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Research Article

Energy Efficiency Audit Based on Wireless Sensor and Actor Networks: Air-Conditioning Investigation

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This paper investigates the energy performance of new design air-conditioning system combined with energy audit in KSA governmental building since air conditioning is responsible for more than 60 % of electricity consumption. Alternative solutions are provided. Based on the results, the old conditioners will be replaced for 113 rooms in three floors of the MUAB. The applied methodology uses Wireless Sensor and Actuator Networks (WSAN) for sensing and measuring technique characteristics of the conditioners and compares them with the ones available on the market, which were selected according to ASHRAE Standard 62.1-2007 specified by the manufacturers. Energy balance examination proves that operational conditioners have greater electric consumption and power factor comparing to the known standards. Energy audit applied in the MUAB provided a saving of 10% in the average consumption of electric energy. More than that an exploration is performed to insert Stirling engine in air conditioning cycle proving that it can be a promoted solution and can reduce significantly energy consumption; an alpha Stirling engine has been tested numerically for the same temperature and pressure reigned in the refrigeration cycle proving that it can work with energy efficiency around 42%.

1. Introduction

Energy necessities have amplified weirdly according to the prompt expansion of the global economy. The awareness that fossil fuel possessions required for the generation of energy are becoming scarce and the climate change is toughly connected to carbon emissions leads engineers and researchers to give more consideration and concern to energy saving and environmental protection.

Table 1 includes the temperature, the humidity, and the wind speed data collected in different 20 stations in Saudi Arabia in 2006 which demonstrate that wind energy can be a promising source of renewable energy in KSA as shown in this table which mentions the maximum wind velocity extents at 16.5 m/s in Guriat station, and it is well known that power is a function of the cube of the wind velocity. The measured wind speeds at all the stations are averaged; the maximum wind speed reaches up to 16.5 m/s in Guriat station, while the minimum wind speed is 7.7 m/s in Gizan. The power available from the wind is a function of the cube of the wind speed. The rising electric energy request and current crisis of the energetic sector lead to meaningful increase of the electric energy. The most consuming part of electricity comes from air conditioning which reaches around 60 % of the total building consumption. In order to lessen electric energy costs, several researchers and engineers have developed and investigated diversities of theoretical and experimental model of air conditioning, and many prototypes have been designed and built [1–7]. On the other hand, the community behavior should be changed and required two foundations: (i) habit change when using electric equipment and (ii) technology innovation replacing old equipment by efficient equipment [8].

Replacement of the ineffective apparatus as traditional air conditioning by other energetic efficient technologies is highly requested. Air conditioners are the primary energy consumer in the KSA due to the hot weather (70% of the year). Figure 1 shows the temperature changes over month

Table 1: Weather data from meteorological station in KSA.

S. N.	Station	Pressure (mb)	Rain (mm)	temperature Mean	temperature min	temperature max	Relative humidity (%) Mean	Wind speed mean	Wind speed max
1	Riyadh	942.4	70.0	26.7	0.0	47.8	26.2	3.09	8.8
2	Jeddah	1007.3	55.0	28.2	9.8	49.0	61.4	3.71	11.3
3	Dhahran	1006.7	125.0	26.4	25	49.0	52.5	4.38	11.8
4	Guriat	954.8	36.5	19.5	-8.0	47.6	43.5	4.22	16.5
5	Al jouf	936.1	34.0	22.0	-6.0	46.7	32.1	4.02	15.9
6	Gizan	1007.7	90.0	30.2	11.8	45.3	68.4	3.24	7.7
7	Abha	794.0	119.9	18.6	0.0	34.1	54.6	2.94	14.9
8	Tabouk	926.0	36.0	22.1	-3.5	46.4	34.0	2.73	15.5
9	Yanbu	1007.8	73.2	27.7	4.7	49.0	53.8	3.76	10.3
10	Hail	901.3	47.5	22.4	-9.4	44.5	33.2	3.24	10.8

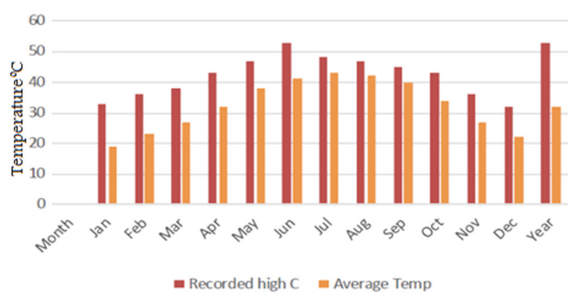

Figure 1: Temperature data for Riyadh, Saudi Arabia [8].

during one year. The average of high recorded temperature is 42.6 Celsius and the average of the temperature averages is 32.2 Celsius.

Due to the complex execution, the conditioners retrofit is a significant challenge due to the high cost and the implementation of alternative solutions such as saving plans and power consumption scheduling solutions. Conditioning technologies have improved in the last years. More efficient conditioners are manufactured with a high-energy efficiency. Moreover, environmental pollution of air conditioning should be concerned and the noise level the air conditioner emits is increasingly important; for this reason introducing Stirling engine in the refrigerator cycle will reduce vibration and noise [9]. Split conditioners consume a very huge amount of power and are also characterized by low quality production [10]. In order to revise, modify, and enforce the Saudi standard SASO 2663/2012, the technical team of the Saudi Energy Efficiency Program adopted an approach based on Consensus and Unanimity.

On the other hand, a pure mechanical engineering solution should be applied to air conditioning to reducing energy consumption as replacing compressor by Stirling engine. Stirling engines are significant for low pollution and small noise, since the vibration is very low, with higher durability, simple structure, and capability to self-start; for these reasons, it can be used for air conditioning. Being a regenerative external heated engine with higher performance, it is characterized by an extensive variety of energy resources and it can be a motivated solution for energy consumption in air conditioning [11–16].

D.G. Thombare et al. [17] deliver and investigate the important efforts taken for the development of the Stirling cycle engine and techniques used for engine analysis. They conclude that for fruitful operation of engine system with higher efficiency a cautious design of heat exchangers, appropriate assortment of drive mechanism, and engine configuration are essential. Recently Stirling cycle engine working with relatively low temperature with air of helium as working fluid is potentially attractive engines of the future air conditioning particularly in case of low-temperature differential Stirling engines with alpha configuration. Variations of engine torque, shaft power, and brake thermal efficiency at various heat inputs with engine speed and engine performance are presented by B. Kongtragool et al. [18] who designed and made a gamma-configuration for low-temperature differential Stirling engine; they verified the engine with numerous heat suppliers. They conclude that the engine performance will increase with increasing heat input. The engine torque, shaft power, brake thermal efficiency, speed, and heater temperature also increase with increasing heat input. P. Puech et al. [19] provide a theoretical exploration on the thermodynamic analysis of a Stirling engine with linear and sinusoidal variations of the component volume; they show that the dead volume strongly amplifies the imperfect regeneration effect, and the engine performance with perfect regeneration does not depend on the regenerator dead volume. The mean pressure power formula is very adequate and appropriate for the calculation of Stirling engine especially a gamma-configuration, low-temperature differential Stirling engine power output as shown by S. Wongwises et al. [20]; in their study thy provide a study on power output determination of a gamma-configuration Stirling engine with low-temperature differential. B. Cullen et al. [21] developed a model for theoretical decoupled Stirling cycle engine that is to be used as a tool for analysis of the ideal Stirling cycle engine and the limits on its real-world realization.

This paper will discuss two ways for reducing air-conditioning consumption; in the first part authors will

Table 2: Energy classification and concert requirements for air conditioners.

Air Conditioner appliance type	Cooling capacity limit (CC) (Btu/h) At testing conditions T1 (35°C)	Mandatory EER (Btu/h)/watt **Phase 1:** 7 September 2013 T1 (35°C)	T3 (46°C)	Mandatory EER (Btu/h)/watt **Phase 2:** 1 January 2015 T1 (35°C)	T3 (46°C)
Window type	CC <18,000	8.5	6.12	9.8	7.06
	18,000 ≤CC< 24,000	8.5	6.12	9.7	6.98
	CC ≥ 24,000	8.5	6.12	8.5	6.12
Split type and other types	All Capacities	9.5	6.84	11.5	8.28

Table 3: Star rating of air-conditioner quality.

EER limits	Star Rating
EER > 10	6
9.5 < EER ≤ 10	5
9 < EER ≤ 9.5	4
8.5 < EER ≤ 9	3

perform an energy audit for air-conditioning system used in the most governmental building with economic influence. In the second part authors will expose an original mechanical solution to lessening energy depletion by introducing a Stirling engine in the cycle in parallel with compressor and then perform an energetic investigation.

2. Regulation and Endorsement

The choice of the appropriate conditioner depends on different parameters; consequently a new regulation established by the ministry of electricity requires clear information from manufactures to the consumers. The Saudi standard SASO 2663/2015 provided an energy labeling to show the minimum energy performance requirements for air conditioners. Table 2 shows the main air conditioners parameters for Windows and split types [22].

Starting from 7/9/2013, SASO will not issue licenses to air conditioners that do not comply with phase 1 of the modified standard and starting 1/1/2015 for phase 2. SASO provides quality methods to follow to recognize the efficiency of electrical devices. Table 3 provides the star rating to be applied from 3 stars and above only. This starting system is a measure used by SASO to control the quality of the air conditioners.

Conditioners characterized by some difficulties in maneuver created by environmental conditions such as dust and high temperature difference between day and night. The energy consuming is based on various complex parameters that are difficult to follow or to control. Therefore, in this paper, the energy consumption is the primary parameter in the study and other parameters will remain constants.

Figure 2 presents the new label and the main parameters that should be considered in the replacement process.

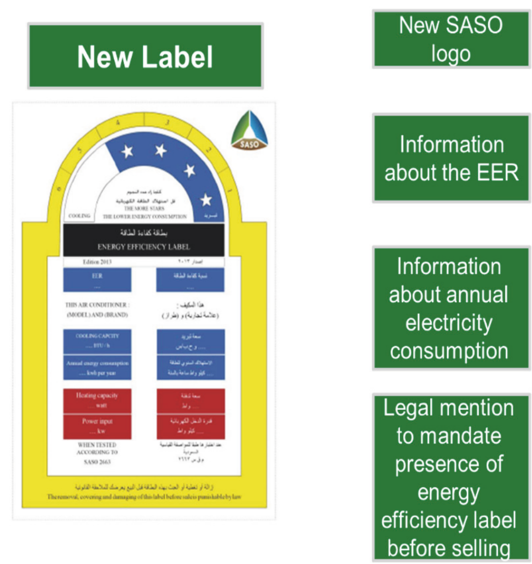

Figure 2: New label of new star energy efficiency standard [8].

As seen, the adopted parameter is the annual electricity consumption. In this research, the electricity consumption is measured and collected during nine months. Every air conditioner had its own data file gathered by sensors and its data analyzed as individual.

3. Energy Efficiency Systems Using WSAN

The designed WSAN monitoring system architecture contains three phases as shown in Figure 3. The three phases are as follows.

3.1. Sensing and Actuating Phase (Pervasive Layer). In this phase, sensors provide the Graphical User Interface (GUI) data about the energy consumption in different rooms in different floors within the building. The sensing process is a continuous process that is provided every half an hour. The sensed device was mainly a conditioner, printer, light of the offices, and classrooms.

All sensors are linked to each other using wireless transmission, and it has a WSN specification that has a

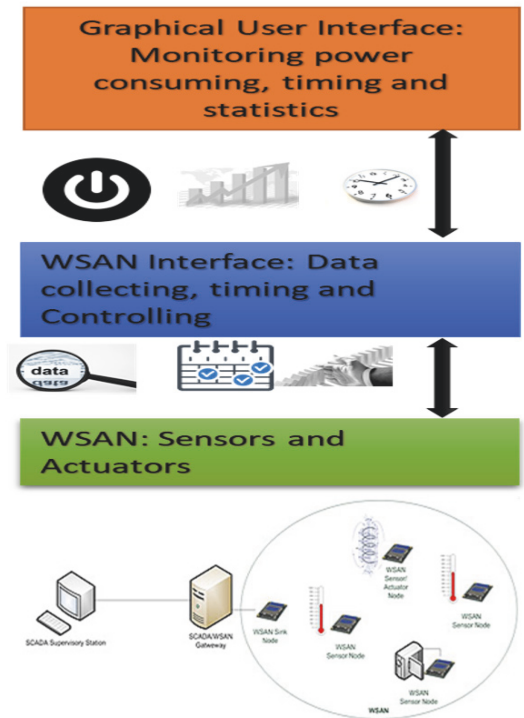

FIGURE 3: The architecture of energy efficiency system.

range up to 10 meters among devices. It is a coordinator that controlled the other devices for connection and data exchange. It is similar to Bluetooth Protocol using Master and slaves network architecture [23].

3.2. WSAN Interface Phase (Controlling). In this phase, the WSAN interface is acting as a gateway for supporting the controlling mechanism provided by actors and gathering data by sensors. In this phase, an integration to wireless networking protocol is performed.

3.3. Implementation Layer (Applications). The software used is suitable for a web browsing and smartphones. It is connected to the system to support secure access.

The adaptability of any wireless system is the critical issue to achieve a high dynamic environment. Some factors can be applied to attain high-energy efficiency, e.g., [24].

4. Design Specification for Air Conditioning Based on Stirling Engine

Several researches concerning Stirling engine were carried out because of their advantages; however, in the best authors knowledge no investigation dealt with air conditioning including Stirling engine. We apply here this model with the best choice configuration of Stirling engine and an optimization of pertinent specification for higher performance. The most advantages of the Yoke Ross mechanism are being distinguished by the nonsinusoidal volume variations. Different studies prove that alpha Stirling engine Figure 4 has different advantage compared to beta or gamma Stirling engine. A numerical simulation which takes account of thermal and mechanical losses has been investigated recently [1–7]. The results obtained are more realistic and are very suitable with the working environment. The model is used to determine different thermodynamics parameters of the Yoke Ross Stirling engine with specification as displayed in Table 6 and to predict the engine performance inside air conditioning.

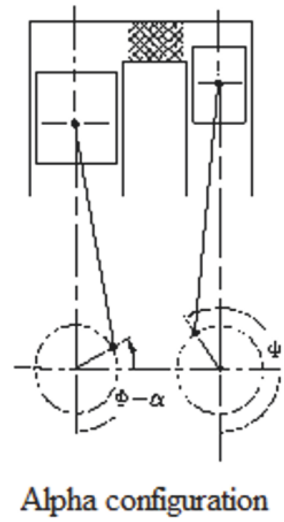

FIGURE 4: Alpha Stirling engine configuration.

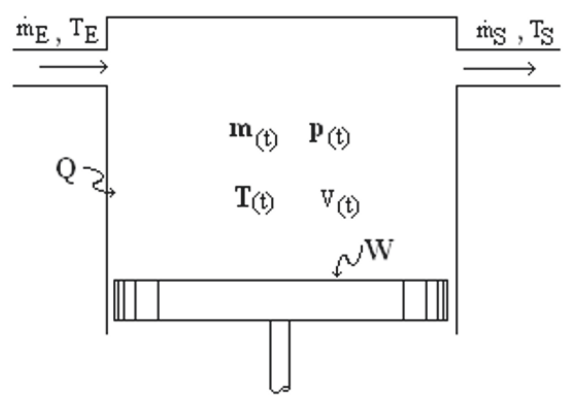

FIGURE 5: Generalised cell.

5. Equations of Thermodynamic Model

The temperatures in different section are given as below using law of gas perfect as shown by the generalised cell in Figure 5

$$T_c = \frac{P_c \cdot V_c}{R \cdot m_c} \tag{1}$$

$$T_f = \frac{P_f \cdot V_f}{R \cdot m_f} \tag{2}$$

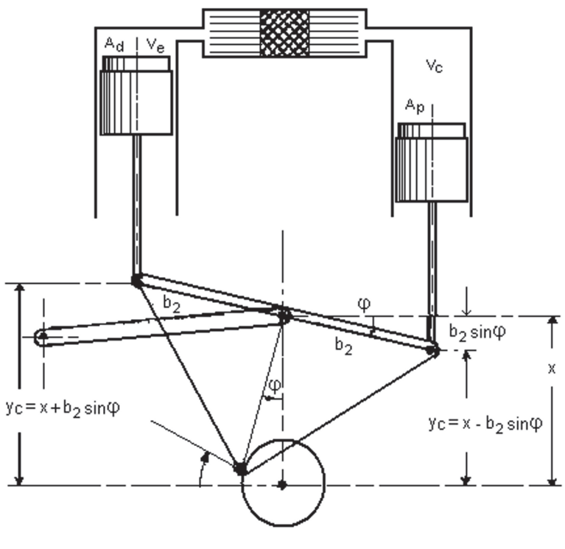

Figure 6: Yoke Ross Stirling engine configuration.

$$T_h = \frac{P_h \cdot V_h}{R \cdot m_h} \tag{3}$$

$$T_d = \frac{P_d \cdot V_d}{R \cdot m_d} \tag{4}$$

The temperatures for the two regenerator cell are, respectively,

$$T_{r1} = \frac{P_{r1} \cdot V_{r1}}{R \cdot m_{r1}} \tag{5}$$

$$T_{r2} = \frac{P_{r2} \cdot V_{r2}}{R \cdot m_{r2}} \tag{6}$$

The boundary temperatures between the tree major sections are expressed as follows [2]:

$$T_{r-f} = \frac{3T_{r1} - T_{r2}}{2} \tag{7}$$

$$T_{r-r} = \frac{T_{r1} + T_{r2}}{2} \tag{8}$$

$$T_{r-h} = \frac{3T_{r2} - T_{r1}}{2} \tag{9}$$

Therefore, the engine thermal efficiency is

$$\eta = \frac{W}{Q_h} \tag{10}$$

And the total engine volume V_T represents the sum of all section volume and the model involves Yoke Ross Stirling engine configuration as shown in Figure 6.

The pertinent other parameter for the thermodynamics model introducing energy conservation is as follows [3]:

(i) Energy conservation equation [4, 5] is

$$\delta\dot{Q} + C_p T_E \dot{m}_E - C_p T_S \dot{m}_S = P\frac{dV}{dt} + C_v \frac{d(mT)}{dt} \tag{11}$$

6. Research Methodology

The Energy Efficiency Program developed by the KSA in the vision 2030 concentrated on the investment in the energy efficiency measuring and power saving technologies. It is one of the primary objectives "Business Environment, Restructure Our Economic Cities, Create Special Zones and Deregulate the Energy Market to Make It More Competitive" [25].

The WSAN technique that presented in this paper connects WSANs with Ethernet/Internet to perform an energy saving algorithm that can be performed online to implement some steps that measured the energy consumption. This technique is managed and controlled by the distribution of WSANs in the lecture halls, laboratories, and faculty members' offices in the assigned building using the communication protocols such as ZigBee and 6LoWPAN. Such protocols are integrated into a large number of home automation devices that are usually integrated with computation and sensing; WSAN devices are available commercially with low cost and radio communication capabilities [26] systems, most with small size and low power features.

In the proposed energy saving technique, these devices contain nodes with joined sensors computing energy and mutual power adjustment and instruments to measure pertinent other parameter [25–27].

The energy consumption of the air conditioner in room 802 shows different values based on the time of day and the month.

The average cost of the air conditioner that satisfies the Saudi standard SASO 2663/2015 (24,000 BTU) unit is around 2500 SAR (667$).

Recently refrigerants 407C and 410A replaced the old one R-22 refrigerant and even they have less efficiency compared to R-22 refrigerant. The decreasing is about 10% at 46°C.

Air conditioner power consumption trumps that of most appliances. The power consumption of air conditioners averages 228 watts (for a 24,000 BTU unit) in most KSA buildings per month. That would cost the following: the average energy consumption for survey dwellings based on the type of air-conditioning systems: kWh/m^2/year for Central 221.5, Mini-Split 144.3, Window-type and 183.3 Window-type and Mini-Split 156.8 [28].

Table 4 shows applying New Consumption for all Categories of Service According to Council of Ministers' Decree dated 12/12/2017; this consumption tariff will be applied from 1/1/2018. For private educational facilities and private medical facilities, there is one category.

The total price of the energy consumed by the air conditioner (Type 24,000 BTU Mini-Split unit) with SASO Compliance Standards is *144.3 (kWh/m^2/year) X8m^2X (0.048$/kWh)=55.8$*. The total price of the energy consumed by the air conditioner as shown in Table 5 (Type 24,000 BTU Mini-Split unit) monitored by WSAN is *1602 (kWh/16m^2/year) (0.048$/kWh)=76$*.

The saving difference between the two air conditioners is 20$ and for 113 rooms, and the total saving is 2326. Assuming 5-year plan cost compensation, the total saving is 11632.67$.

Table 4: Energy consumption over 9 months for room 802.

Time of Day	10:00 kWh	11:00 kWh	11:30 kWh	12:00 kWh	12:30 kWh	The average
Month						
June	1738	1660	1829	1891	1785	1780.6
July	1733.1	1591	1596.7	1585.4	1624	1626.04
August	1643	1567.5	1644.9	1666.4	1729.2	1650.2
September	1353	1423.7	1428	1267	1290.5	1352.44
The average = 1602.32 kWh						

Table 5: Consumption tariff.

Consumption categories (Kwh)	Governmental (Halalah / kwh)	Industrial (Halalah / kwh)	Private educational facilities, private medical facilities (Halalah / kwh)
1-6000	32 (0.088 $)	18 (0.048$)	18 (0.048$)

7. Results of the Analysis

In this section, some preliminary results are shown by monitoring the energy consumption of air conditioner in 802 in the University during one academic year tracing the change in the consumption during the different seasons. Figure 7 shows the energy consumption for 3 months (July, August, and September). Other months are not considered due to the low average energy consumption during the winter and spring days.

The retrofiring process is very expensive and the saving difference based on the electricity costs will be compensated only after 75145/2326=32.3 years.

The alternative solution is the merged power saving plan using optimization energy saving plans that can save up to 10% and the total saving will be 113X16$=1808$ per year. Using the difference in energy consumption cots, three air conditioners can be replaced and this will give additional 60 $ per year.

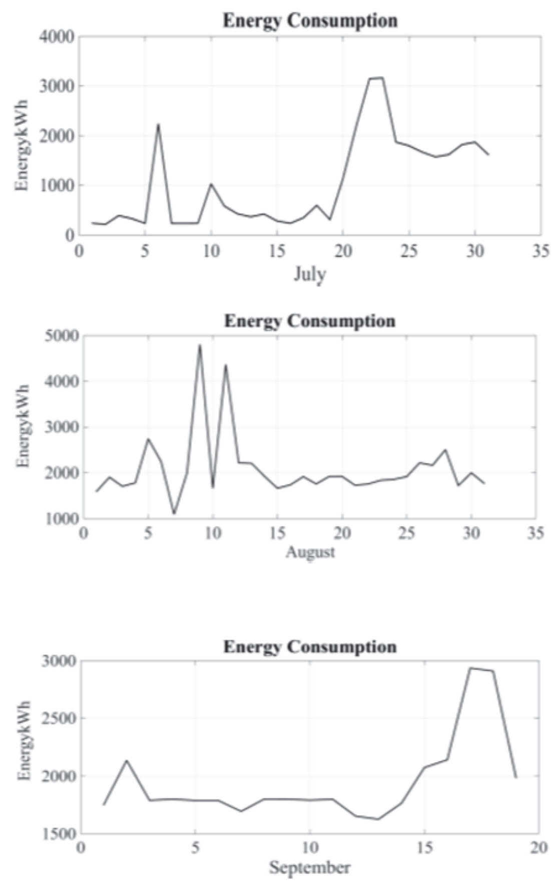

Figure 7: The energy consumption of the room 802 in 3 months.

7.1. Temperature Variations in Different Compartment. The temperature variations and the temperature profile of the model are shown in Figure 8. In the regenerator, we notice that the temperature variation of the matrix (T_{par1}, T_{par2}) is about 10°C what shows that the quantity of heat stored is low. The difference between the matrix and the associated gas temperature (Tr1, T_{r2}) is about 20°C which proves that the regenerator has good effectiveness. Figures 9 and 10 display, respectively, the pressure variation along the cycle and the P-V diagram. The gas in the heater and the cooler, however, shows a very much higher temperature variation, respectively, of more than 100°C and 50°C over the cycle.

Different researches prove that regenerator represents the most important section in Stirling engine; therefore, a regenerator with higher efficiency leads to significant increase in the overall energy efficiency of the engine.

Tlili et al. [10–14] study the effect of the heat capacity of regenerator matrices and the conductivity on the engine performance; they demonstrate that an optimal value for both heat capacity of regenerator matrices and the conductivity leads to the highest energy efficiency of the Stirling engine. In our case, Figure 11 depicts that rise of thermal conductivity on matrices c1 and c2 lessens significantly the engine; this can be explained by the fact that the irreversibilities related to the conduction have been increased [12]. Figure 12 represents that the heat capacity of the regenerator matrix leads to enhancing the engine performances. We can conclude that the engine

Table 6: Specifications of the Ross Yoke Stirling engine.

Crank length	7.6 mm
displacement	Ymin = 17.75 mm
Dead volume	Vmc = 1.14 cm3
Piston Diameter	38 mm
Swept volumes	24.42 cm3
Volumes of the exchangers	Vcol = 5 cm3 Vr = 6.75 cm3 Vhot = 4.78 cm3
Angular phase shift	90°
Average pressure	1 bar
Mass of working fluid	0.0276 g
Hot temperature	323 K
Cold temperature	283 K

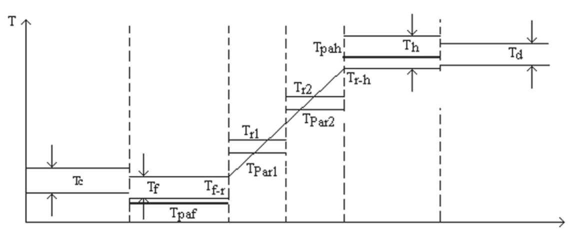

Figure 8: Temperature distribution.

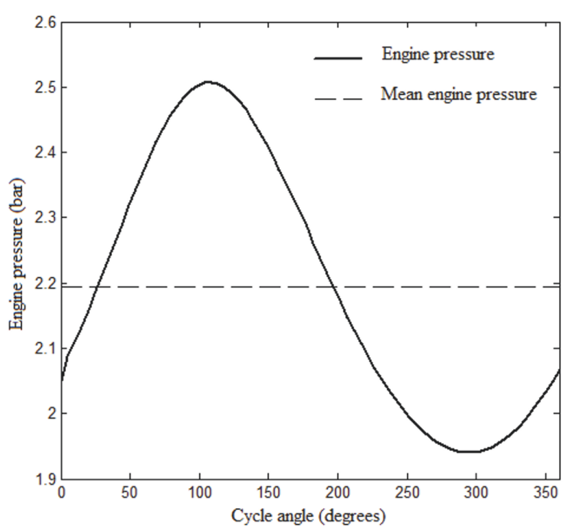

Figure 9: Engine pressure variation.

performance depends on the material nature of matrices c1 and c2.

7.2. Performance Optimization of Alpha Stirling Engine

7.2.1. Influence of Working Fluid Mass. Tlili et al. [15, 16] study the effect of working fluid mass on engine performance; it

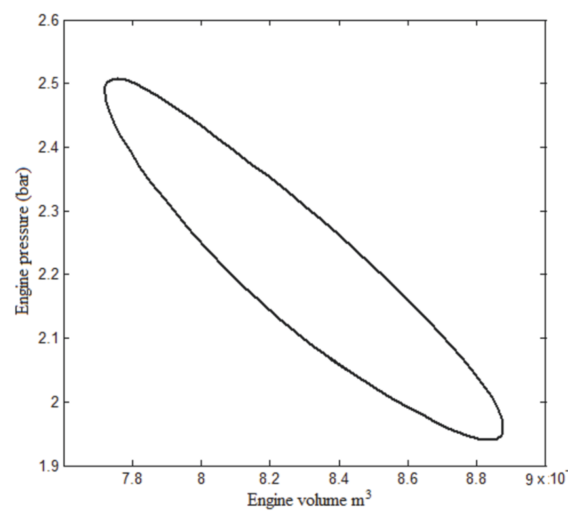

Figure 10: Pressure volume diagram.

is well known that an augmenting on mass affects meaningfully gas velocity, load, and pressure, since all the sections are closed volume. Consequently, irreversibilities related to pressure drop and energy losses augment [17]; nevertheless, the engine power grows and it is found that an optimum value of working fluid mass gives an extreme engine efficiency around 42% for m = 1 g, as revealed in Figure 13. This can be explained by the increasing in pressure loss and the capacity restriction of matrices c1 and c2 in terms of conductivity. The results found show that for m = 4 g we obtain a perfect performance for the engine.

Also, we notice that the increase of the total mass of gas induces an increase continuously in heat exchanged. It is also noticed that the temperature also supports the heat exchanged.

7.2.2. Effect of Heater Temperature. Figure 14 depicts the variation of engine performance with heater temperature. It is perceived that an increasing in heater temperature leads to an augmentation on engine performances, whereas the engine

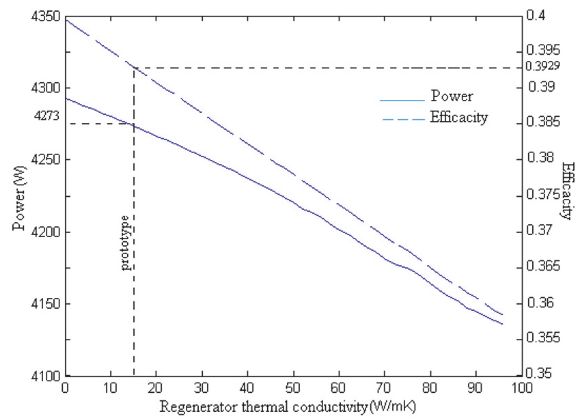

Figure 11: Power and efficiency variation with regenerator section conductivity.

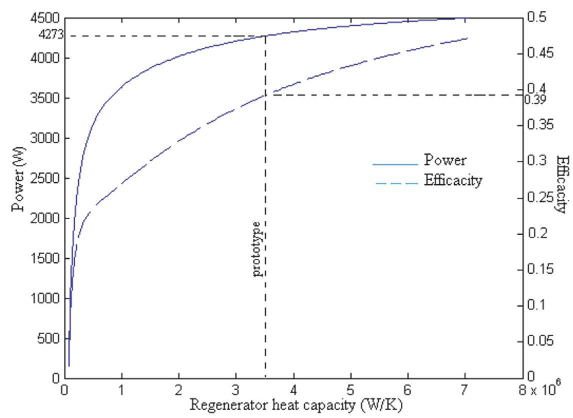

Figure 12: Power and efficiency variation with regenerator section heat capacity.

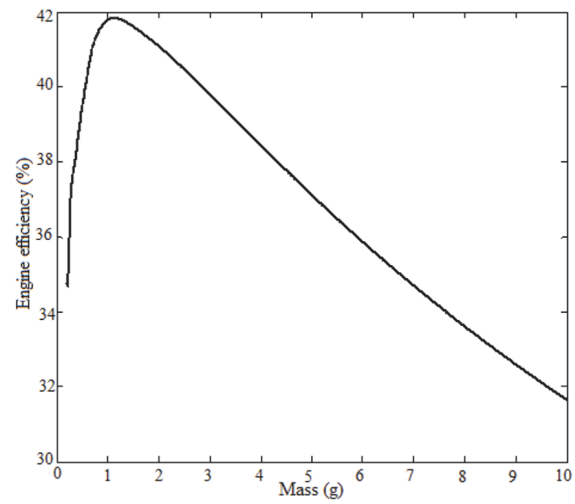

Figure 13: Engine efficiency variation with working fluid mass.

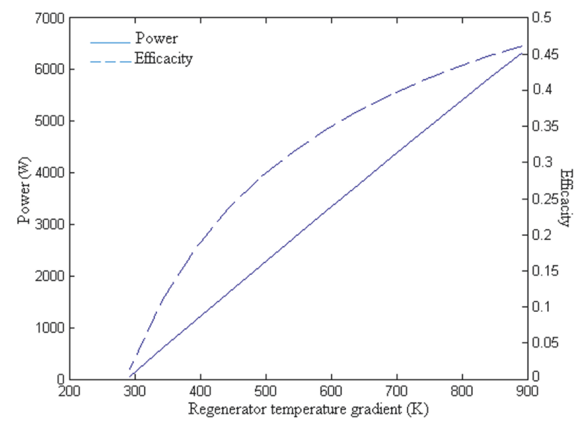

Figure 14: Power and efficiency variation with regenerator the temperature gradient.

power enhances with the operating frequency. Furthermore, it is well known that an increasing in heater temperature leads to engine thermal losses [3]; while in our case the engine performance increases, this can be interpreted by the fact the heat transferred in the regenerator between working fluid and matrices has been increasing meaningfully. It can be seen that growth of the heater temperature makes an unceasingly growth in heat exchanged. It should be pointed out that the development technology related to material will enhance the performance of Stirling engines and as a consequence in air conditioning systems.

8. Conclusion

The production and consumption of energy are responsible for a large portion of the environmental problems worldwide. In addition, the need to boost the efforts for further development and promotion of renewable energy sources and energy efficiency has been felt world over in light of rising exhaustible energy resources prices. Since energy security, economic growth, and environment protection are the national energy policy drivers of Saudi Arabia, it continues its commitment toward the utilization of more efficient energy systems based on the long-term importance of sustainable energy sources as in playing a supportive role to reducing energy consumption. That is why the Kingdom is at the forefront of a number of research initiatives into exploring more potential and deployment of energy efficiency technologies, in particular showing itself to be a leader in this issue. However, barriers to the deployment of more efficient energy on a wide scale still remain. This paper investigates the energy efficiency and the economic impact provided by air conditioning in KSA governmental building (Majmaah University Administrative Building MUAB), since air conditioning is responsible for more than 60 % of electricity consumption. Alternative solutions are provided. More than that an investigation performed to insert Stirling engine in air conditioning cycle proves that it can be a promoted solution and can reduce significantly energy consumption; an alpha Stirling engine has been tested for the same temperature and pressure reigned in the refrigeration cycle proving that it can work with energy efficiency around 42%. To carry out this study, we presented initially the constraints of the Yoke Ross Stirling engine into a thermodynamic model; the attained results were very close to other results [4–7]. Then, we examine the effect of pertinent parameter of the proposed engine; the main results show that the lessening of the matrix porosity and conductivity of the regenerator raise the performance. The increasing of the working fluid mass leads to augmenting the engine power and pressure; nevertheless, the effectiveness reaches the maximum. Also, it is demonstrated that when the exchanger piston section increased and its stroke diminished, the engine output increases and the efficiency reaches the maximum. Finally, the model optimizing these parameters show that Yoke Ross Stirling engine can work between T_h= 330 K and T_c = 280 K. Applying this study to prototypes of air conditioning will lead to the determination of their design optimal parameters and consequently to enhance performance.

Nomenclature

A: Area, m^2
Cp: Specific heat at constant pressure, Jkg-1K^{-1}
Cv: Specific heat at constant volume, Jkg^{-1} K^{-1}
D: Diameter, m
ε: Regenerator efficiency
k: Thermal conductivity, Wm^{-1} K^{-1}
L: Length, m
M: Mass of working gas in the engine, kg
$\dot{m}$: Mass flow rate, kgs^{-1}
m: Mass of gas in different component, kg
P: Pressure, Pa
Q: Heat, J
$\dot{Q}$: Power, W
R: Gas constant, $JkgK^{-1}$
T: Temperature, K
V: Volume, m^3
W: Work, J
c: Compression space
ch: Load
cd: Conduction
d: Expansion space
E: Entered
ext: Outside
f: Cooler
h: Heater
pis: Piston
r: Regenerator
θ: Crank angle, rd
ρ: Density, kgm^{-3}
ω: Angular frequency, $rads^{-1}$.

Data Availability

All data generated or analysed during this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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