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RESEARCH ARTICLE

Non-combustion non-solar deployment characterization of a free-piston Stirling engine to integrate with an exothermic reactor

[version 1; peer review: 1 approved, 1 approved with reservations]

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Abstract

Background: A small 1 kW free-piston β type Stirling engine was tested for its feasibility of integration with an exothermic reactor under the EU funded research project SOCRATCES (GA 727348). The engine's heat receptor was minimally modified to adapt it to the reactor's integration needs, introducing, instead of a combustion chamber, a CFD-optimized hooded enclosure. The open-loop configuration also included a small plate heat exchanger acting as a recuperator. The study attempted to investigate the performance of the Stirling engine under these non-combustion non-solar deployment conditions, focusing on conversion efficiency and thermal loss.
Methods: A number of tests were run under different temperatures and flowrates to assess the engine's response. Temperature, power, pressure and flowrate were measured at points of interest.
Results: It was found that the engine is able to operate at efficiencies comparable to that of gasoline engines at much lower working fluid temperatures. It was possible to demonstrate, with the aid of a downstream recuperator, that the system in an open-loop configuration can minimize thermal loss significantly, virtually eliminating it in some cases.
Conclusions: The Stirling engine appears to be a sound choice, in terms of conversion efficiency, at comparatively low temperatures, to be integrated with an exothermic reactor, at least at small-scale applications.

Keywords

Stirling, exothermic, reactor, performance, non-combustion

Open Peer Review

Approval Status ✓ ?

	1	2
version 1 21 Dec 2021	✓ view	? view

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Any reports and responses or comments on the article can be found at the end of the article.



This article is included in the Horizon 2020 gateway.



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Author roles: Eusha M: Conceptualization, Data Curation, Formal Analysis, Investigation, Methodology, Project Administration, Software, Supervision, Validation, Visualization, Writing – Original Draft Preparation, Writing – Review & Editing; **Schulz W**: Investigation, Software, Validation; **Schumacher G**: Data Curation, Investigation, Validation; **Mir FR**: Project Administration, Supervision, Validation; **Schories G**: Conceptualization, Funding Acquisition, Project Administration, Supervision

Competing interests: No competing interests were disclosed.

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Introduction

SOCRATCES is an EU-funded project investigating the feasibility of calcium-looping in renewable energy storage[1]. The core concept includes capturing solar energy by its application in breaking down $CaCO_3$ into CaO and CO_2, followed by an exothermic reunification of the products to regenerate $CaCO_3$[2]. The heat liberated in the second of these two steps in a reactor named carbonator[3] is then utilized to drive a power cycle. Calcium-looping itself is a proven technology[4], with the carbonation and calcination reactor design being at the center of focus[5].

In the pilot 10 kW_{th} capacity installation of SOCRATCES in Seville, Spain, a small Stirling engine was considered for integration. The engine was a 1 kW_e free-piston β Stirling machine manufactured by Microgen Engine Corporation[6]. To the best of the authors' knowledge, it is the first instance of such a combination, that of a Stirling engine with an exothermic reactor. Barring solar applications, Stirling engines are commonly deployed with a burner in which a fuel is consumed to provide the required thermal power[7], the dominant non-combustion application being that of power generation from waste heat[8,9]. Therefore, the idea of combining a Stirling engine with the exothermic reactor is unique. While many different power cycles were considered for implementation[10], the Stirling cycle was chosen for SOCRATCES for its novelty and uniqueness.

Experimental setup

As the deployment involved no combustion, it was essential to modify the engine's external construction to facilitate integration. The engine's heater is a dome with radially protruding rows of fins. It was decided, after extensive computational fluid dynamic analysis of the heat transfer, that it would be most feasible to feed the hot air received from the carbonator in an opposed-blast configuration, which involves bifurcating the flow and introducing it to the engine's heater in two centrally-opposite feeders.

The process and instrumentation diagram of the experimental setup has been presented in Figure 1. The Stirling engine receives hot air carrying the heat liberated during the exothermic reaction in the carbonator and absorbs a fraction of the available energy. The "exhaust" is then passed on to a heat exchanger which preheats the input of fresh air to the carbonator. It has to be noted that the cycle is ideally expected to be closed; however, for economic and technical conveniences, given that it was an experimental pilot scale plant, it was kept open. A small pump circulated a cooling fluid (water) to cool the cold side of the engine, the heat finally being rejected to the atmosphere with the aid of a fan-powered radiator. Temperatures, pressures and flow rates are measured at the points shown in the P&ID. A three-dimensional CAD model of the setup has been shown in Figure 2.

The engine was tested using two high temperature electric heaters to simulate the carbonator. Two blowers were used to force atmospheric air through the heaters at variable flowrates. The temperature were controlled separately using controllers. Thus, it was possible to achieve virtually any combination, within a particular range, of temperature and flowrate to be fed to the Stirling engine. It has to be mentioned here that the feeder and the enclosure were heavily insulated to minimize heat loss. Figure 3 shows the power block in its late stage of construction with the Stirling engine mounted on a frame. The Stirling engine's bifurcating inlet can be seen. The plate heat exchanger is on top of the frame connected to the enclosure outlet. In Figure 4, the heaters deployed in initial tests without insulation can be seen. The container houses the engine along

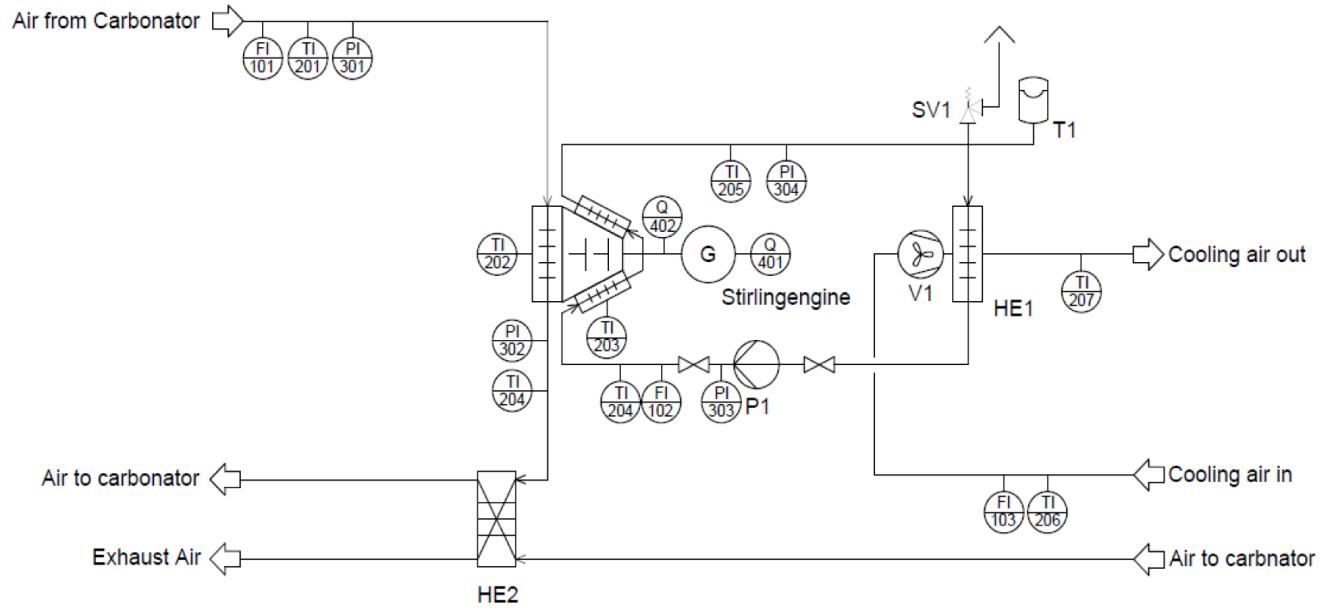


Figure 1. P&ID of the experimental setup.

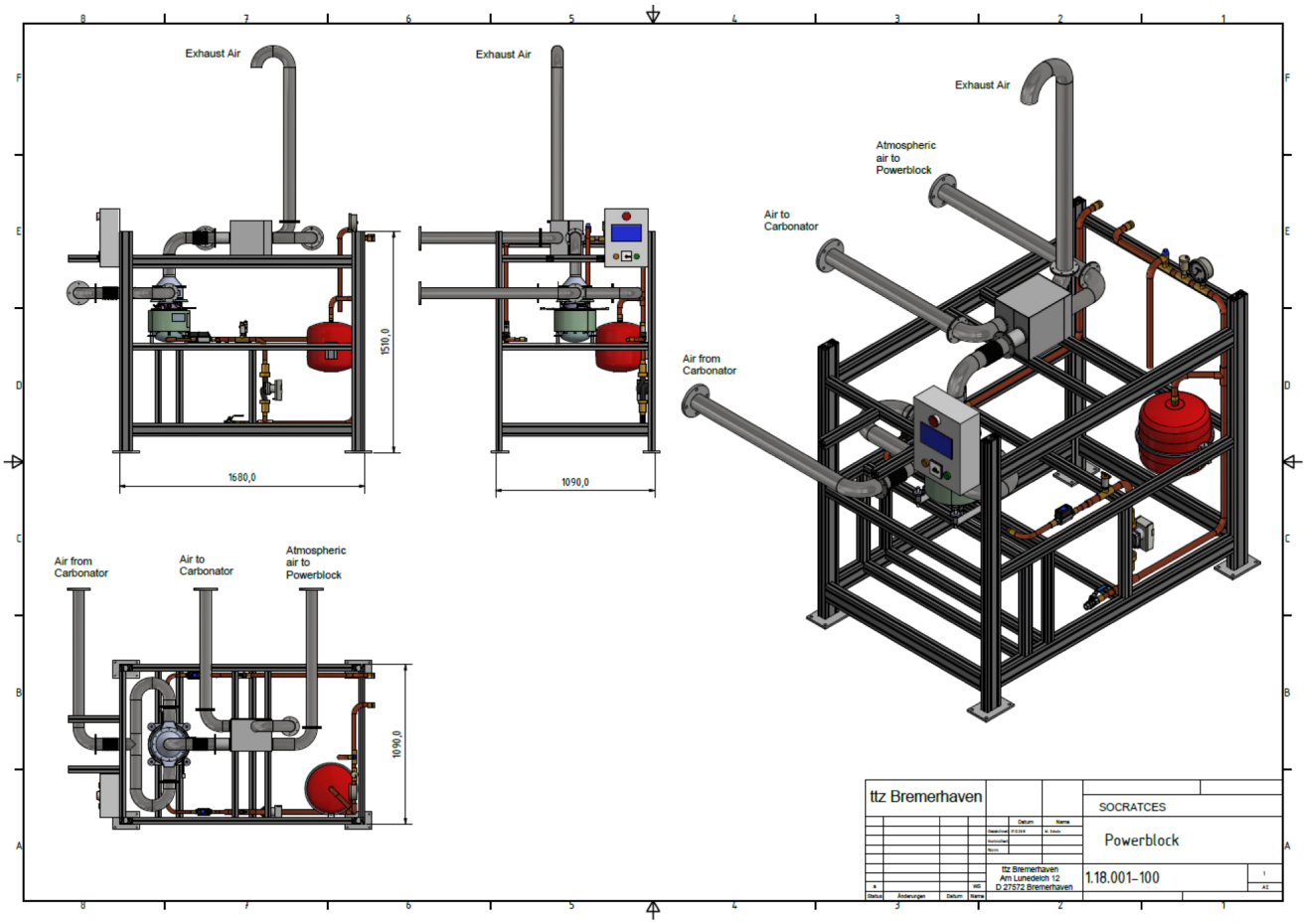


Figure 2. **SOCRATCES power block CAD model showing components and connections (uninsulated).**



Figure 3. **Power block in its late stage of construction.**



Figure 4. **Heaters deployed in testing the engine.**

with the controls. The structure outside has the blowers and heaters mounted on it. The blower seen here is sending air to the heat exchanger to be preheated. The radiator can be seen on top of the container.

The installed recuperator was a Bosal® (Vianin, the Netherlands) P5 thin-walled heat exchanger able to operate at an effectiveness of about 80–90% within the range of flow specified by the carbonator[11]. It has a welded and compact plate modular design. A 6.46 kW axial fan-powered Anthermo® (Kamen, Germany) radiator was used to cool the cold side of the engine. The cooling pump was a Wilo-Yonos® model able to generate a maximum flowrate of 13 l/min. Both the radiator fan and the pump had speed control functions to allow variation of flowrates. The heaters used were Herz® (Neuwied, Germany) XL92HT (15 kW, 400 VAC). They were fed with air using high-pressure Herz® (Neuwied, Germany) blowers (HD 140).

Methods

The engine was fed with flowrates at temperatures expected to be encountered from the carbonator. It was noticed that it took about a quarter of an hour for the system to stabilize at any combination of temperature and flowrate. These combinations were achieved using the controllers on the heaters (temperatures) and blowers (flowrates). When the steady-state was attained, all the temperatures, pressures, flowrates and the power produced by the Stirling engine was recorded using the installed sensors shown in the P&ID (Figure 1). When the temperature and the flowrate, either separately or together, were altered, the engine responded with a shift in its power production. The electric power climbed with time until the rate of increase became negligible, indicating steady-state.

Several Key Performance Indicators (KPIs) were considered in the evaluation of the performance of the system. These are described below.

KPI-1 Power production

The electricity produced is directly read from the wattmeter mounted on the control box that accompanies the engine.

KPI-2 Energy provided to the enclosure

The difference in enthalpy between the inlet and the outlet indicates how efficiently heat is absorbed by the Stirling engine. It indicates the heat flux in the direction of the engine core.

$$\Delta E_{enclosure} = m_{in}(h_{in} - h_{out}) \tag{1}$$

KPI-3 Logarithmic mean temperature difference (LMTD)

The heat recovery efficiency of the recuperator is indicated by the LMTD of the heat exchanger.

$$LMTD = \frac{\Delta T_{hot} - \Delta T_{cool}}{ln\Delta T_{hot} - ln\Delta T_{cool}} \tag{2}$$

KPI-4 Heat lost

Efficiency of the preheating process in the integration scheme is reflected in the heat lost. The fluid in this case is air.

$$h_{lost} = m_{in}\, c_p (T_{stirling\ out} - T_{carbonator\ in}) \tag{3}$$

KPI-5 Heat rejected

The cooling performance of the Stirling engine is measured by the amount of heat rejected to the atmosphere. The fluid in this case is water.

$$h_{rejected} = m_{coolant}\, c_{p,coolant} (T_{out,coolant} - T_{in,coolant}) \tag{4}$$

KPI-6 Conversion efficiency

Knowing the power produced and the enthalpy difference across the Stirling engine, the conversion efficiency can be computed by dividing the former by the latter.

Results and discussion

The parameters studied are identified in Table 1. Collected experimental data and the derived variables are tabulated in Table 2 and Table 3.

The Stirling engine's power was found to be a linear function of the temperature of the head of the Stirling engine (Figure 5). This is consistent with the characteristics reported by the manufacturer. The engine begins to move at a temperature of approximately 180 °C, the minimum head temperature

Table 1. Variables and parameters.

T_a	Ambient temperature
m_{in}	Hot air flowrate to the engine
T_{in}	Temperature of the hot air to the engine
T_{out}	Temperature of the hot air exiting the engine
T_{head}	Engine head temperature
m_w	Cooling water mass flowrate
$T_{w,in}$	Temperature of incoming cooling water
$T_{w,out}$	Temperature of outgoing cooling water
m_c	Carbonator blower flowrate
$T_{c,in}$	Temperature of air delivered to the carbonator
T_r	Temperature of rejected hot air
P	Power
CFS	Cooling fan speed
KPI1	Power
KPI2	Enclosure energy
KPI3	Log mean temperature difference of the heat exchanger
KPI4	Heat lost
KPI5	Heat rejected
KPI6	Conversion efficiency

Table 2. **Measured experimental data.**

No.	T_a (°C)	m_{in} (kg/s)	T_{in} (°C)	T_{head} (°C)	T_{out} (°C)	m_w (l/min)	$T_{w,in}$ (°C)	$T_{w,out}$ (°C)	m_c (kg/s)	$T_{c,in}$ (°C)	T_r (°C)	CFS (RPM)
1	17	0.013	470	250	358	13	32.2	33.6	0.0345	136	31	1200
2	17	0.013	470	250	358	13	32.2	33.6	0.0121	242	49	1200
3	17	0.013	530	298	399	13	33	34.5	0.0345	155	39	1200
4	17	0.013	530	298	399	13	33	34.5	0.0121	279	83	1200
5	17	0.013	603	350	438	13	33	34.9	0.0121	329	102	1200
6	17	0.013	603	350	438	13	33	34.9	0.0345	199	56	1200
7	17	0.0163	351	199	267	13	30	31.3	0.0345	122	34	1200
8	17	0.0163	351	199	267	13	30	31.3	0.0121	218	49	1200
9	17	0.0163	437	254	335	13	30	31.5	0.0121	291	53	1200
10	17	0.0163	437	254	335	13	30	31.5	0.0345	161	31	1200
11	17	0.0163	522	316	400	13	32	34.0	0.0345	155	31	1200
12	17	0.0163	522	316	400	13	32	34.0	0.0121	335	150	1200
13	13	0.026	519	358	416	13	26.9	29.2	0.0345	245	43	1200
19	13	0.0326	363	246	311	13	18.7	20.8	0.0121	281	153	1200
20	13	0.0326	363	246	311	13	18.7	20.2	0.0345	235.6	63	1200
21	13	0.0326	465	325	403	13	24.6	26.2	0.0345	283.8	63	1200
22	13	0.0326	465	325	403	13	24.6	26.2	0.0121	371.5	224	1200
23	13	0.0326	556	393	478	13	26.6	28.7	0.0121	436.4	266	1200
24	13	0.0326	556	393	478	13	26.6	28.7	0.0345	351.6	90	1200

Table 3. **"Key Performance Indicators".**

No.	KPI1 (W)	KPI2 (kW)	KPI3 (N/A)	KPI4 (kW)	KPI5 (kW)	KPI6 (%)
1	173	1.49	205.77	2.94	1.26	11.65
2	173	1.49	264.78	1.54	1.26	11.65
3	310	1.74	231.53	3.24	1.40	17.85
4	310	1.74	288.16	1.59	1.40	17.85
5	448	2.19	323.85	1.45	1.69	20.48
6	448	2.19	269.75	3.17	1.69	20.48
7	15	1.40	160.59	2.41	1.21	1.07
8	15	1.40	209.38	0.81	1.21	1.07
9	190	1.70	277.98	0.73	1.33	11.20
10	190	1.70	214.13	2.89	1.33	11.20
11	365	2.03	234.87	4.07	1.78	17.99
12	365	2.03	282.64	1.08	1.78	17.99
13	510	2.73	296.94	4.53	2.10	18.67

No.	KPI1 (W)	KPI2 (kW)	KPI3 (N/A)	KPI4 (kW)	KPI5 (kW)	KPI6 (%)
19	221	1.73	208.18	1.00	1.90	12.78
20	221	1.73	235.07	2.51	1.40	12.78
21	425	2.06	304.09	3.96	1.45	20.61
22	425	2.06	258.44	1.05	1.45	20.61
23	636	2.59	305.61	1.38	1.87	24.52
24	636	2.59	362.74	4.20	1.87	24.52

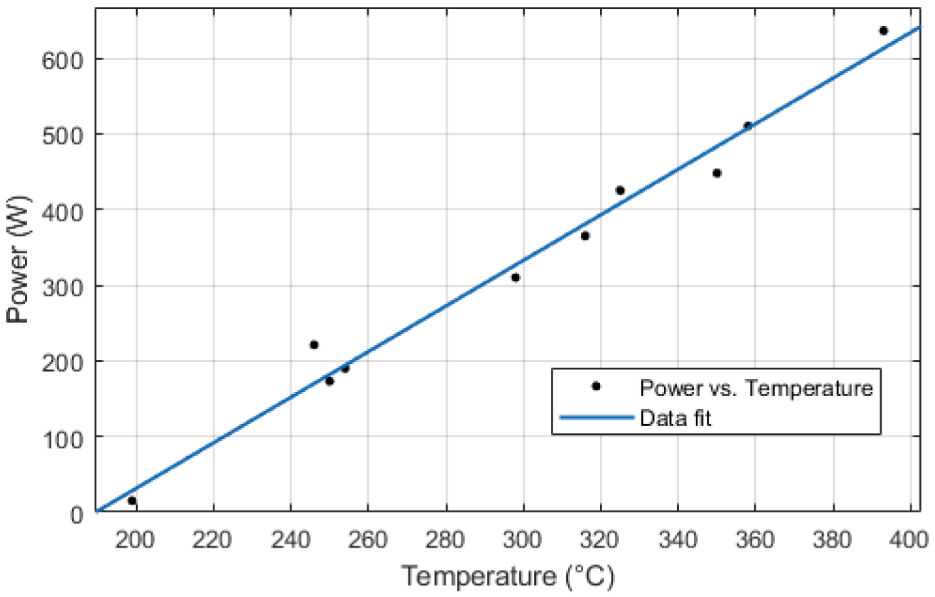


Figure 5. Power versus head temperature plot.

for electricity generation. The electric power and the head temperature are related by the following empirical relationship:

$$P = 3.01T_{head} - 571;\ 400 \geq T_{head} \geq 180 \quad (5)$$

The head temperature can be empirically related, using a logistic function, for the sake of operational convenience of the carbonator or any other heat source, to the temperature and the flowrate of the incoming heating fluid.

$$T_{head}(m_{in}, T_{in}) = \frac{T_{in}}{1+\exp(0.056\, m_{in} T_{in})};\ 400 \geq T_{in} \geq 600, 0.04 \geq m_{in} \geq 0.02 \quad (6)$$

A surface plot of this relationship is given in Figure 6.

Combining Equation 5 and Equation 6, we get

$$P(m_{in}, T_{in}) = \frac{3.01\, T_{in}}{1+\exp(0.0048\, m_{in} T_{in})} - 571;\ 400 \geq T_{in} \geq 180, 0.032 \geq m_{in} \geq 0.013 \quad (7)$$

This expression will be useful in the integration of the power block with the carbonator as it will be possible to estimate the power output as a function of the flowrate and the temperature using a simplistic relationship. While extrapolation beyond the recommended range is possible, some inaccuracy should not be unexpected. It is also important to mention that as the system takes a while to reach the steady-state, some inaccuracy is in the model is unavoidable.

Coolant rate variations' impact on power production was tested. The system's response was an increase in the coolant temperature without a significant impact on the electrical power. The power fell only slightly when the flowrates was below 10 l/min.

Perhaps the most interesting observation apparent in these tests is that the Stirling engine has an attractive thermal to

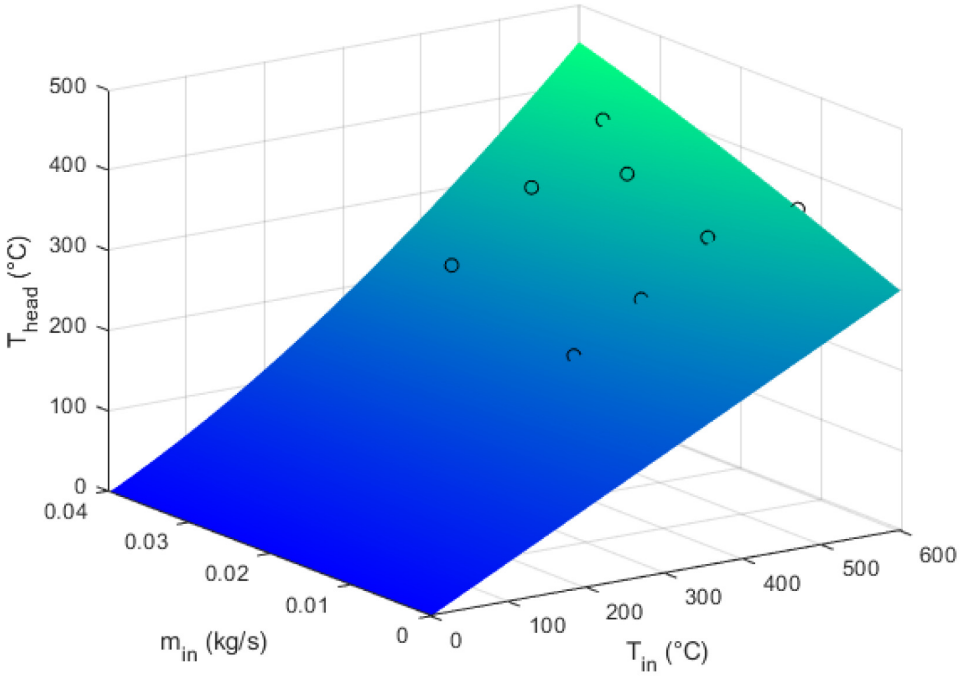


Figure 6. The head temperature as a function of the mass flowrate and the incoming temperature.

electricity conversion efficiency (25%). While it would have been ideal had it been able to absorb more thermal power, it is noted that the installation of a downstream heat exchanger alleviates the difficulty considerably. The heat exchanger is able to send out significantly preheated air to the reactor. This is obvious from the data collected in the 23rd test (Table 2) where it is seen that the heat exchanger, one with a very high effectiveness, is sending out preheated air at 436 °C to the carbonator. This heat, of course, can be used as process heat for industrial applications as well. It can be thus said that this implementation is remarkably efficient. One also has to take note that this efficiency is achieved at a comparatively much lower working fluid temperature. Even though internal temperatures were not measured in this test, it is clear that they would be much lower than the heating fluid's temperature. For example, in the 23rd recorded test, a heating fluid temperature of 556 °C was able to reach an efficiency of near 25%. Since about 2.59 kW of heat was injected into the interior, it is clear that a substantial temperature difference existed between the heating and the working fluids.

Since the SOCRATCES concept is environmentally completely safe, its combination with the Stirling cycle, the latter being emission free, is thus revealed to be extremely interesting, warranting future investigations. While the study reported in this paper used a pair of heaters to assess the feasibility of integration with the carbonator, it would be interesting to study the engine's response as a function of the reactor parameters, such as reactant flowrate, temperature and pressure. In addition, optimization of the design of the engine core to enhance compatibility with the exothermic reactor can also be of great interest.

Data availability

Underlying data

All data underlying the results are available as part of the article and no additional source data are required.

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Version 1

Reviewer Report 15 November 2022

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Leszek Remiorz
Silesian University of Technology, Gliwice, Poland

The article concerns an interesting application with a Stirling engine manufactured by Microgen Engine Corporation associated with an exothermic reactor. This connection itself seems to be, in my opinion, an exciting solution.

My comments on the discussion are as follows:

1) Figure 1 does not describe the parameters that are later included in the tables (e.g. in Table 2).

2) Figure 2 is a CAD drawing. As such, it doesn't match the others (in my opinion). Each of the devices in this drawing should be described separately. The table and border don't add anything, so why were they placed?

3) Even though the motor is known, it is worth giving at least its efficiency characteristics provided by the manufacturer.

4) The information given in Table 2 should be presented in graphs, at least the achieved efficiencies.

5) Obtained efficiencies (Table 2) should be compared with Carnot efficiencies obtained in the same temperature ranges. This will allow you to enrich the final conclusions. The results will be more readable.

6) Figure 6 should be drawn as sections for successive mass flux values (isolines for m=0.01, 0.02..., kg/s).

7) The given literature is worth supplementing.

Is the work clearly and accurately presented and does it cite the current literature?

Yes

Is the study design appropriate and does the work have academic merit?
Partly

Are sufficient details of methods and analysis provided to allow replication by others?
Partly

If applicable, is the statistical analysis and its interpretation appropriate?
I cannot comment. A qualified statistician is required.

Are all the source data underlying the results available to ensure full reproducibility?
Partly

Are the conclusions drawn adequately supported by the results?
Partly

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: Stirling engines, thermoacoustic phenomenon, measurement systems, hydrogen, renewable energy

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard, however I have significant reservations, as outlined above.

Reviewer Report 02 February 2022

https://doi.org/10.21956/openreseurope.15499.r28396

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HÜSEYİN SERDAR YÜCESU
Faculty of Technology, Department of Automotive Engineering, Gazi University, Ankara, Turkey

One of the strongest aspects of this article is the generation of mechanical power with a renewable energy source.

Secondly; The basic concept involves capturing solar energy through the application of splitting CaCO3 into CaO and CO2, followed by exothermic recombination of products to regenerate CaCO3. In the second of these two steps, the heat released in a reactor called a carbonator is then used to drive a power cycle. The calcium cycle itself is a proven technology to be the focus of carbonation and calcination reactor design .These two aspects make the article stand out.

Information should be given about the beta-type stirling engine used in this study. It is useful to give some parameters and data that affect the performance of the engine in order to make a correct evaluation.

1. For example, does this engine have a crank-connecting rod mechanism or is it a free-piston stirling engine?

2. Is a regenerator used?

3. What is the working gas (air, helium etc.)?

4. What is the working gas pressure?

5. What are the maximum and minimum volume ratios?

6. The diameters of the work piston and the displacer piston should be given?

7. The operating frequency of the motor should also be given.

Is the work clearly and accurately presented and does it cite the current literature?
Yes

Is the study design appropriate and does the work have academic merit?
Yes

Are sufficient details of methods and analysis provided to allow replication by others?
Yes

If applicable, is the statistical analysis and its interpretation appropriate?
Yes

Are all the source data underlying the results available to ensure full reproducibility?
Yes

Are the conclusions drawn adequately supported by the results?
Yes

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: Internal Combustion Engines, Stirling Engines, Fuels, Combustion and Exhaust Emissions

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard.