413-3051/2008/v19i3a3329>
- [21] Naseri, A., Fazlikhani, M., Sadeghzadeh, M., Naeimi, A., Bidi, M., & Tabatabaei, S. H. (2020). Thermodynamic and Exergy Analyses of a Novel Solar-Powered CO<sub>2</sub> Transcritical Power Cycle with Recovery of Cryogenic LNG Using Stirling Engines. *Renewable Energy Research and Applications*, 1(2), 175-185. <https://doi.org/10.22044/rera.2020.9282.1023>
- [22] Najafi Amel, A., Kouravand, S., Zarafshan, P., Kermani, A. M., & Khashehchi, M. (2018). Study the Heat Recovery Performance of Micro and Nano Metfoam Regenerators in Alpha Type Stirling Engine Conditions. *Nanoscale and Microscale Thermophysical Engineering*, 22(2), 137-151. <https://doi.org/10.1080/15567265.2018.1456581>
- [23] Heywood, J. B. (2018). *Internal Combustion Engine Fundamentals* (2nd ed.). McGraw-Hill Education. <https://www.accessengineeringlibrary.com/content/book/9781260116106>
- [24] Lee, G. H., & Yoo, J. Y. (2000). Performance analysis and simulation of automobile air conditioning system. *International Journal of Refrigeration*, 23(3), 243-254. [https://doi.org/10.1016/S0140-7007\(99\)00047-X](https://doi.org/10.1016/S0140-7007(99)00047-X)
- [25] Krishnaswamy, H., Muthukrishnan, S., Thanikodi, S., Arockiaraj, G. A., & Venkatraman, V. (2020). Investigation of air conditioning temperature variation by modifying the structure of passenger car using computational fluid dynamics. *Thermal Science*, 24(1B), 495-498. <https://doi.org/10.2298/TSCI190409397K>
- [26] Izadiamoli, N., & Sayyaadi, H. (2018). Conceptual design, optimization, and assessment of a hybrid Otto-Stirling engine/cooler for recovering the thermal energy of the exhaust gases for automotive applications. *Energy Conversion and Management*, 171, 1063-1082. <https://doi.org/10.1016/j.enconman.2018.06.056>

- [27] Aladayleh, W., & Alahmer, A. (2015). Recovery of Exhaust Waste Heat for ICE Using the Beta Type Stirling Engine. *Journal of Energy*, 2015(1), 495418. <https://doi.org/10.1155/2015/495418>
- [28] Batooei, A., & Keshavarz valian, A. (2016). Thermal analysis and efficiency optimization of an Otto-Stirling combined cycles with SI engine exhaust heat recovery. *Modares Mechanical Engineering*, 16(2), 147-158. <http://mme.modares.ac.ir/article-15-8350-en.html>
- [29] Amarloo, A., Keshavarz, A., Batooei, A., & Alizade Nia, S. (2017). Thermodynamic analysis of performance parameter of a novel 3 cylinder Stirling engine configuration. *Modares Mechanical Engineering*, 16(10), 448-458. <http://mme.modares.ac.ir/article-15-3190-en.html>
- [30] Hasanpour Omam, S. (2021). Exhaust waste energy recovery using Otto-ATEG-Stirling engine combined cycle. *Applied Thermal Engineering*, 183(2), 116210. <https://doi.org/10.1016/j.applthermaleng.2020.116210>
- [31] Hassanzadeh, E., aliehyaei, M., Jafari Mehrabadi, S., Mohammadi, A., & Mazaheri, H. (2020). Experimental investigation on the gamma model Stirling engine for cooling production using various gases. *The Journal of Engine Research*, 59(59), 17-28. [https://www.engineerresearch.ir/article\\_697867\\_en.html?lang=en](https://www.engineerresearch.ir/article_697867_en.html?lang=en)