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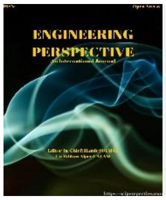

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Research Paper

Capacity Analysis Based on Vehicle Trajectory Data on a Weaving Bottleneck in Nanjing

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ABSTRACT

This paper investigates the capacity of weaving bottlenecks in Nanjing, where multiple traffic streams merge or diverge closely, causing significant traffic disruptions. Utilizing trajectory data from 862 vehicles collected through UAV cameras, the study assesses the bottleneck's capacity and performance measures, including traffic flow, speed, and lane occupancy. The analysis employs a combination of the Highway Capacity Manual (HCM) 2010 guidelines and PTV Vissim simulation software. The HCM 2010 framework provides a standardized approach for evaluating traffic flow characteristics and determining the level of service, while Vissim allows for the evaluation of diverse traffic scenarios.

The results reveal that the bottleneck operates at Level of Service E (LOS E), characterized by high congestion, reduced speeds, and prolonged travel times. However, introducing ramp metering to the area improves conditions, resulting in a transition to Level of Service D (LOS D). This study emphasizes the potential of ramp metering to enhance bottleneck performance. Nevertheless, future research should explore other strategies, such as intelligent transportation systems and improved public transportation services, to encourage modal shifts and reduce private vehicle usage. By addressing these challenges, cities like Nanjing can mitigate traffic congestion and create more efficient and sustainable transportation systems. The findings provide valuable insights for urban planners and policymakers seeking evidence-based solutions to optimize traffic flow and mobility in busy cities. By adopting the HCM 2010 guidelines and simulation tools like Vissim, this study contributes to the development of efficient traffic management strategies, ultimately fostering more livable and accessible urban environments.

Keywords: Traffic congestion; bottleneck capacity; weaving bottleneck; HCM 2010; PTV Vissim; LOS; Ramp metering

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1. Introduction

Urban areas worldwide are grappling with the persistent challenge of traffic congestion, which has far-reaching implications for travel efficiency, environmental sustainability, and quality of life. Effective management of congested bottlenecks is crucial to mitigate the negative impacts of congestion and optimize the performance of transportation networks. The capacity analysis of bottleneck sections plays a vital role in understanding traffic flow dynamics and identifying appropriate strategies for congestion reduction(Skabardonis et al., 2016). Numerous studies have focused on analyzing bottleneck capacity and proposing mitigation strategies using various methodologies. The Highway Capacity Manual (HCM) 2010, developed by the Transportation Research Board (TRB), serves as a fundamental reference for evaluating the operational performance and level of service (LOS) of transportation facilities.(Mahdi et al., 2022) The HCM 2010 guidelines provide standardized frameworks for assessing key parameters such as travel time, speed, lane changes, and flow rates to determine bottleneck capacity and LOS(Ryus, Vandehey, Elefteriadou, Dowling, et al., 2011).In parallel, the utilization of advanced simulation tools has revolutionized capacity analysis by allowing researchers to create virtual models of road networks and assess traffic flow under diverse scenarios(Raju et al., 2018). PTV Vissim, a widely adopted microscopic traffic simulation software, offers a powerful platform for analyzing traffic dynamics, simulating different traffic conditions, and evaluating performance measures within bottleneck sections(Suthanaya & Upadiana, 2019; WSDOT, 2014). This study aims to conduct a comprehensive capacity analysis of a weaving bottleneck in Nanjing, employing a combined methodology that incorporates the HCM 2010 guidelines and PTV Vissim simulation software. The primary objectives are to characterize traffic flow patterns, assess the bottleneck's LOS, and propose effective congestion reduction strategies to enhance traffic management.

The remainder of this paper is structured as follows: Section 2 presents materials and methodology, Section 3 provides results and discussion, outlining the application of the HCM 2010 guidelines and the use of PTV Vissim for simulation and presents the results of the capacity analysis, discussing the findings specific to the weaving bottleneck in Nanjing. Finally, Section 4 offers concluding remarks and suggestions for future research and implementation. Research on bottleneck capacity analysis has witnessed significant advancements in recent years. Many studies have utilized the HCM 2010 guidelines as a foundation for assessing and understanding the operational performance and LOS of bottlenecks.(Rouphail & Williams, n.d.) These studies have successfully applied the HCM 2010 methodologies to evaluate key parameters such as flow rates, speed, and lane changes, enabling a standardized assessment of bottleneck capacity. However, while the HCM 2010 provides a robust framework, some limitations exist in terms of its applicability to specific types of bottlenecks and the representation of certain traffic conditions(Raju et al., 2018). Moreover, the use of simulation tools, such as PTV Vissim, Anylogic, Ainsum, and Sumo, has significantly contributed to the analysis of bottleneck capacity and the exploration of congestion reduction strategies(Wang et al., 2014). Simulation-based studies have enabled researchers to create virtual models of road networks, evaluate various traffic scenarios, and estimate performance measures with a high degree of accuracy. These studies have highlighted the advantages of simulation-based approaches, including the ability to capture real-world complexities, investigate dynamic traffic patterns, and assess the impact of different operational strategies. However, it is important to consider the inherent limitations of simulations, such as the accuracy of input data and calibration of model parameters, to ensure reliable results(*Bottleneck-Removal-1-Pg*, n.d.). Despite the progress made in bottleneck capacity analysis, there are still knowledge gaps that warrant further investigation. For example, there is a need for more research on the capacity analysis of specific types of bottlenecks, such as complex urban intersections. Additionally, the interaction between bottleneck capacity and emerging technologies, such as connected and autonomous vehicles, requires further exploration to understand their influence on traffic flow and capacity(Zhao et al., 2017).

The existing research in bottleneck capacity analysis and congestion mitigation strategies has provided valuable insights and methodologies. However, there remains a need for current and future research projects to address several challenges. These include the development of more accurate and comprehensive models, the incorporation of real-time data for dynamic capacity analysis, the integration of intelligent transportation systems for improved traffic management, and the evaluation of sustainable transportation solutions to reduce congestion and environmental impacts. In light of the outlined research trends, strengths, weaknesses, knowledge gaps, and the need for further research, this study aims to contribute to the existing body of knowledge by conducting a capacity analysis of this bottleneck in Nanjing, employing a combined methodology of the HCM 2010 guidelines and PTV Vissim simulation software. The findings from this study will shed light on the specific characteristics of the weaving bottleneck and provide insights for effective congestion reduction strategies and improved traffic management in similar contexts.

2. Data collection

Secondary data was collected online from the website seutraffic.com, where it was recorded using an Av high-resolution camera. The data was captured within a duration of 450 seconds, encompassing trajectory data for 862 vehicles traveling unidirectional on a 5-lane highway, with the study area extending over a length of 386 meters.

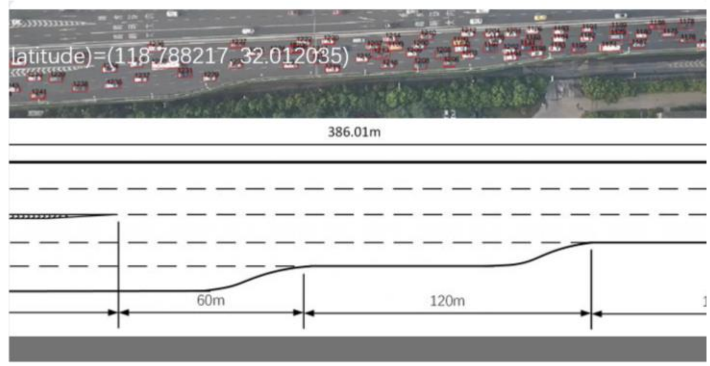

Figure 1. Bottleneck section under study (http://seutraffic.com/)

In this traffic configuration, there are three continuous lanes and two merging ramps that eventually converge into a downstream segment with three lanes as shown above in Figure 1. The collected dataset encompasses various attributes for each vehicle, including acceleration, vehicle ID, velocity, latitude, longitude, vehicle length, vehicle width, and lane ID, all observed at different time intervals. Accompanying this dataset is a video recording capturing the progression of each vehicle, from its entry into the bottleneck area to its exit. The analysis of this data reveals a significant frequency of lane changes within the merging section. Many drivers opt to reduce their speed or decelerate upon approaching the merging influence zone. Once they navigate past the merging zone, they resume acceleration and regain the free flow speed of 110 km/h. Notably, during the merging area, the free flow speed is determined to be 45 km/h, a finding drawn from the comprehensive data collection. Graphical representation of collected vehicle speeds is seen on Figure 2.

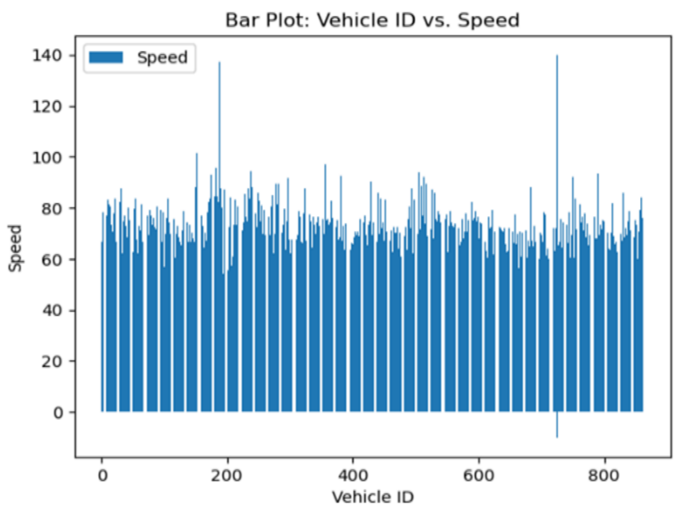

Figure 2. Vehicle ID vs Speed

3. Materials and Methodology

This study employed a mixed-methods approach to conduct a comprehensive capacity analysis of bottlenecks. The methodology consisted of two main components: the application of the Highway Capacity Manual (HCM) 2010 guidelines for capacity analysis and the utilization of PTV Vissim simulation software for traffic simulation. To assess the capacity of the weaving bottleneck, the HCM 2010 guidelines were utilized as a standardized framework. The guidelines provided a systematic approach for evaluating key parameters such as flow rates, speed, and lane changes. Data collection for the capacity analysis involved the extraction of recorded vehicle trajectory data at the bottleneck location. The collected data included vehicle speed, vehicle width, vehicle length, headways, lane positions, lane changes, and others. Using the HCM 2010 methodology, the extracted trajectory data were analyzed to calculate various performance measures such as the level of service (LOS), speeds, and flow rates. These measures provided insights into the operational performance of the bottleneck and facilitated the characterization of traffic flow patterns and congestion levels. Additionally, the HCM 2010 guidelines allowed for the identification of potential capacity constraints and bottlenecks within the weaving section. In parallel to the capacity analysis, traffic simulation using PTV Vissim software was conducted to further investigate the traffic dynamics and assess the performance of different congestion reduction strategies. PTV Vissim provided a powerful platform for creating a virtual model of the road network and simulating various traffic scenarios. The simulation model was calibrated and validated using the collected trajectory data to ensure its accuracy in representing real-world traffic conditions.

Once the simulation model was established, different operational strategies were evaluated to identify effective congestion reduction measures. These strategies included ramp metering and others. Through the simulation experiments, the impacts of each strategy on traffic flow, capacity, and LOS were assessed, enabling the identification of the most promising approaches for congestion mitigation. The capacity analysis results obtained from the HCM 2010 guidelines and the findings from the PTV Vissim simulations were integrated to provide a comprehensive understanding of the weaving bottleneck in Nanjing. The combined methodology allowed for a multi-dimensional analysis of the bottleneck, considering both the observed real-world data and the simulated scenarios. This integrated approach provided valuable insights into the traffic flow dynamics, capacity constraints, and potential congestion reduction strategies for the weaving bottleneck in Nanjing.

4. Results and discussion

4.1. Using HCM (2010)

The Highway Capacity Manual (HCM) 2010 is a widely used resource for analyzing and evaluating the operational performance of highways and transportation systems(Ryus, Vandehey, Elefteriadou, Dowling G, et al., 2011). It provides guidelines and methodologies for conducting various types of transportation analysis, including data analysis. The data collected were analyzed by doing calculations based on the guidelines of HCM (2010) where different flowrates, speeds, and other parameters have been calculated as detailed below:

Calculation of f_{HV} = heavy vehicle adjustment factor;

$$f_{HV} = \frac{1}{(1)+P_T(E_T-1)+P_R(E_R-1)} \quad (1)$$

where:

E_T and E_R are passenger car equivalents for trucks buses and recreational vehicles (RVS), respectively

P_T is the Proportion of trucks and buses, and RVS, respectively in the traffic stream

The terrain is in a class of level terrain hence, E_T (Truck and buses) is 1.5, and E_R for (RV_S) is 1.2. The proportion of Trucks and buses in collected data is 0.006 and 0.0015 respectively.

Then $f_{HV} = \frac{1}{(1)+0.006(1.5-1)+0.0015(1.2-1)} = 0.99$

Based on existing data, we have 6965 Veh/hr. where the free-flow speed in the downstream segment is 110 km/h and the free-flow speed at the merging influence area is 45km/h.

Conversion of volume (Veh/h) to flowrate pc/h;

Using this equation: $$v = \frac{V}{(PHF)(f_{HV})(f_p)} \quad (2)$$

Where V: is the hourly volume (veh/h), V is Peak 15-min flow rate in an hour (pc/h), f_{HV}: Heavy vehicle adjustment factor, f_p is: Driver population factor.

Peak Hour Factor (PHF) = $\frac{Hourly\ Volume}{\text{Peak flow rate (within hour)}} = 1$

Checking for maximum flow entering merge influence area;

$V_F = \frac{4776}{(1)(0.99)(1)} = 4824$ pc/h, $V_R = \frac{2120}{(1)(0.99)(1)} = 2141$ pc/h,

$V_{23} = V_{12} x1.12 = 4863 \text{ x } 1.12 = 3330$ pc/h

$\boldsymbol{V_{12}} = \frac{2944}{(1)(0.99)(1)}$=2974pc/h, ,

$\boldsymbol{V_{R23}}$ = V_{23}+V_R=3330+2141=5471pc/h and

$\boldsymbol{V_{FO}} = V_R + V_F$=4824+2141= 6965 pc/h,

Where: V_{12}: Flowrate entering ramp influence area (pc/h)
V_{R12} = sum of flow rates for ramp (V_R) and vehicles entering ramp influence area (pc/h);
$\boldsymbol{V_R}$ = flow rate on-ramp (pc/h)

For this analysis, we have two conditions;
Checking for 1st condition:
1st condition states that the total departing freeway flow (v) may exceed the capacity of the downstream freeway segment. Failure (LOS F) is expected. Here no further calculations are needed, and queues will form upstream from the merged segment. When the downstream freeway capacity is exceeded, LOS F exists regardless of whether the flow rate entering the ramp influence area exceeds its capacity. For the given road section, the free flow speed is 110 km/h at the downstream street with 3 lanes in the same direction. Hence the estimated capacity (V_{FO}) of the downstream segment is 6965 pc/h which is less than 7050 pc/h which is suggested by HCM LOS F will not exist.

Table 1. Capacity values for merge area (*Highway Capacity Manual 2000 RAMPS AND RAMP JUNCTIONS CONTENTS*, n.d.)

Freeway Free-Flow Speed(km/h)	Maximum Downstream Freeway Flow, v(pc/h)				V_{R12} (pc/h/ln)
	Number of Lanes in One Direction				
	2	3	4	>4	
120	4800	7200	9600	2400	4600
110	4700	7050	9400	2350	4600
100	4600	6900	9200	2300	4600
90	4500	6750	9000	2250	4600

V_{R12} is the Maximum Downstream Freeway Flow**.** Checking for maximum flow entering merge influence area;
For our case, we have V_{R12}=V_{12}+V_R=2697+2141=4838pc/h, here based on Table 1 (Exhibit 25-7 in HCM 2010)The maximum flow entering the influence area exceeds the desired maximum flow as recommended by HCM, but there will be no LOS F according to this second condition:

2nd condition states that when the total flow entering the ramp influence area exceeds its maximum desirable level but the total freeway flow (v) does not exceed the capacity of the downstream freeway segment. In this case, locally high densities are expected, but no queuing is expected on the freeway. The actual lane distribution of entering vehicles is likely to consist of more vehicles in the outer lanes than is indicated by the models herein. Overall, the operation will remain stable, and LOS F is not expected to occur. But when the total downstream flow exceeds the basic freeway capacity of the downstream segment, LOS F exists. In such cases, no further computations are needed, and LOS F is assigned. For all other cases, including cases in which VR_{12} exceeds its stated limit, LOS is determined by estimating the density in the ramp influence area.

4.1.1. Calculating level of service (LOS)

Computing density;

This equation is used to estimate the density in the merge influence area

$$D_R = 3.402 + 0.00456V_R + 0.0048V_{12} - 0.01278L_A \quad (3)$$

$L_{Aeff} = 2L_{A1} + L_{A2}$

where: D_R: Density of merge influence area (pc/km/ln), V_R: On-ramp peak 15-min flowrate (pc/h), V_{12}: Flowrate entering ramp influence area (pc/h), L_A: Length of acceleration lane (m)

D_R=3.402+0.00456*2141+0.0048*2974-0.01278*240

=24.37pc/km/ln. Basing on exhibit 25-7 in HCM(2000) and also as it shown in table 2, we were able to determine the Level of Service of the section under study.

Table 2. LOS criteria for merging and diverging (Ryus, Vandehey, Elefteriadou, Dowling, et al., 2011)

LOS	Density (pc/km/ln)
A	≤6
B	>6-12
C	>12-17
D	>17-22
E	>22
F	Demand exceeds capacity

The merging area is under LOS E as the density of the merging influence area is greater than 22pc/km/ln (see Table 2).

4.1.2. Characteristics of LOS E;

LOS E is indicative of moderately congested traffic flow. It implies that the roadway is operating at or near its capacity, and vehicles are traveling at speeds slightly below the posted speed limit. Vehicles in LOS E experience reduced speeds compared to free-flow conditions, with the average speed typically around 45-50% of the posted speed limit. Traffic density in LOS E is relatively high, and vehicles are closely spaced. The roadway is operating at or near its maximum capacity. Travel time in LOS E is longer than under free-flow conditions, with moderate delays and periodic fluctuations in speed due to congestion. Vehicles in LOS E may frequently need to accelerate and decelerate due to the changing traffic conditions. This is particularly evident in areas with merging lanes, intersections, or other areas where traffic flow is disrupted(*Highway Capacity and Level of Service*, 1991; Volosenko & Laurinavičius, 2020).
Although lane changes may still occur in LOS E, they may be less frequent and more difficult due to the high traffic volume and limited gaps between vehicles. The roadway is operating at or near its maximum capacity, and small disruptions or fluctuations in traffic flow can quickly lead to congestion or breakdown conditions. LOS E may be perceived as moderately uncomfortable for

drivers. The close proximity of vehicles and the need for frequent adjustments in speed and position can contribute to a higher level of driver stress. Safety concerns may arise in LOS E due to the increased traffic density and closer spacing of vehicles, with a slightly higher risk of rear-end collisions, lane merging conflicts, and other traffic-related incidents compared to lower levels of service (Abdullah & Sadullah, 2017)

4.1.3. Computing speeds as supplemental information;

Finding average speed in the outer lane Ramp influences area;

$$M_S = 0.321 + 0.0039e^{\frac{V_{R12}}{1000}} - 0.004(\text{LAeff}S_{FR}/1000)$$

S_{FR} is the free-flow speed of the ramp (km/h);

$L_{Aeff} = 2LA1 + LA2$=240m

where: L_{Aeff} Is the effective length of the acceleration lane

$S_{FR} = 45km/h,$ Here it indicates that the capacity of the ramp roadway itself should be 3500 pc/h for Two-Lane Ramps according to Exhibit 25-3 in HCM2010

M_S =0.321+0.492-0.0432=0.77 where: M_s is the intermediate speed determination variable for the merge area

$$S_R = S_{FF} - (S_{FF} - 67)M_S$$

S_R =110-(110-67) *0.77=76.89 Km/h

$$V_{OA} = \frac{V_F - V_{12}}{N_O} = \frac{4824-2974}{2} = 925\text{pc/h}$$

Where V_{OA} = average per-lane flow rate in outer lanes at begin of ramp influence area

SR = space mean speed of vehicles within ramp influence area (km/h); for merge areas, this includes all vehicles in VR_{12}; for diverge areas, this includes all vehicles in V_{12}

Here V_{OA} lies between 500pc/h to 2300 pc/h, then the second formula in HCM has been used;

$S_O = S_{FF} - 0.0058(V_{OA} - 500)$, S_O = 110 − 0.0058(925-500) =107.535Km/h

$$\boldsymbol{S_w} = \frac{V_{12} + V_{OA}N_O}{\frac{V_{12}}{S_R} + \frac{V_{OA}N_O}{S_O}} = 86.31\text{Km/h}$$

where: S_O = space mean speed of vehicles traveling in outer lanes (Lanes 3 and 4, where they exist) within 450-m length range of ramp influence area (km/h);

SFF = free-flow speed of freeway approaching merge or diverge area (km/h);

VR12 = sum of flow rates for ramp (VR) and vehicles entering ramp influence area (pc/h);

VOA = average per-lane flow rate in outer lanes at the beginning of ramp influence area

NO = number of outside lanes in one direction (not including acceleration or Deceleration lanes or Lanes 1 and 2),

VF = total approaching freeway flow rate (pc/h), and

V12 = demand flow rate approaching ramp influence area (pc/h)

4.2. Simulation of collected data using PTV VISSIM

PTV Vissim is a leading software application for microscopic traffic simulation. It is widely used by transportation professionals and researchers to model and analyze traffic operations and behavior in various transportation systems. PTV Vissim enables users to simulate and visualize the movement of individual vehicles and their interactions within a detailed virtual environment (Planung Transport Verkehr GmbH - Copyright, 2022; Utomo et al., 2020).

Setting Up the VISSIM Model for the Study Area;

VISISM needs to prepare to run the simulation of estimating the capacity of the study area. There are a few steps in VISISM microsimulation that have been described below.

1. An overlapped geometry of the study section was drawn in where the total section of the bottleneck was redrawn in VISSIM as it is shown in Figure 3.
2. Next, five types of vehicles were selected. Car and heavy goods vehicles (HGV) are considered traditional vehicles, For all types of vehicles, driving behavior was determined as Freeway (free lane selection)
3. The desired speed was customized as a requirement. In this paper, a total of 8 types of speed distributions were selected with lower and upper bounds. The calibration, validation, and simulation setup for various free-flow speeds describes a detailed speed distribution.
4. The next part includes vehicle composition, In the vehicle input part, traffic demand needs to be set as input. This demand value was found in the collected data. For capacity checking, traffic demand was kept at 6965veh/h for all five lanes. For vehicle inputs, each lane was given a number of vehicles that is similar to that one contained in collected trajectory data. The first 3 minutes were spent for warm-up, which means running different vehicles initially and counting for the next 60 minutes.
5. Finally, the simulation parameter setup and evaluation parameter setup were completed to get the result. A total of 3 data collection points were set up at the end of each lane to get the VISSIM output.

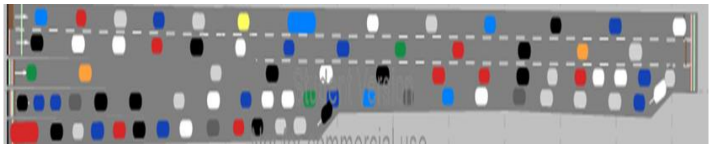

Figure 3. First simulation in Vissim without Ramp metering

4.3. Simulation Results

The results of this simulation were characterized by congested traffic conditions in the merging influence areas as it is shown in Figure 3 and in table 3, The simulation results proven it, as it is characterized by with long queues, slow speeds, and significant delays. The simulation results demonstrate a decrease in average and maximum speeds compared to other free-flow conditions, indicating reduced mobility and capacity utilization on the road network. The congestion leads to increased travel times, with longer journey durations, moreover, it was associated with reduced traffic flow rates. In order to propose a method by which the performance of this bottleneck can be improved, the simulation was repeated with the same conditions as the first one. But by applying ramp metering at the entrance ramps as it is shown in Figure 4, Ramp metering was applied to section of the road under study. Ramp metering systems typically consist of traffic signals installed at the entrance ramps. After setting ramp metering to VISSIM software the simulation was repeated again. After the ending of the second simulation, the results showed reduced queuing and improved overall performance of the bottleneck as its capacity falls under LOS D. And also, simulation results demonstrated a noticeable reduction in delays and smoother traffic progression through the bottleneck.

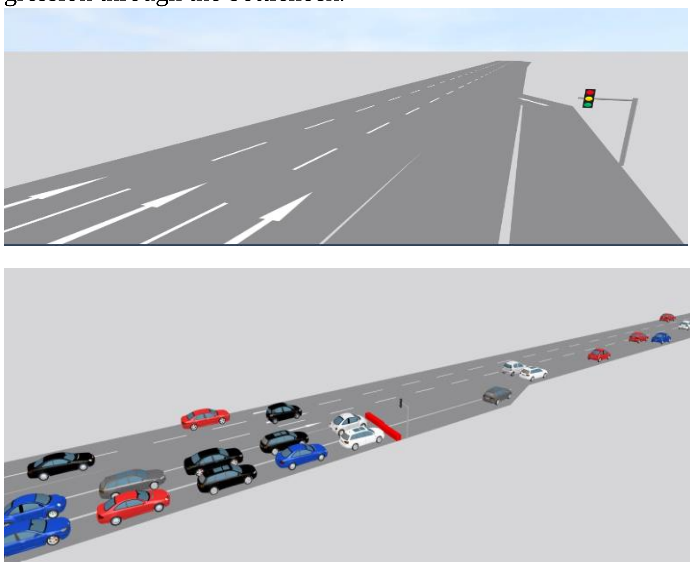

Figure 4. Second simulation process after application of Ramp metering

The effectiveness of these strategies was assessed through comprehensive performance metrics derived from the simulation results. Figure 4 also proves the successful contribution of Ramp metering to the reduction of Queue length, as there are some empty spaces between moving vehicles.

Table 3. VISSIM simulation results before and after the application of Ramp metering

Performance Indicator	**Before Ramp Metering**	**After Ramp Metering**
Average free flow Speed for downstream segment (km/h)	110	120
Average Merge area speed (km/h)	76.89	87.4
Queue Length (m)	102	40
Delay (s/vehicle)	85	32
Calculated Density (pc/km/ln)	24.37	20.2

The simulation demonstrated a significant improvement in the performance of the bottleneck, as evidenced by reduced queue lengths, improved average speeds, and decreased travel delays. These positive outcomes validate the efficacy of the implemented strategies and highlight the potential benefits of using PTV Vissim simulation as a decision-support tool for bottleneck management.Top of Form

5. Results interpretation

After conducting the analysis using the Highway Capacity Manual (HCM) methodology and simulating the performance of the bottleneck using VISSIM, the results indicated that the Level of Service (LOS) of the bottleneck was initially evaluated as E. This LOS suggests significant congestion and delays, indicating a suboptimal traffic flow. To improve the performance of the bottleneck, a ramp metering strategy was implemented using VISSIM simulation. The ramp metering approach involved controlling the flow of vehicles entering the mainline from the on-ramp. By regulating the rate at which vehicles merge onto the mainline, it aims to alleviate congestion and enhance overall traffic flow efficiency. The comparison of results before and after the implementation of ramp metering provides significant insights into the effectiveness of this traffic management strategy. The average free-flow speed for the downstream segment saw a notable increase from 110 km/h to 120 km/h after ramp metering was introduced. This improvement signifies enhanced traffic flow and better mobility within the downstream segment, attributed to the controlled entry of vehicles through ramp metering.

The merge area speed, a critical factor in bottleneck performance, exhibited a positive change as well. Prior to ramp metering, the merge area speed was 76.89 km/h, which notably rose to 87.4 km/h post-implementation. This change indicates that the introduction of ramp metering has facilitated smoother merging of vehicles at higher speeds, effectively reducing the potential for congestion and delays in this critical zone.

The queue length, often indicative of the level of congestion and delays experienced by drivers, showed a substantial reduction from 102 meters before ramp metering to a significantly diminished 40 meters after its application. This reduction in queue length translates to shorter waiting times for vehicles at the merge point, resulting in improved traffic flow and a less congested roadway environment.

One of the most critical aspects, delay per vehicle, experienced a substantial decrease from 85 seconds to 32 seconds following the implementation of ramp metering. This decrease indicates that vehicles spent significantly less time in traffic queues, leading to shorter travel times and an overall enhancement in traffic efficiency. Additionally, the density of vehicles on the roadway, a vital measure of traffic congestion, exhibited a positive change. Density decreased from 24.37 pc/km/ln to 20.2 pc/km/ln after ramp metering. This reduction implies that vehicles were better spaced out, contributing to smoother traffic flow and a less congested road network.

Overall, the Level of Service (LOS) transitioned from E to D after ramp metering was introduced. This shift underscores a substantial enhancement in the overall traffic conditions, with reduced congestion, lowered delays, and improved traffic flow. Top of Form

The successful implementation of ramp metering suggests its effectiveness in mitigating congestion and improving the bottleneck's performance. The results align with previous studies and empirical evidence supporting the positive impact of ramp metering on traffic flow and capacity enhancement. These findings demonstrate the practical application of the HCM methodology in evaluating bottlenecks and identifying potential solutions for improving traffic performance. Moreover, the VISSIM simulation provided a valuable platform to assess the effectiveness of the ramp metering strategy and its impact on the bottleneck's LOS.

6. Conclusions

In conclusion, the application of the Highway Capacity Manual (HCM) methodology combined with VISSIM simulation has provided valuable insights into the performance of a bottleneck and the effectiveness of a ramp metering strategy. The initial evaluation of the bottleneck indicated a Level of Service (LOS) E, highlighting significant congestion and delays. However, after implementing the ramp metering strategy in the simulation, the LOS improved to D, indicating a noticeable enhancement in traffic flow and a reduction in congestion. These results align with previous studies [2] that have demonstrated the effectiveness of ramp metering in improving traffic performance. The successful application of the HCM methodology and VISSIM simulation emphasizes the importance of utilizing advanced tools and techniques for traffic analysis and mitigation strategies. By employing these methods, transportation planners and engineers can gain valuable insights into the causes of congestion and identify effective solutions for enhancing traffic flow and reducing delays.

The results strongly suggest the implementation of a ramp metering strategy at the bottleneck location to improve traffic flow and reduce congestion. Ramp metering should be further studied and optimized by considering factors such as traffic demand patterns, control algorithms, and coordination with adjacent intersections.

Continuous Monitoring and Evaluation: Regular monitoring and evaluation of the bottleneck's performance are crucial to identify any changes in traffic conditions and assess the effectiveness of the implemented ramp metering strategy. This will enable transportation authorities to make timely adjustments and fine-tune the system for optimal performance.

Integration of ITS technologies, such as real-time traffic monitoring, adaptive control systems, and advanced data analytics, can further enhance the effectiveness of the ramp metering strategy. These technologies can provide valuable data for decision-making, optimize control parameters, and facilitate proactive traffic management. Comprehensive Analysis of Alternative Strategies: While ramp metering has shown promising results, it is essential to explore alternative strategies and conduct a comprehensive analysis to identify the most effective combination of measures for further improving the bottleneck's performance. This may include considering changes in lane configurations, signal timing adjustments, or other operational and infrastructure improvements. By implementing these recommendations, transportation agencies can strive towards achieving a more efficient and sustainable transportation system, providing better mobility and reducing congestion for the traveling public.

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Conflict of interest declaration:

The authors declare that they have no conflicts of interest concerning this article.

Credit Author Statement

Sugira Jean Claude: Conceptualization of the study, devising the methodology, developing the necessary software tools for data analysis, writing of the original draft.
Nshimiyimana Marc: Conceptualizing the research, overseeing the project's progress, and writing the original draft.
Nsengimana Jean Pierre: Curating the trajectory data collected from the website "seutraffic.com.", visual representations, and interpretation of the results.

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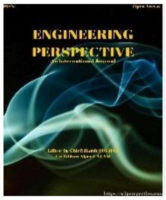

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Impact of Energy Accessibility to Household Welfare in Developing Countries: Case Study Rwanda

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ABSTRACT

Nowadays, the world's socio-economic development and well-being of society are based on energy accessibility. As the number of energy accessors increases some global problems have been highlighted including climate change and global warming. Those problems lead the developing countries including Rwanda to food insecurity and poverty. Easily accessible energy in Rwanda is biomass energy which occupies above 83% of the total energy consumption. Electrification and green energy like solar and gas energy are considerably increasingly accessed by Rwandans. Those clean energies are mostly available in the cities compared to the rural villages. Industries and other businesses are located in the city due to the energy accessibility, and youth are shifting from rural areas to the cities to look for jobs and a civilized way of living. Therefore, in this study, we assessed and analysed the impact of energy accessibility on the household's welfare. The econometric approach method with Integrated Household Living Conditions Survey 5 (EICV5) has been used to assess the country's level of energy access and the impact of energy access on the households 'welfare is identified. We used simple regression analysis's ordinary least squares test (OLS) to analyze those impacts. The data from the National Institute of Statistics Rwanda that are treated using STATA software show that access to electricity affects a household's welfare generally increasing. From the coefficient estimates, the non-farm business increased by 68.4% in rural areas. In the education sector, there is an impact of clean energy accessibility which has 52.6%. Therefore, the general consideration of the impact of energy accessibility impact to the household's welfare plays an important role at a rate of 68% in people's way of living in both rural areas and cities of Rwanda.

Keywords: Energy, Household, Electricity, Econometrics, Socio-economy

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1. Introduction

1.1 Energy Welfare in Developing Countries

Energy is necessary for the socio-economic development and well-being of society. Many of today's global issues, such as climate change, poverty, and food security, necessitate the provision of low-cost, dependable, long-term energy services. Electrification and clean energy have become both a requirement for any society's development and a symbol of civilization. Access to clean energy is essential for economic activity as well as community health and well-being [1,2]. Despite the fact that global access to electricity increased from 78 to 89% between 2000 and 2017, an estimated 800 million people remained without access in 2017. Low-income countries (especially those in Sub-Saharan Africa) and rural communities continue to face access issues. Concurrently, the quality of connections, such as electricity generation capacity, affordability, durability, safety and health, and convenience, are other factors that may influence an end user's ability to use electricity when needed [3].

In developing countries, a major impediment to rural economic growth and development is a lack of access to electricity. Along with a result, the World Bank and other development organizations have made modern energy access, particularly access to electricity, one of their top priorities. It is widely acknowledged that electrification improves household quality of life and stimulates the economy as a whole. The immediate benefit of electrification is improved lighting, which encourages long hours of study for students and, as a result, contributes to higher educational achievement. Other household activities, such as sewing by women, social gatherings after dark, and so on, can benefit from lighting as well [4]. Rwanda's total power supply has grown by 10% since 2008, to 502,053 MWh. Year after year, total consumption has increased in a logarithmic trend. The seasonal variations in power demand are negligible. The total installed capacity of electricity generation is currently 119.6MW, with hydrological resources accounting for roughly 60% and diesel-powered generators accounting for 40%. Rwanda has a significant peak demand load between 6 and 9 p.m., which, on an annual basis, was recorded at 87.9 MW in 2013. This is because household lighting is the most common use of electricity.

1.2. Energy accession in Rwanda

Energy has a huge impact on people's lives and is a driving force behind social and economic development. Energy has aided in the transformation of societies and the advancement of human civilization over the centuries. Energy contributes to the fulfillment of some of the most fundamental human needs, such as nutrition, warmth, and light. Furthermore, there is ample evidence that having reliable, efficient, cost-effective, and safe energy carriers can directly impact productivity, income, and health, as well as improve gender equity, education, and access to other infrastructure services. The immediate applications of electricity in newly electrified households are lighting and appliances, communications, and entertainment. Public/street lighting, refrigeration, health centers, and schools, piped water, communication, and the like are among the most frequently mentioned public needs. The use of a variety of electricity-powered appliances benefits households. There is a clear progression in the energy services available to those with electricity access. The initial applications are in lighting and entertainment. Following that, thanks to appliances such as electric lamps, radios, televisions, computers, refrigerators, fans, stoves, and electric pumps, a wide range of benefits are potentially available, ranging from security, comfort, and convenience to education, health, and home productivity [5]. Bhattacharyya et al.[6], highlight levels of income are normally associated with higher levels of energy access, as expected; however, rapid improvement in access level occurs within an income band bounded by a lower threshold income level of around $1000 per person in PPP terms 2005 and an upper saturation level of around $15,000 per person in PPP terms. Those below the lower threshold clearly do not have access to clean energy, whereas those above the upper threshold do.

Rwanda is a small country in East Africa with a population of 12,089,721 people and a land area of 26,338 square kilometers. It is located between the latitudes of 1.050- and 2.84^0, and the longitudes of 28.86^0 and 30.9^0. Rwanda's economy has expanded rapidly in recent decades, and the country has substantial energy resources that have yet to be fully utilized. Despite abundant natural energy resources such as hydro, solar, peat, gas, and biomass, Rwanda currently has only about 216 MW of installed electricity capacity to serve the country. Despite encouraging economic growth, the country has a low per capita GDP of $696 and a low per capita electricity consumption (30 kWh) when compared to Uganda (66 kWh), Kenya (140 kWh), and Tanzania (85 kWh). Furthermore, when the highest regional electricity tariff of US$0.12 to US$0.18/kWh is compared to the local Rwandan electricity tariff of US$0.22/kWh, the local Rwandan electricity tariff wins (REG, 2018c). According to the research, Rwanda's electricity price is approximately 22.2 percent higher than the EAC's highest electricity tariff [7]. In 2008, the total primary energy supply was 111 PJ2, with traditional biomass accounting for the vast majority. Households consume the most energy (91%) followed by transportation (4%), industry (3%), and public services (3%) 2 percent. Households are also the largest users of electricity for lighting (51 percent). The industrial sector is the second largest consumer (42 percent of total consumption), owing primarily to motor drivers and lighting. The public sector's consumption (6 percent of total consumption) is primarily driven by public buildings, street lighting, and water pumping [7].

The energy sector is critical to the Rwandan economy because it is interconnected with almost every other sector, including transportation, housing and urbanization, manufacturing, agro-processing, mining, and information and technology services. The supply and transmission of electricity remain a top priority.

Electricity can be generated in Rwanda using a variety of technologies and natural resources, such as petroleum-based fuels, hydro, solar, methane gas, peat, geothermal, biomass, waste, and wind. Energy efficiency and conservation measures, which include both demand-side and supply-side components, are also gaining popularity [8,9]. In terms of Households (91 percent) consume the most energy, primarily using traditional fuels such as wood, followed by the transportation sector (4%), industry (3 percent), and public services (3 percent) (3%). 2% Households are also the largest consumers of electricity (51%), with lighting accounting for the majority of demand. The industrial sector (42%) consumes the most energy, with motor drivers and lighting being the primary sources. Cement, mining, textile, and agricultural companies are among the largest industrial consumers (including tea estates). Energy is required for the majority of industrial and commercial wealth creation and is essential for increased social and economic well-being [10]. It is critical for alleviating poverty, enhancing human welfare, and raising living standards. However, as important as energy is for development, it is only a means to an end. The goals are good health, a high standard of living, a sustainable economy, and a clean environment.

The Rwandan government made a clear policy decision throughout the development of the EDPRS to diversify electricity sources away from the traditional dominant grid and includes off-grid connections. As a result, households outside of the planned national grid coverage have been encouraged to use alternatively cheaper connections, such as Mini-grids and Solar Photovoltaics (PVs), to lower the cost of access to electricity while relieving constraints on previous government subsidies. Household well-being is commonly expressed in terms of real income. A rise in real output and real incomes implies that people are doing better, and thus household welfare rises [11]. Economic activity is dependent on reliable supply – not just access – because reliability affects the economic realm through income-generating activities, the ability of business operations to remain open for longer periods of time during the day, and thus increasing utilization of installed capacity. Electricity reduces the burden and time required for household work, which may influence labor supply decisions. Electricity availability has an impact on capacity utilization and employment rates. Rwanda's government plans to transition the country from developing to middle-income status. To that end, the government intends to achieve 100 percent electricity access by 2024. Rwanda is rich in natural energy resources such as hydropower, solar power, and methane gas. It has only 218 MW of installed capacity at the moment. Rwanda's national electrification rate is estimated to be 30% by the International Energy Agency (IEA), (12%) in rural areas and 72 percent in urban areas [11].

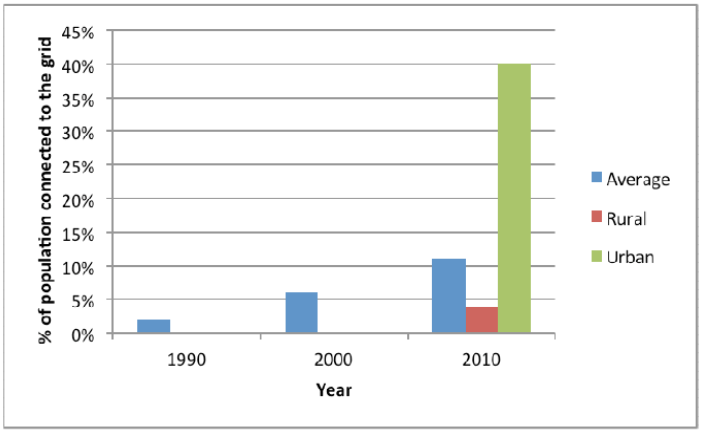

Figure 1. Percentage of Rwandan households have access to electricity (connected to the grid).

At the moment, 1.5 billion people in developing countries lack access to electricity, and 3 billion rely on solid fuels for cooking. A comparable number of people in Sub-Saharan Africa do not have access to electricity or modern fuels (respectively 560 and 625 million people). People in Asian countries may have access to electricity, but they frequently do not have access to modern fuels. Less than 200 million people in East Asia and the Pacific lack access to electricity, but nearly 1.1 billion rely on solid fuels for cooking [12]. An estimated 1.64 billion people lack access to electricity worldwide, with roughly 80% living in rural South Asia and Sub-Saharan Africa. (IEA, 2002). According to the 2001 Census of India, roughly 44% of rural Indians have access to electricity [13]. Lack of access to electricity is inextricably linked to rural poverty. This is because electricity is not only necessary for raising living standards, but it is also a necessary input for productive and economic activities. Because of the bundling of socioeconomic benefits, the positive impacts of electricity inputs for basic activities such as pumping water for drinking and irrigation; lighting for extending working and learning hours; and powering small-scale rural industry are significantly greater for vulnerable rural populations [5]**.**

According to his book, energy has a significant impact on people's lives and serves as a catalyst for social and economic development. Energy has aided in the transformation of societies and the advancement of human civilization over the centuries. Energy helps to meet some of the most basic human needs, such as nutrition, warmth, and light. Furthermore, there is ample evidence that having access to reliable, efficient, cost-effective, and safe energy carriers can have a direct impact on productivity, income, and health, in addition to improving gender equity, education, and access to other infrastructure services. Energy issues are both serious and widespread in the developing world. Up to 90% of the population in many developing countries lacks access to adequate and sustainable energy supplies. Some 2 billion people lack access to electricity, and a similar number cook their meals with fuels such as animal dung, crop residues, wood, and charcoal. People's efforts to engage in productive activities or improve their quality of life are hampered in the absence of efficient, clean energy. People cannot farm or produce goods efficiently if they must spend a significant portion of their time traveling further and further afield in search of diminishing wood fuel. Grzegorz S et al. [14] stated that as civilization progresses, more and more energy resources are required to meet basic social needs as well as production. Inconsistent strategies and inefficient resource use result from a lack of integration in resource assessment and policy making. Electricity access has been linked to increased productivity, business creation, and employment. Businesses that are newly established and rely solely on electricity access may have the potential to improve the overall economic situation and business environment. Electricity is a critical driver of modern technology and socio-economic development, enabling industrial processing activities, value addition, export growth, and job creation for both low-consumption devices like lights and mobile phones and large users like industries. Despite accounting for only about 4% of Rwanda's primary energy consumption, Electricity consumption is expected to skyrocket in the coming years. Rwanda currently has one of the world's lowest per capita electricity consumption rates. Despite Rwanda's dense population, which should make network expansion and access to electricity easier, only 19% of Rwandan households are currently connected to the grid. Human development and modern societies are propelled forward by energy. Access to energy promotes economic and human development, as well as the transition of agrarian societies to industrial societies. As a result, industrialization increases household income, eliminates many contagious diseases, lowers child mortality rates, and extends life expectancy. Many healthcare facilities in developing countries are unable to function due to a lack of energy access, which is required for storing vaccines and performing life-saving procedures. Improved energy access in healthcare facilities will help to increase life expectancy by ensuring timely service delivery [15].

According to current discourses of developmental studies, which conclude that income inequality affects educational opportunities, education is widely recognized as one of the most important components for poverty reduction. Furthermore, primary education yields the highest return on investment. Poor families enroll and complete fewer students because direct and indirect educational costs are significant burdens on them. Poor households face a lack of employment opportunities as a result of their low educational attainment [16]. Literacy levels are influenced by electricity access. Improved boarding school provision of clean water, sanitation, lighting, and cooking energy is facilitated by cleaner and more affordable energy. Rural electrification attracts qualified teachers due to the improved quality of life that comes with having access to electricity. Electricity enables learning to be digitized through the use of electronic equipment such as computers and overhead projectors for learning. Children raised in electrified homes have higher educational attainment and more study time than those rose in non-electrified homes [15]. In the work done by M. Arsene et al. [17], they demonstrated that the effect of access to electricity on educational attainment is theoretically unclear due to the possibility of multiple mechanisms at work. As one possible mechanism, increased access to electricity may increase the demand for low-skilled labor. This would increase the opportunity cost for students to stay in school, resulting in lower educational attainment. Another possibility is that manufacturing jobs are attracted by access to electricity. There are numerous other mechanisms that could influence educational attainment, complicating the impact of electricity on educational attainment uncertain. Economic activity is dependent on reliable supply – not just access – because reliability affects the economic realm via income-generating activities, the ability of business operations to remain open for longer periods of time during the day, and thus increased utilization of installed capacity. Electricity lessens the burden and time required for household chores, which may have an impact on labor supply decisions. The availability of electricity has an impact on capacity utilization and employment rates. The ability to access and use available capital resources has an impact on wages and household income. If electrification is the foundation for inclusive development, a reliable and consistent supply of electricity reduces the amount of time spent on home production, potentially increasing the labor supply of adults, particularly women, in the household. The time saved by not having to go out and buy cooking fuel can be put to better use, increasing household consumption, income, and assets.

Table1. Descriptive of variables

Variables	Description
Household age	Household age indicates the age of family members
Household size	Household size indicates the number of people living as an economic unit means that they indicate the population growth
Household expenditure	Household expenditure stands for the expenses spent on electricity, aggregate consumption, food consumption, and non-food consumption of the sample household
Household salary	Household salary is the salary gained by the household as discussed in the literature energy access impacts the household salary
Household Education	Household education stands for the general number of household heads and spouses who have primary up to university education, education, and access to energy and have a relationship
Electricity accessibility	Electricity access stands for the total population that is connected to the national grid and another source as the main focus is how it affects the household welfare
Non-farm business	Non -farm business stands for all business done by the household other than agriculture in the previous chapter discussion state that electricity access should affect the nonfarm business done by households

2. Methods and materials

2.1 Variable description of NISR with EICV5

This study's data is derived from the NISR's EICV5, which was conducted between 2016 and 2017. This data source contains information on population well-being changes Poverty, inequality, employment, living standards, education, health and housing conditions, household consumption, and so on are examples of such factors. The research framework is made up of the following components: Household income, household expenditure, household education, access to electricity, and nonfarm business, as shown in Table 1.

2.2 Econometric Approach with EICV5

This section describes the general econometric methods used in this study with EICV5 data. To avoid spurious regression, the properties of the variables must be examined in the empirical analysis. The hypothesis demonstrated that energy access has a significant impact on household welfare, including household expenditure, education, nonfarm business, and household member salary. We create an equation to investigate the relationship between energy access and household welfare. The independent variable is on the right side of the equation. "Electricity access" is explicitly used because it affects household welfare. As a result, the model specification can be written in the regression model as follows.

$$log_{hhexp} = \beta o + \beta 1hhage + \beta 2hhsize + \beta 3electricityaccess + \beta 4nonfarmbusiness + \beta 5hhed + \beta_6 salary + \varepsilon_t \quad (1)$$

Data exploration and regression analysis of variables of interest in this study was performed to draw conclusions about the impact of energy accessibility on household well-being. The data used in the study is cross-section data which looks at information from a group of people at a single point in time. The data for this study were derived from the NISR EICV5 survey, which is conducted every three years and polled 14,580 families across the country between late October 2016 and early October 2017.

3. Results and discussion

3.1 Statistical description

Figure 2 shows the descriptive statistics for the variables used in the study. The binary and discrete variables are included in the table. The binary variables have two responses (0 and 1), whereas the discrete variables have numbers such as household head age, household size, salary, and household expenditure, with the exception that the binary response variables include all of the other variables mentioned. It shows that, among the 14,580 observations, the size of the household varies from 1 to 22, and its average of 4.41, which is similar to 1, indicates that households have an average of 4 individuals, which appears to be small compared to 22. The findings show that the age of the head of households is an average of 45.2, with most heads of households appearing to approach 14 years of age than household heads who have 109.

The people who have a salary are likely to be higher than those who do not have a wage and salary the mean is 12.0 with a minimum salary of 2.08 and a maximum of 18.4. Household access to electricity has an average of about 0.25, tending to value between 0 and 1 total use of electricity, the degree of variability shows that the standard deviation of household access to electricity is 0.43 which indicates that the data is not scattered away of mean value this means that the people who are access to electricity are likely to be low than those who are not access.

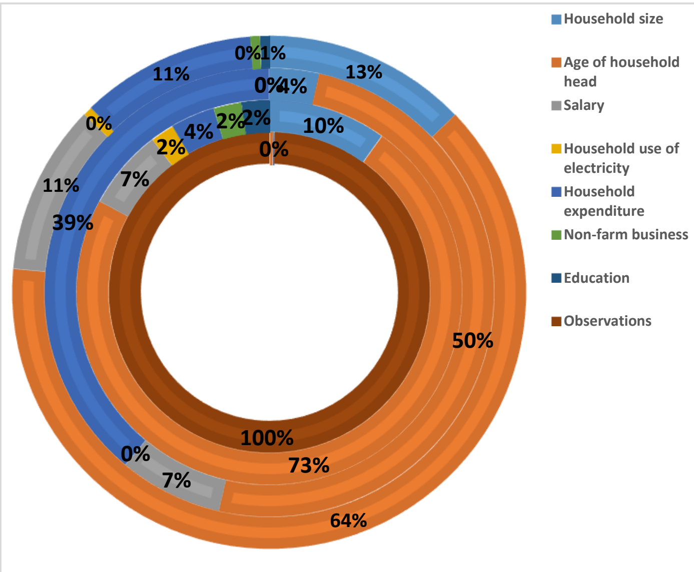

Figure 2. Descriptive statistics

The results show that the household expenditure average value is 14.5 which means that the expenditure of a household is likely to be a high value with a minimum average of 10.9 spending and maximum spending of 18.9. Non-farm business: individuals who practice non-firm business have an average of 0.52, meaning there are more people involved in nonfarm business. The findings show that the number of households who attend the class from primary to university is likely to be low means that the more household has formal education among households under consideration, the household with who have formal education have an average of 0.45.

3.2. Regression Analysis

The use of the regression analysis method allows us to conduct the different impacts of energy access on household welfare that are required to justify the economic models built. They include the impact of Electricity Access on household expenditure, the impact of electricity access on non-farm business, and the effect of access to electricity on household education.

Table 2 shows that access to electricity can affect household welfare through the expenditure of 68.7 % and acceptable at 1%, with all coefficients examined being significantly positive, implying that when the household has access to electricity, the other activities improve. Robust standard errors are represented by values in parentheses which have been defined by (*** p<0.01, ** p<0.05, * p<0.1). Other household and community characteristics, such as nonfarm business and education spending, influence household expenditure. The size of a household, for example, directly impacts expenditure at 12%, education at 26.1%, salary at 13%, and nonfarm business at 13%t. The size of a household, for example, has a direct impact on expenditure (12%), education (26.1%), salary (13%), and nonfarm business (13%): The size of a household, among other things, has a direct impact on food consumption and children's education. Community characteristics, such as rural households, appear to have a negative impact on food consumption and education spending. This finding implies that rural or remote households spend less on food and education for their children. The findings also suggest that rural households live in a subsistence economy in which their labor is not valued and they produce their own food.

Table 2. Regression analysis of household expenditure

Variables	**Household expenditure**
Household use of electricity	0.687***
	(0.0159)
Household size	0.123***
	(0.00277)
Salary	0.130***
	(0.00551)
nonfarm business	0.119***
	(0.0119)
Education	0.261***
	(0.0111)
Constant	12.00***
	(0.0624)
Observations	11,253
R-squared	0.518

Table 3. Regression analysis of non-farm business

Variables	**Nonfarm business**
	0.526***
Household use of electricity	(0.0352)
	(2.67e-06)
Household size	-0.00926
	(0.00627)
Age of household head	-0.0111***
	(0.000815)
Household expenditure	0.587***
	(0.0216)
Non-farm business	0.684***
	(0.0247)
Education	0.118***
	(0.0247)
Constant	6.661***
	(0.621)
Observations	11,253
R-squared	0.359

Table 3 lists the coefficient estimates of non-farm businesses. It increases in access to electricity by 1% will impact non-farm businesses by 52.6% means that when the electricity is more accessible will increase the investment of businesses other than farm businesses for the people because the small and big industries' production needs electricity. Access to electricity is supposed to improve socioeconomic well-being and poverty reduction. These benefits are expected to be realized through a variety of mechanisms. Domestic and economic productivity has increased, as well as the creation of new economic opportunities, many of which are not related to agriculture, are expected as a result of new and/or improved access. Positive externalities could result from potential increases in household and corporate wealth.

Table 4 shows that access to electricity can impact education at 52.6% this means that more people's access to electricity encourages people to study by expanding the hour of study which may yield the desired results. Electricity is frequently assumed to improve educational outcomes, and there are several potentials and theorized causal pathways by which this may occur. The main mechanism highlighted in the studies included new and/or improved lighting, which would allow for an extended effective school day and flexible home study. The primary point is that having access to electricity leads to improved educational outcomes, which implies more and better human capital accumulation, which translates into increased labor supply and household incomes. Access to electricity, in particular, appears to promote women's economic participation by relieving them of tasks such as biomass collection and, more broadly, by allowing them to make better use of their time. In this vein, increases in female employment are primarily the result of increased small-scale self-employment. Increased nighttime light intensity. In terms of mechanism, in addition to overall electricity access, does not contribute to increased average years of schooling. This finding implies that having access to electricity during the day, rather than just at night, benefits household cluster educational attainment. This discovery implies that the impact of electricity on education may have occurred through channels other than illumination, such as labor savings.

Table 4. Regression analysis of household salary

Variables	**Salary**
Household use of electricity	0.526***
	(0.0352)
Hhid	-1.58e-05***
	(2.67e-06)
Age of household head	-0.0111***
	(0.000815)
Household size	-0.00926
	(0.00627)
Household expenditure	0.587***
	(0.0216)
Non-farm business	0.684***
	(0.0247)
Education	0.118***
	(0.0247)
Constant	6.661***
	(0.621)
Observations	11,253
R-squared	0.359

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

According to the coefficient estimates of electricity access on salary, the household is likely to increase their salary by 52.6% for every 1% increase in access to electricity. This indicates that every percentage point of electricity access has an effect on household earnings, same as non-farm business and education also can impact the household salary by 68.4% and 11.8%

Household income increased as access to electricity improved, Non-farm income has a larger effect size, as reported. Despite the fact that separating farm and non-farm income produced no statistically significant effect sizes for either source of employment [18], farm employment increased only marginally.

3. Conclusions

In this research, EICV5 data from Rwanda's National Institute of Statistics have been used to conduct a more detailed assessment of the impact of energy access on household expenditure, salary, non-farm business, and education. However, simple Ordinary Square regression analysis was used to investigate the impact of electricity on household expenditure, salary, education, and non-farm business. The findings revealed that access to electricity directly impacts expenditure via various channels such as salary generated from non-farm business and increasing the level of study up to the university level. The results indicate that access to electricity has a positive and statistically significant impact on household expenditure, which plays a critical role in household welfare at a rate of 68%. This means that access to electricity has a significant impact on household life. Additionally, the findings show that electricity access continues to play a vital role in household welfare and where positively impacts the salary, education, and non-farm business at a significant level. This means that as the government continues to increase the level of energy connectivity, especially rural electrification will increase the well-being of people as well as economic growth occurs.

Nomenclature

EDPRS	Economic Development and Poverty Reduction Strategy
PPP	Purchasing Power Party
GDP	Gross Domestic Product
EAC	East African countries
KWH	Kilowatt-hour
REG	Rwanda Energy Group
MW	Megawatt
IEA	International Energy Agency
USAID	United States Agency for International Development
EICV	Integrated Household Living Conditions Survey
NISR	National Institute of Statistics
OLS	Ordinary Least Square
%	Percentage
MININFRA	Ministry of Infrastructure

Conflict of Interest Statement

The authors declare that there is no conflict of interest in the study.

CRediT Author Statement

U. Redempta: Conceptualization, Data curation, investigation, Software, Writing-original draft, Validation, Formal analysis, **U. Julie:** Writing-original draft, Validation, **T. Pacifique:** Writing review & editing.

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Review Paper

A Comprehensive Review on Stirling Engines

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ABSTRACT

Stirling engines work with all kinds of heat sources thanks to the external heat supply. It has many advantages over internal combustion engines, especially in terms of noise emissions and pollutant emissions. Since the first Stirling engine invented by Robert Stirling, development work continues on it. Considering the problems caused by fossil fuels, Stirling engines are promising in the recovery of solar energy, geothermal energy and waste heat. As a result of the studies carried out from the past to the present, many Stirling engine types, cylinder configurations and drive mechanisms have been designed. In this study, the importance, advantages-disadvantages, usage areas and working principles of Stirling engines are explained. The Stirling cycle has been analyzed in detail. Carnot cycle and Ericsson cycle are mentioned and these three cycles are compared with each other in terms of work and efficiency. Stirling engine classifications, cylinder configurations and drive mechanisms are explained in detail. The design differences, operating characteristics, technological details and structural features of these configurations are examined. The advantages and disadvantages of all these different structures in terms of design, production, cost, power, efficiency, friction, wear, sealing, weight, dead volume, noise and number of parts are stated.

Keywords: Drive mechanisms, Low temperature, Stirling configuration, Stirling cycle, Stirling engines

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1. Introduction

Energy is the most important requirement for countries to have developing technology and to reach a modern life level. The energy needs of countries are increasing in proportion to their economic growth, and the energy provided from existing energy sources is becoming more costly day by day. It is not possible to meet this increasing energy need with existing energy resources. Today, most countries meet their energy needs with primary energy sources such as oil, natural gas and coal. These fuels, which constitute a large part of the energy need, cause global warming. In particular, the increase in the concentration of CO_2 in the atmosphere is one of the main causes of global warming. In addition, emissions that occur during energy production from fuels such as coal, oil and natural gas pollute vital environments. Pollution of these vital environments such as air, water and soil harms nature, human life and ecological system. The negative effects of fossil energy sources, which are called primary energy sources, have brought to the fore renewable energy sources that are easily available and do not harm the environment. Many countries accelerated their search for renewable energy sources with the energy crisis in the 20th century. Solar and wind energies come to the fore in electricity production. On the other hand, biomass energy is accepted as one of the main energy sources that are shown as an alternative to fossil fuels, which are depleted over time.

Stirling engines can work with many alternative energy sources. Since it is seen as a solution to the problems caused by fossil fuels, the interest in these external combustion engines is increasing day by day. In addition, its high efficiency and advantages in the recovery of waste heat at relatively low temperatures stand out. In Stirling engines (Patent No. 4081) [1], invented by Robert Stirling in 1816, heat energy is converted into mechanical work by using different working fluids such as air, helium and hydrogen. The Stirling cycle theoretically has the same thermal efficiency as the Carnot cycle. These engines are operated with any external heat source and there is no restriction in terms of fuel type. Stirling engines, which can operate at low temperature differences (LTD), are particularly striking in the utilization of low-temperature sources such as geothermal energy [2,3].

Although Stirling engines were developed long before internal combustion engines, rapid developments in internal combustion engines made Stirling engines unable to compete with these engines. However, these engines have come to the fore again due to the decrease in fossil fuels and their damage to the environment. The advantages of Stirling engines are explained as follows. Combustion is continuous. There are no intake and exhaust valves. Pressure changes are sinusoidal. Noise formation is at minimum level due to the fact that it has fewer moving parts compared to internal combustion engines. Therefore, maintenance and repair operations are easy. First actuation is easy. They can work with all fuel types and heat energy types. Parts wear is less. Since there are no sudden pressure rises as in internal combustion engines, moving engine parts are less damaged. Therefore, they work longer. Since the lubricating oil does not act as a cooling agent, thermal losses do not occur as in internal combustion engines. The oil change interval is longer and the oil consumption is lower. Thanks to externally controlled combustion, CO, unburned HC, NO_X and particulate emissions are low. They can be designed in different mechanical arrangements and in different sizes. They require less maintenance due to the absence of auxiliary systems such as ignition, fuel and valve mechanism [3-8]. The disadvantages of Stirling engines are explained as follows. They have greater mass and dimensions compared to an internal combustion engine of the same power. The power/weight ratio is less than internal combustion engines. There are sealing problems between the piston-cylinder and the mechanical power output. Deceleration and acceleration responses are very low due to thermal inertia in the heater and cooler regions. Many parts have design difficulties. In addition, since it requires experimental knowledge, the design costs are high. Research and development studies are still continuing. In these engines, in which gases such as helium and hydrogen are used as the working fluid, the gas discharge over time increases the operating costs. Over time, a corrosion layer forms on the surface of the parts exposed to high temperatures [9,10].

Today, development work on these engines is still ongoing. Different studies are carried out on the selection of the drive mechanism, working fluid, regenerator material and optimization of the dimensions of the engine. It is aimed to reduce dead volumes, improve in-cylinder flow and heat transfer, prevent losses due to friction and working fluid leakage, and reduce production and maintenance costs. With the development of Stirling engines, the energy needed will be produced economically without polluting the environment. Various energy sources such as solar energy, radioisotope, biomass, geothermal energy can be used in Stirling engines thanks to external controlled heat generation [9-13]. Stirling engines, which have a wide range of uses, are used in the production of electricity from solar energy, in space vehicles, in marine vehicles, in irrigation of agricultural fields, in submarines and torpedoes, in cooling systems, in nuclear reactor power stations, in heat pump systems, in automotive field and as auxiliary power engine [10,14-16].

In this article, the thermodynamic cycles of Stirling engines are analyzed and explained in detail and comparatively. Information is given about the classifications, cylinder arrangements and drive mechanisms of Stirling engines. Different structures within these headings are compared on important issues such as power, thermal efficiency, ease of design, production and maintenance cost, dead volume, friction, lubrication, leakage and weight. In addition, an idea is given about the technological details and system performances of Stirling engines.

2. Thermodynamics of Stirling Engines

The basic principle of the Stirling cycle is based on the compression of the cold working fluid and the expansion of the hot working fluid. During these processes, heat is converted to work, as the amount of work required for compression is less than the amount of work resulting from expansion.

The cycle consists of two constant temperature and two constant volume operations. Heat is given to the system by a heater and this heat is thrown out by another heat exchanger called a cooler. The heat required for work production is given by an external heat source such as coal, gas, solar energy, nuclear energy, which is outside the engine, and the cycle is maintained without interruption. For this reason, Stirling engines are examined in the category of external combustion engines.

2.1 Ideal Stirling cycle

In the Stirling cycle, isoentropic compression and expansion processes in the Carnot cycle are replaced by constant volume regeneration processes. With the regeneration processes, heat transfer takes place at every stage of the Stirling cycle. During the regeneration processes, the heat of the working fluid is stored in the regenerator and is used to heat the cooled working fluid again in the later stages of the cycle. The regenerator can also be defined as a reversible heat transfer device. Regenerators are generally produced from ceramic mesh, wire or porous material with high thermal mass. One side of the regenerator is defined as the expansion volume (high temperature zone), and the other side is defined as the compression volume (low temperature zone). It is assumed that the working gas moves between these zones without friction and pressure losses.

P-V and T-S diagrams of the Stirling cycle are shown in Figure 1. The area under the P-V diagram constitutes the net work, and the area under the T-S diagram constitutes the heat transfer.

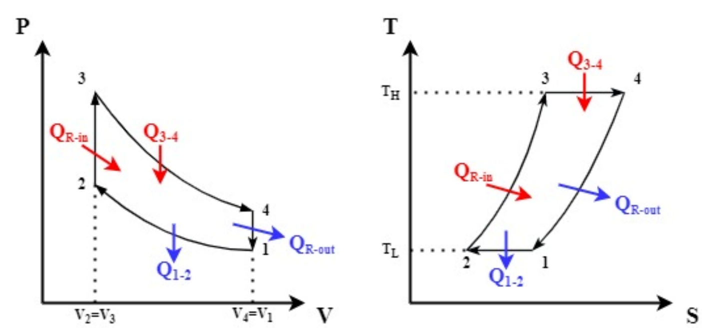

Figure 1. P-V and T-S diagrams of the Stirling cycle

The Stirling cycle process includes:

1-2 isothermal compression: The temperature increased during compression is kept constant by cooling the system.

2-3 constant volume regeneration: Heat is transferred from the regenerator to the low temperature working fluid.

3-4 isothermal expansion: The increased temperature during expansion is kept constant by heat input into the system from an external source.

4-1 constant volume regeneration: Heat is transferred from the high temperature working fluid to the regenerator.

While the working fluid passes from the hot volume to the cold volume, it stores the heat on the regenerator, and when it passes from the cold volume to the hot volume, the heat energy stored in the regenerator is given back to the working fluid. With this feature, the regenerator reduces the dead volume of the coolant and brings the heat thrown back into the system. This situation increases the efficiency of the system while saving heat.

For a better understanding of the thermodynamic processes, the working processes of a Beta type Stirling engine are shown in Figure 2.

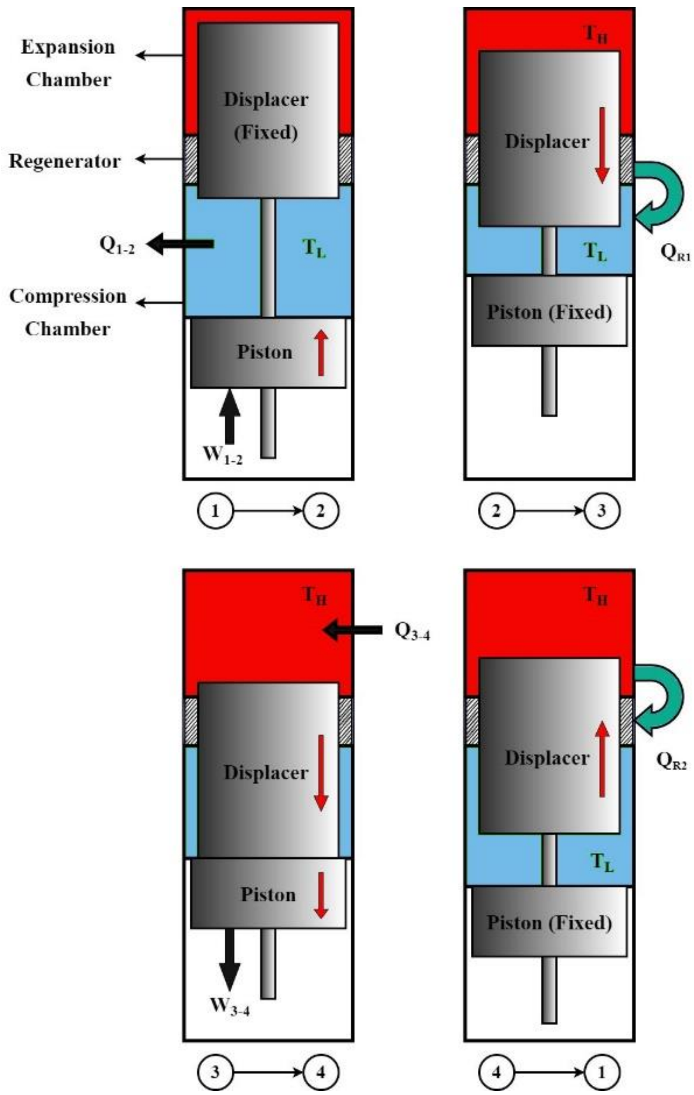

Figure 2. The cycle of the Beta-type Stirling engine

In 1-2 isothermal compression processes, the displacer piston is stationary at the top dead center of the cylinder. Most of the working fluid is in the compression zone and at low temperature T_L. In this process, the working fluid is compressed by the power piston at the bottom dead center, while the system is cooled to maintain its low temperature T_L. The W_{1-2} compression work required for this process is expressed as the area under the P-V diagram.

In 2-3 constant volume regeneration processes, the power piston is stationary at top dead center of the cylinder. As the displacer piston at the top dead center moves downwards, the working fluid flows from the compression zone to the expansion zone. There is a low temperature T_L in the compression region and a high temperature T_H in the expansion region. No work is done during this process. However, heat transfer from the regenerator to the low temperature working fluid takes place.

In 3-4 isothermal expansion processes, the power piston and the displacer piston move downwards together. Most of the working fluid is at high temperature T_H in the expansion zone. The high temperature T_H is maintained by providing heat to the system from an external source. The resulting expansion work W_{3-4} in this process is the sum of compression work W_{1-2} and net work W_{net}.

Finally, in 4-1 constant volume regeneration processes, the power piston is stationary at bottom dead center of the cylinder. As the displacer piston at the bottom dead center moves upwards, the working fluid flows from the expansion zone to the compression zone. There is a low temperature T_L in the compression region and a high temperature T_H in the expansion region. No work is done during this process too. However, in contrast to process 2-3, heat transfer occurs from the high temperature working fluid to the regenerator.

The same working fluid with high thermal conductivity is used in each cycle of the Stirling engine. Examples of common working fluids in these engines are oxygen, helium, air and nitrogen. These gases provide rapid heat transfer with their low molecular mass. Stirling engines do not have valves, as in internal combustion engines. There is no gas input or output to the system during the cycle. Pressure changes are smooth in Stirling engines. Since there is no valve, exhaust and intake, they operate more quietly and require less maintenance. The main reason why Stirling engines have not been widely used in automotive applications is the slow change in power output. In addition, for high efficiency, it must be operated in high pressure conditions where sealing problems occur. The net work and the amount of heat transferred from the Stirling cycle are shown in Equations (1-14).

$$W_{net} = \oint PdV \tag{1}$$

$$W_{net} = W_{3-4} + W_{1-2} \tag{2}$$

$$PV = mRT \rightarrow P = \frac{mRT}{V} \tag{3}$$

$$W_{net} = \int_3^4 \frac{mRT_H}{V} dV + \int_1^2 \frac{mRT_L}{V} dV \tag{4}$$

$$W_{net} = mRT_H \ln\left(\frac{V_4}{V_3}\right) + mRT_L \ln\left(\frac{V_2}{V_1}\right) \tag{5}$$

$$V_2 = V_3 \;\; and \;\; V_1 = V_4 \rightarrow \ln\left(\frac{V_4}{V_3}\right) = -\ln\left(\frac{V_2}{V_1}\right) \tag{6}$$

$$W_{net} = mRT_H \ln\left(\frac{V_4}{V_3}\right) - mRT_L \ln\left(\frac{V_4}{V_3}\right) \tag{7}$$

$$W_{net} = mR \ln\left(\frac{V_4}{V_3}\right)(T_H - T_L) \tag{8}$$

$$W_{net} = Q_{in} - Q_{out} \tag{9}$$

$$Q_{in} = Q_{3-4} = W_{3-4} = mRT_H \ln\left(\frac{V_4}{V_3}\right) \tag{10}$$

$$-Q_{out} = Q_{1-2} = W_{1-2} = mRT_L \ln\left(\frac{V_2}{V_1}\right) \tag{11}$$

$$\eta_{Th} = \frac{W_{net}}{Q_{in}} \tag{12}$$

$$\eta_{Th} = \frac{mR(T_H - T_L)\ln\left(\frac{V_4}{V_3}\right)}{mRT_H \ln\left(\frac{V_4}{V_3}\right)} \tag{13}$$

$$\eta_{Th} = \frac{T_H - T_L}{T_H} = 1 - \frac{T_L}{T_H} \tag{14}$$

Since heat transfer takes place at constant temperatures in the Stirling cycle, the thermal efficiency is higher than that of the Otto and Diesel cycle and equal to that of the Carnot cycle. The thermal efficiency in the Stirling cycle depends on the temperature difference T_H and T_L. Since the increase of this temperature difference increases the efficiency, it should be worked with hot-cold temperature differences that cause high thermal loads. High loads caused by heat and pressure require production with expensive materials with high strength. In Stirling engines, the equations related to the heat stored in the regenerator are shown between Equations (15-22). In addition, the amount of heat stored in the regenerator was calculated to obtain 50 joules of net work by using the heat capacity ratio of different working fluid. The resulting graph, which is obtained as a result of the calculations for hydrogen, air and helium, is shown in Figure 3.

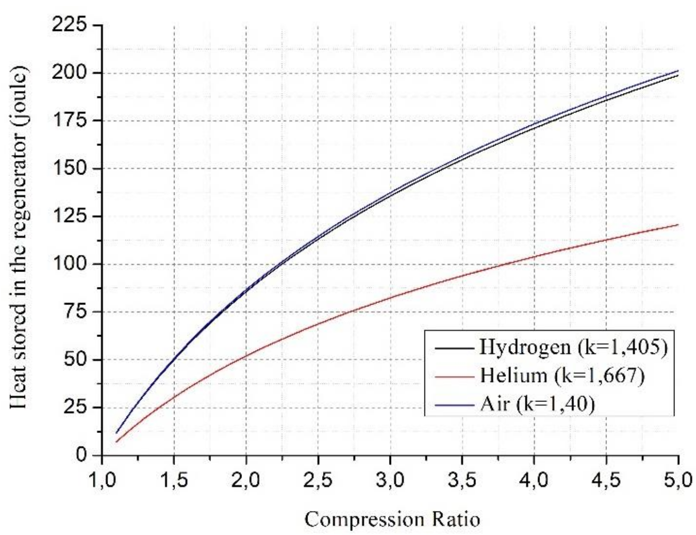

Figure 3. Heat stored in the regenerator for 50 joules of net work

$$Q_R = m\Delta U = mC_V \Delta T \tag{15}$$

$$Q_{Rin} = Q_{2-3} = mC_V (T_H - T_L) \tag{16}$$

$$Q_{Rout} = Q_{4-1} = mC_V (T_L - T_H) \tag{17}$$

$$W_{net} = mR\ln\left(\frac{V_1}{V_2}\right)(T_H - T_L) \tag{18}$$

$$\varepsilon = \frac{V_1}{V_2} \tag{19}$$

$$Q_{Rin} = Q_{2-3} = C_V \frac{W_{net}}{R\ln(\varepsilon)} \tag{20}$$

$$\frac{C_V}{R} = \frac{1}{k-1} \tag{21}$$

$$Q_{Rin} = Q_{2-3} = \frac{W_{net}}{(k-1)\ln(\varepsilon)} \tag{22}$$

2.2 Carnot cycle

The isoentropic and isothermal processes in the Carnot cycle do not occur as desired in practice. Therefore, power machines cannot achieve the high thermal efficiency of the cycle. The Carnot cycle is basically used as a basic reference in the analysis of power machines. P-V and T-S diagrams of the Carnot cycle are shown in Figure 4.

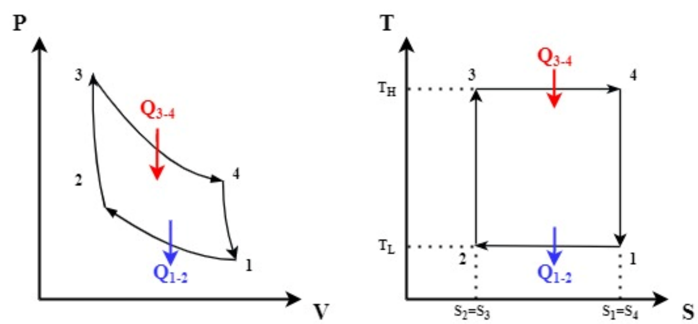

Figure 4. P-V and T-S diagrams of the Carnot cycle

The Carnot cycle process includes:

1-2 isothermal compression: The temperature, which tends to increase due to compression, is kept constant at the low temperature TL by cooling the system.

2-3 isoentropic compression: Compression takes place at constant isoentropy.

3-4 isothermal expansion: The temperature, which tends to decrease due to expansion, is kept constant at the high temperature T_H by heat input into the system.

4-1 isoentropic expansion: Expansion takes place at constant isoentropy.

In the Carnot cycle, the constant volume processes in the Stirling cycle are replaced by isoentropic compression and expansion processes. If it is assumed that the heat is given to the system at the temperature T_H, and the heat is removed from the system at the temperature T_L, the efficiency of the Carnot and Stirling cycles with regenerator are equal to each other. However, since the Stirling cycle takes place at a constant volume, the net work output is higher than the Carnot cycle. The superposition of the P-V and T-S diagrams of the Stirling and Carnot cycles within the pressure, volume and temperature limits is shown in Figure 5.

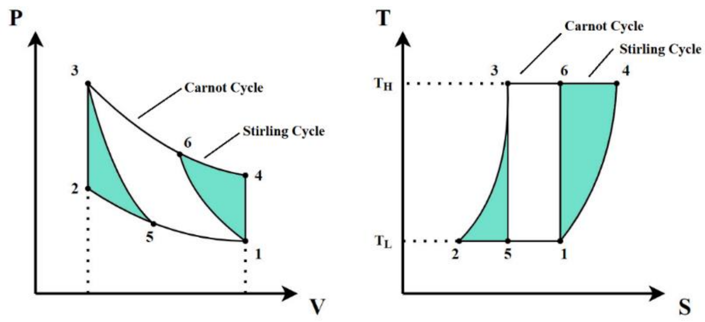

Figure 5. P-V and T-S diagrams of the Stirling and Carnot cycles

As seen in the diagrams, constant volume displacement processes replace isoentropic processes and provide additional fields (5-2-3 and 6-4-1) to the Stirling cycle in P-V and T-S diagrams. The 1-5 and 3-6 isothermal processes in the Carnot cycle are expanded with the 1-2 and 3-4 isothermal processes in the Stirling cycle, increasing the amount of heat supplied to and removed from the system and the net work amount. The amount of heat given to the system is the same in both cycles. In this case, it is assumed that the heat exchange is at a constant temperature, and the thermal efficiency is considered to be at its maximum value according to the second law of thermodynamics. Thus, it ensures that the thermal efficiencies of both cycles are the same.

2.3 Ericsson cycle

Ericsson cycle is quite similar to Stirling cycle. Constant volume regeneration processes in the Stirling cycle are replaced by constant pressure regeneration processes in this cycle. The efficiency of Ericsson with regenerator, Stirling with regenerator and Carnot cycles operating at equal temperature differences are considered equal. Ericsson cycle is used at lower pressure ratios compared to Stirling and Carnot cycles. In these cycles, the thermal efficiency depends on the difference between low and high temperature values. The thermal efficiency (η_{Th}) equation of these cycles is shown in Equation (23). P-V and T-S diagrams of the Ericsson cycle are shown in Figure 6.

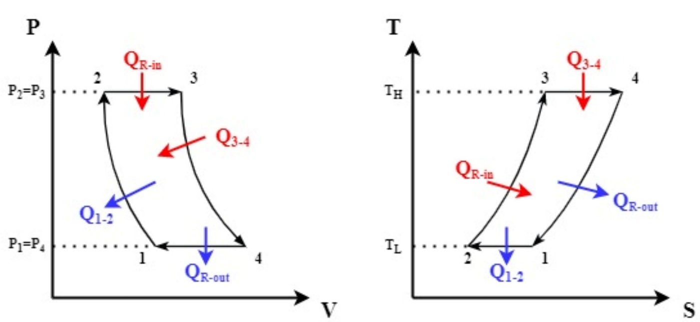

Figure 6. P-V and T-S diagrams of the Ericsson cycle

$$\eta_{Th,Stirling} = \eta_{Th,Carnot} = \eta_{Th,Ericsson} = 1 - \frac{T_L}{T_H} \tag{23}$$

The Ericsson cycle process includes:

1-2 isothermal compression: The temperature, which tends to increase due to compression, is kept constant at the low temperature TL by cooling the system.

2-3 constant pressure regeneration: Heat is transferred from the regenerator to the low temperature working fluid.

3-4 isothermal expansion: The temperature, which tends to decrease due to expansion, is kept constant at the high temperature T_H by heat input into the system.

4-1 constant pressure regeneration: Heat is transferred from the high temperature working fluid to the regenerator.

In the Ericsson cycle, the regeneration process takes place at constant pressure instead of at constant volume as in the Stirling cycle. The superposition of the P-V and T-S diagrams of the Carnot and Ericsson cycles are shown in Figure 7. Ericsson cycle efficiency is on par with Carnot and Stirling cycles with regenerator. However, the amount of heat transferred and converted into work at the pressure, volume and temperature limits is greater than the Carnot cycle.

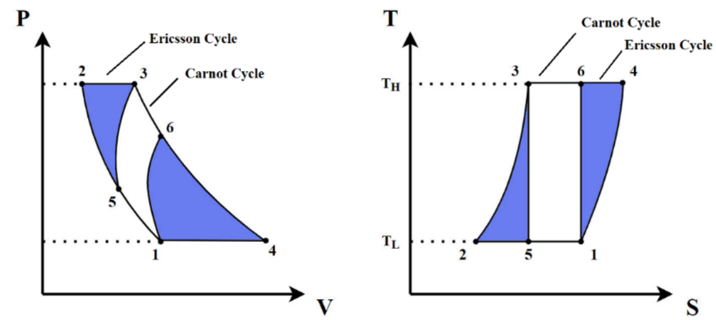

Figure 7. P-V and T-S diagrams of the Ericsson and Carnot cycles

3. Classification of Stirling Engines

After the first Stirling engine manufactured by Robert Stirling in 1816, many engines with similar features were developed. Although the working principles of these engines are the same, some design differences have occurred due to reasons such as increasing their thermal efficiency, reducing dead volumes, reducing manufacturing costs and maintenance costs [10].

We can basically classify Stirling engines according to their mechanical configurations or operating principles. Examples of engines classified according to their mechanical configurations are kinematic Stirling engines and free-piston Stirling engines. Kinematic Stirling engines have mechanical connections between the crankshaft, power piston and displacer piston. With these connections, the movements of the power piston and the displacer piston are limited. Piston movements are transmitted to the flywheel by mechanisms such as slider crank, rhombic mechanism, swash plate or ross-yoke. On the other hand, in free-piston Stirling engines the power piston and the displacer piston move in the same cylinder with a certain phase difference and there is no mechanical connection between them. In free-piston Stirling engines, the movement resulting from pressure changes is usually transmitted by the power piston to the linear alternator [17].

Double-acting Stirling engines, low temperature differential (LTD) Stirling engines and thermoacoustic Stirling engines can be given as examples to Stirling engines that we can classify according to their working principles. In double-acting Stirling engines, a wide variety of arrangements with few parts can be created by placing a heater and regenerator between the expansion volume of one cylinder and the compression volume of the other cylinder. LTD Stirling engines, as the name suggests, can operate at very low temperature differences between their hot and cold ends. Because of this feature, these engines are preferred in benefiting from solar energy, in geothermal applications and in the recovery of wastes as a heat source.

In thermoacoustic Stirling engines, work is produced by causing pressure changes in the system with high amplitude acoustic waves caused by temperature difference. The interest in thermoacoustic systems is increasing day by day due to their low cost, simple structure and absence of moving parts. Liquid piston Stirling engines, have no moving mechanical parts and the liquid columns act as pistons. Oscillatory movements occur in the liquid columns due to the temperature difference. This situation creates pressure changes and provides work to be obtained.

3.1 Kinematic Stirling engines

In kinematic Stirling engines, the power piston and the displacer piston are connected to the output shaft by a mechanical connection. Many types of mechanical connections have been designed to improve power transmission and increase engine strength over time. The development and analysis of these connection types remains an active area of study. In addition, crank and motion transmission mechanisms in kinematic Stirling engines generate lateral forces and require lubrication. A gasket is used to prevent the working fluid from escaping between the crankcase and the cylinder. The high number of moving parts also increases the need for maintenance in these systems. The kinematic Stirling engine with Beta-type rhombic drive mechanism designed by Andy Ross is shown in Figure 8.

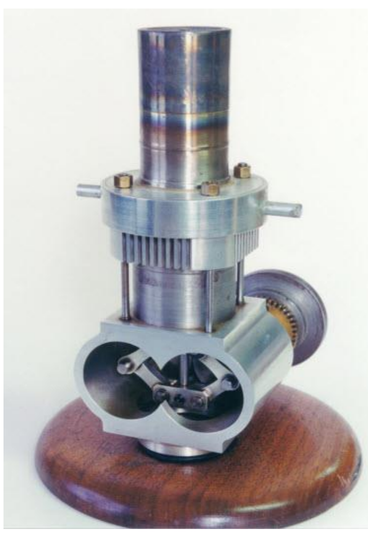

Figure 8. Beta-type kinematic Stirling engine [18]

Kinematic Stirling engines are mechanically complex, like internal combustion engines, due to their mechanical conection. The amplitude of the power piston and displacer piston movement is constrained by these mechanical connections. Today, 60% of companies working on Stirling engine development prefer kinematic Sitrling engines. The reason why these engines, which have mechanical connections and shafts, are preferred is the familiarity with the working methods similar to internal combustion engines [19].

3.2 Free-Piston Stirling engines

Free-piston Stirling engines were designed by Beale at Ohio University in the 1960s with the aim of reducing sealing problems and eliminating the difficulties in lubricating the drive mechanism [17,20-23]. In free-piston Stirling engines, there is no mechanical connection between the displacer piston and the power piston. It is therefore mechanically quite simple compared to kinematic Stirling engines. In free-piston engines, which are similar to Beta-type Stirling engines in terms of cylinder structure, displacer piston movement is free [21]. The power piston works in connection with a linear alternator.

Generally, the outer surface of the cylinder functions as heater, cooler and regenerator. As in kinematic engines, gases such as helium and hydrogen with high heat transfer coefficient are used as working fluid in this type of engines. While the reciprocating movement of the piston creates the compression-expansion processes, the displacer piston moves the working fluid between the hot and cold regions, thus providing the heat flow required for the cycle. The oscillation of the displacer piston, which has a very small mass compared to the power piston, is damped by the working fluid flowing from the regenerator and is supported by springs and the compressibility effect of the working fluid. The heavy power piston, oscillates without damping except for the magnetic field forces produced by the linear alternator. The spring between the two pistons provides the force required to initiate the harmonic oscillations of the displacer. The temperature difference in the system maintains the oscillations, allowing the system to operate at the natural frequency of the mass-spring system [19]. The schematics of the Beta-type free-piston Stirling engine and its basic parts are shown in Figure 9.

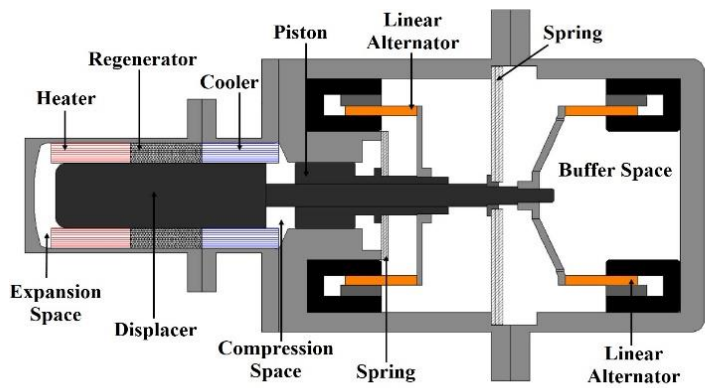

Figure 9. The free-piston Stirling engine [24]

The free-piston Stirling engine, which is directly connected to the linear alternator, allows long-term operation due to the small amount of part movement it has. It stands out with its low amount of wear and less maintenance need. Generating the engine working volume as a single closed unit has eliminated the problem of working fluid leakage [10]. In addition, the use of flexible rings in this type of engine provides an advantage in terms of sealing by reducing friction and wear.

In this type of engines, obtaining the power at the engine output linearly is a disadvantage in systems such as pumps and compressors [21]. In addition, the oscillations of the moving parts cannot be adjusted mechanically. It is determined by the interactions of the whole system with each other. Complex calculations are required to obtain the appropriate motion and power output. Due to its oscillating nature, the response time is delayed compared to kinematic Stirling engines and internal combustion engines. Piston positions during operation are quite critical and difficult to control. The imbalance in piston movements directly affects the power output [19].

3.3 Double-Acting Stirling engines

One of the easiest ways to increase power output in Stirling engines is to increase the swept volume. However, the performance of a single-cylinder Stirling engine with a large cylinder is limited due to increased dead volume and inefficient heat transfer. By increasing the number of cylinders, these negativities can be prevented and the sweeping volume can be increased. The double-acting Stirling engine designed for this purpose takes its name from the fact that its piston is under the influence of hot and cold working fluid on both sides.

The theory of the double-acting Stirling engine was first put forward by Franchot in 1853, and Babcocok produced the first double-acting engine in 1885. In 1959, after Finkeistein and Polanski's studies on this type of engine, Siemens designed the four-cylinder double-acting Stirling engine. The production of this engine was carried out by Weenan with the invention of the swash plate drive mechanism. The Stirling automobile engine, produced by Philips and Ford companies, was also designed with a four-cylinder double-acting structure, and a swash plate drive mechanism was used in this engine [10,25]. Double-acting Stirling engine, which is a joint production of Ford and Philips, is shown in Figure 10.

Figure 10. Ford and Philips' double-acting Stirling engine [26]

Double-acting Stirling engines generally consist of four cylinders and are generally used with a swash plate drive mechanism. In this engine configuration, the expansion volume of one cylinder and the compression volume of the other cylinder are connected by flow channels. There are heater, regenerator and cooler on the flow channels. There is a 90° phase difference between the pistons in adjacent cylinders [27]. Since the pistons working with phase difference carry the working fluid between the heater, the regenerator and the cooler, they also act as a displacer. For this reason, double-acting Stirling engines do not have a displacer piston. A wide variety of arrangements can be created with this method. A double-acting Stirling engine has half the number of cylinders and pistons compared to four single-acting Stirling engines. This increases the power density of the engine, reduces production costs and simplifies the design. The disadvantage of double-acting Stirling engines is that the size of the engine cannot be reduced as easily as in single-acting Stirling engines. The schematics of the four cylinder double-acting Stirling engine is shown in Figure 11.

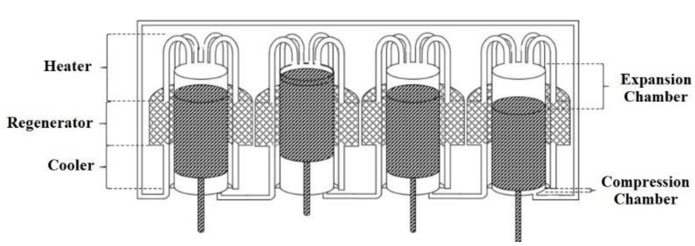

Figure 11. The double-acting Stirling engine [28]

In double-acting engines, only the piston rods are associated with the external environment, reducing working fluid leaks. In these engines, the total net work is shared thermodynamically between the four cylinders with a 90° phase difference. This shows us that the compression and expansion operations are performed by the four cylinders at different times in each cycle [29]. The most common of the double-acting Stirling engines is the Alpha-type four cylinder engine configuration [30].

3.4 Low temperature differential (LTD) Stirling engines

This type of engine, which has a different structure from other Stirling engines, is called low temperature differential Stirling engine (LTD) because it can operate at very low temperature differences [31]. LTD Stirling engines can operate at very low temperature differences between the hot and cold ends of the displacer cylinder. Due to these features, these engines are preferred in utilizing solar energy, in geothermal applications and in the recovery of wastes that can be used as a heat source [10,32,33]. LTD Stirling engines produce relatively low power. However, it is of interest when considering the possibility of power generation from heat sources at temperatures lower than 100 $^\circ$C [33].

The general features of LTD Stirling engines are as follows:

- The displacer piston/power piston swept volume ratio is large.
- The displacer cylinder and piston have a large diameter.
- The heat transfer surface area of the displacer cylinder is large.
- Displacer piston stroke is too small for its diameter.
- Engine speed is low [33,34].

LTD Stirling engines are examined in two groups as kinematic engines and ringbom engines. Many of the kinematic LTD Stirling engines designed in past years have a large diameter short displacer piston, as well as a much smaller diameter power piston. These types of engines are Gamma-type Stirling engines with a slider crank drive mechanism. In kinematic LTD Stirling engines, the displacer piston and the power piston are connected to the crankshaft by a connecting rod.

In some LTD Stirling engines, only the power piston is connected to the crankshaft. The displacer piston moves freely in response to the pressure difference between the cylinder and the atmosphere. This configuration is also known as the LTD ringbom Stirling engine. Ross-yoke drive mechanism is preferred in some medium temperature difference engines. Due to the complexity of the mechanical structures, low and medium temperature differential Stirling engines with Rhombic or swash plate drive mechanisms have not been developed. Many LTD Stirling engines use annular space between the displacer piston and the cylinder as the regenerator, rather than the porous structure [3,31,33]. In 2008, Micro Star International (MSI) company placed LTD Stirling engine on the motherboard for cooling the motherboard in computers. The LTD Stirling engine seen in Figure 12 works by taking heat from the motherboard [10].

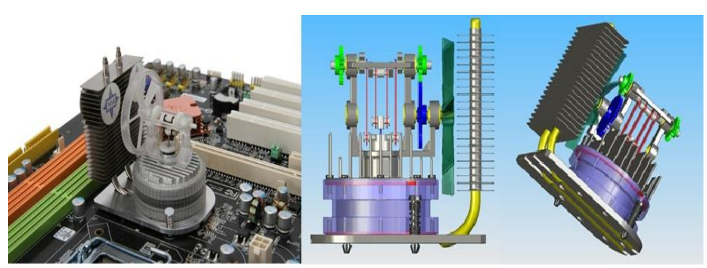

Figure 12. LTD Stirling engine used by MSI company [35]

One of the most important problems to be solved in Stirling engines is to regulate the flow of working fluid between hot and cold regions and to reduce thermal losses. In this way, the conduction heat transfer from the hot region to the cold region can be reduced. By shortening the length of the displacer piston, the compression ratio is also reduced as well as the temperature difference. For this reason, the diameters of the displacer piston and the displacer cylinder are enlarged to provide sufficient volume in the displacer cylinder [31]. Although it has limited application areas, there are many studies in the literature about LTD Stirling engines for the recovery of waste heat thanks to its ability to operate at very low temperature differences. Moreover, the cost of these studies is quite low [36].

3.5 Thermoacoustic Stirling engines

In 1979, Ceperley [37,38] noticed that the phase between the pressure and velocity of the working fluid in the regenerator of a Stirling engine is the same as in a moving acoustic wave. Thus, the idea of using acoustic waves instead of moving pistons was put forward to control the gas movement and gas pressure in the Stirling cycle [3,39-41].

Thermoacoustic Stirling engines work with the acoustic power created by heating and cooling on the working fluid. With the high amplitude acoustic waves produced, heat can be pumped from one place to another, as well as electricity generation with acoustic-electric converters. Having few moving parts has eliminated sealing and lubrication problems. The high amplitude acoustic standing waves in these engines cause compression and expansion processes similar to the power piston. On the other hand, acoustic motion waves operating with phase difference act as a displacer piston and cause displacement along the temperature gradient. For this reason, thermoacoustic Stirling engines do not have a displacer piston as in Beta or Gamma-type engines. Thermoacoustic Stirling engines are designed in three types, as traveling-wave engines, standing-wave engines and traveling-standing wave hybrid-type engines.

The traveling-wave thermoacoustic Stirling engine consists of a looped-tube in which a thermoacoustic core is inserted. Thermoacoustic core consists of heater, regenerator and cooler. The looped-tube connecting both sides of the thermoacoustic core acts as the piston in Stirling engines. When the temperature difference on the regenerator exceeds a certain value, the gas oscillates. For acoustic oscillation to reach saturation, the power generated in the core must be balanced. In the traveling-standing wave hybrid-type engine, the traveling-wave loop is located near the velocity node of the standing-wave resonator. Thus, viscous losses in the regenerator are reduced and performance is improved. The acoustic power obtained as a result of the oscillations flows from the hot side of the regenerator to the cold side and is amplified by the energy conversion effect of the Stirling cycle. While some of this acoustic power feeds back to the regenerator through the looptube, the rest goes to the resonator as output power [3]. The standing-wave thermoacoustic Stirling engine can be considered as a simplified version without any feedback system. Although this type of thermoacoustic engine does not offer as much efficiency as the traveling-wave configuration, it provides the opportunity to obtain similar operating characteristics and advantages with a simpler structure [42,43]. With standing-wave thermoacoustic Stirling engines, power generation from a low and medium temperature source is also possible. The engine is a straight line with the thermoacoustic core placed close to one end. Intentional imperfect heat exchange between the gas and the walls is necessary for energy conversion to occur with heat exchange during the movement of the working fluid. Therefore, the cycle cannot be reversed. As an example Traveling-standing wave hybrid-type thermoacoustic Stirling engine is shown in Figure 13.

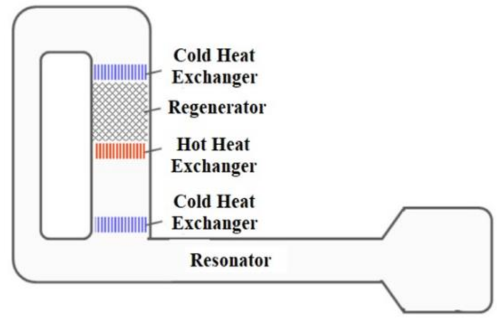

Figure 13. Traveling-standing wave hybrid-type thermoacoustic engine [3]

Thermoacoustic Stirling engines usually have one thermoacoustic core. However, using only one core is efficient at high temperatures, and performance decreases at low operating temperatures. It is recommended to use more than one thermoacoustic core to reduce the starting temperature and increase the efficiency.

3.6 Liquid piston Stirling engines

Liquid piston Stirling engines do not have any moving mechanical parts. In these engines, the water column acts as a piston. Volume changes in the engine are only provided by these liquid pistons. One of the best known of this type of engine, the Fluidyne engine, was patented in 1969 at the UKAEA Atomic Energy Research Establishment's Harwell Laboratory by West [44]. Liquid piston engines consist of three groups as Fluidyne engine, two-phase thermo-fluidic liquid piston engine and hybrid solid-liquid piston Stirling engine. The drawing of the Fluidyne engine designed by West is shown in Figure 14.

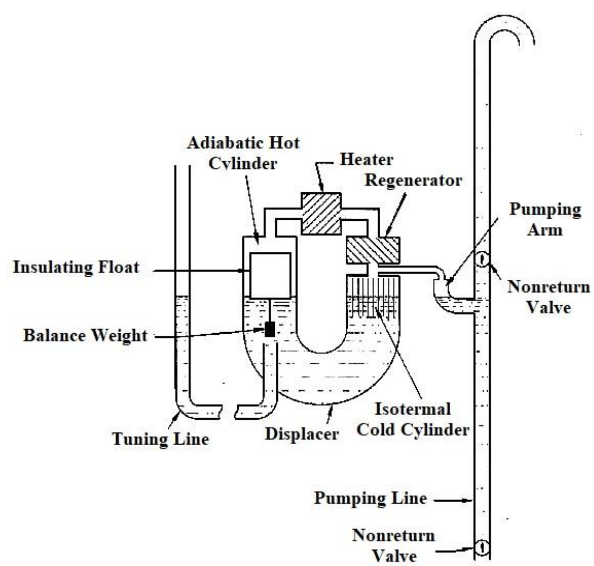

Figure 14. Fluidyne engine [45]

Hybrid solid-liquid piston Stirling engines have both liquid and solid pistons. These engines can be thought of as a combination of Fluidyne engines and kinematic LTD Stirling engines. Liquid piston Stirling engines operate at relatively low temperature differences, low power output and low efficiency. Average working pressures are around 1 bar when air is used as the working fluid. Pressurization cannot be done so that the liquid does not come out of the system.

However, the low cost and effortless production of these engines outweighs these disadvantages. It is generally used for applications such as water pumping in rural areas where solar energy, geothermal energy, biomass energy and industrial waste heat are used [3,17].

Liquid piston Stirling engines first convert the heat energy into the oscillation of the liquid pistons. Then, the output power obtained through the variation of the dynamic pressure of the working fluid can be used as pumping or electrical power [46]. As seen in Figure 14, when the liquid column in the displacer starts to oscillate, it causes the working fluid to oscillate between the hot and cold zones. Temperature changes in the working fluid create dynamic pressure forces that force the liquid column in the outlet line to move up and down periodically. Thus, the applied heat is converted into work in the form of fluid motion periodically observed in the fluid column. In these engines, the hot end column in the displacer is produced shorter than the cold end column, providing a faster response. In this way, the phase difference required for the Stirling cycle is provided.

4. Cylinder Arrangements

Stirling engines are divided into three classes according to their cylinder arrangements: Alpha (α), Beta (β) and Gamma (γ). In α-type Stirling engines, two different pistons in compression and expansion volumes work with 90° phase difference. Piston and displacer piston are used in β and γ-type engines. In β-type engines, a power piston and a displacer piston work in the same cylinder. In γ-type engines, piston and displacer piston move in two different cylinders with a phase difference [3,10,47]. Schematic representations of Alpha, Beta and Gamma Stirling engines are shown in Figure 15.

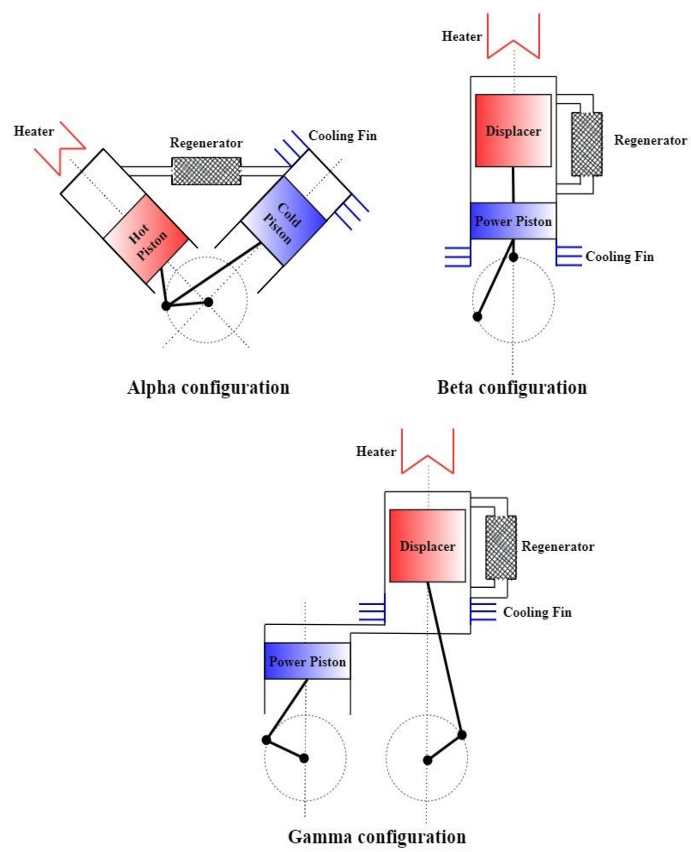

Figure 15. Cylinder arrangements in Stirling engines

4.1 Alpha (α) type Stirling engines

Alpha-type Stirling engines have two different power pistons called compression and expansion pistons. The cylinder with the expansion piston can be called the hot volume, and the cylinder with the compression piston can also be called the cold volume. Power pistons operate with 90° phase difference in different cylinders connected by heater, cooler and regenerator. This phase difference means that when one piston is at the bottom or top dead center, the other piston will be halfway through its stroke. Moving the pistons with a phase difference of 90° ensures the circulation of the working fluid between the hot and cold cylinders. This circulation is most efficient by placing the hot and cold cylinders in a V shape. Alpha-type engines are designed and classified with four different cylinder groups as circular, parallel, V and opposing cylinders. If the cylinders are placed in parallel, the pistons are driven by two different journals on the crankshaft. There is an angle difference of 90° between these journals [48]. The Alpha-type Stirling engine and its basic parts are shown in Figure 16.

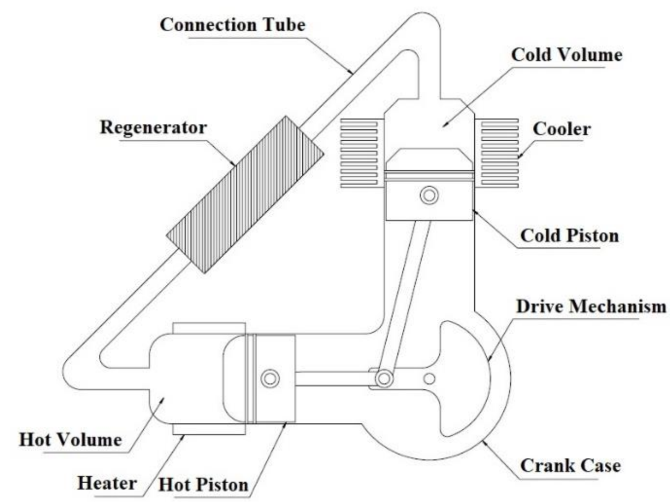

Figure 16. The Alpha-type Stirling engine

Although Alpha Stirling engines have a high power-to-volume ratio, they also have some disadvantages. Having two different power pistons in two different cylinders of these engines, which work with high-pressure working fluid, increases the sealing problems. While one power piston and connecting rod are sealed in Beta-type engines, sealing is essential for both power pistons in Alpha engines. Thanks to the small diameter of the connecting rod, the sealing problem can be solved much more easily than with a power piston.

4.2 Beta (β) type Stirling engines

In Beta-type Stirling engines, a single power piston and a displacer piston work coaxially within the same cylinder. While this cylinder is heated from one end, it is cooled from the other end. The region between the power piston and the displacer piston is called the cold volume (compression chamber), and the region above the displacer piston is called the hot volume (expansion chamber) [23]. During its movement in the cylinder, the working fluid passes through the heater, regenerator and cooler respectively. When the working fluid is in the cold volume, the power piston performs the compression process. When the working fluid passes to the hot end of the cylinder, it expands and pushes the power piston. The power piston, pushed by the effect of the hot working fluid, moves the crankshaft and thus the heat energy is converted into mechanical energy. Beta-type engines can be designed with kinematic or free-piston arrangements. The Beta-type Stirling engine and its basic parts are shown in Figure 17.

While the displacer piston and the power piston are located in the same cylinder in Beta-type engines, these pistons are in different cylinders in Gamma-type engines. The displacer piston, which provides the passage of the working fluid between the hot and cold ends, is located in the cylinder with a space and does not receive power from the working fluid. Many Beta-type Stirling engines do not have a visible regenerator structure. In such arrangements, the surface between the displacer piston and the cylinder provides some regenerative effect and enables the working fluid to exchange heat cyclically. As in Alpha-type Stirling engines, there is a 90° phase difference between the pistons in Beta-type engines [49]. However, since the pistons are in the same cylinder, this phase difference is usually provided by the rhombic drive mechanism.

In low pressure Beta-type Stirling engines, the regenerator area is positioned around the displacer piston, and the flow of the working fluid between the hot-cold volumes is ensured through the space between this piston and the cylinder. In this type of engines, it is necessary to increase the length of the displacer piston, and in engines operating with high charge pressure, the heat transfer surface area should be increased [50]. Increasing the heat transfer surface area is possible by using a separate heater, cooler and regenerator. In Beta-type Stirling engines, the engines with a displacer piston with regenerator are called “Stirling-type”, and those using an external regenerator are called “Rankine-Naiper-type” [10,32,48].

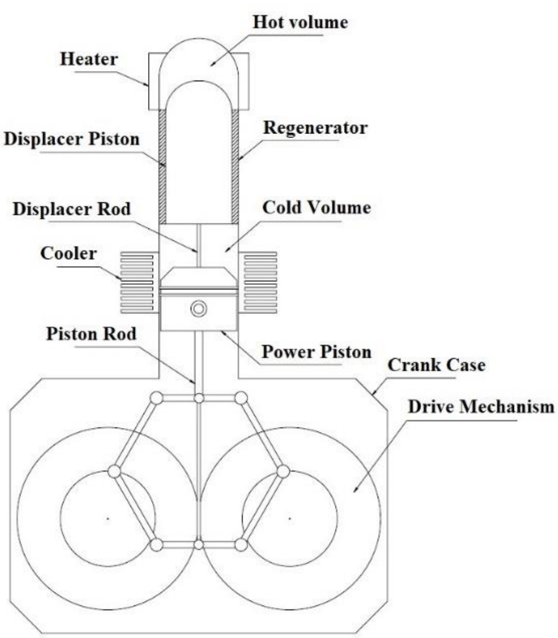

Figure 17. The Beta-type Stirling engine

Beta-type Stirling engines have some design difficulties due to the power piston and displacer piston working with phase difference in the same cylinder. However, contrary to these difficulties, it has many advantages such as low dead volumes, high compression ratios, operation at low temperature differences, less sealing problems compared to other cylinder configurations, and higher efficiency. In addition to these advantages, Beta-type engines are frequently preferred in studies to increase power and efficiency in Stirling engines due to their high power to volume ratio [51].

4.3 Gamma (γ) type Stirling engines

Gamma-type Stirling engines have a power piston and a displacer piston, as do Beta-type engines. However, in this engine type, the displacer piston is not coaxial with the power piston, but in a different cylinder. With this cylinder structure, complications caused by the displacer piston rod passing through the center of the power piston are prevented, and gas leaks in this area are prevented. In Gamma-type engines, cylinders can be designed in parallel as well as with an angle of 90°. As in Alpha and Beta-type engines, there is a 90° phase difference between the movements of the pistons in Gamma-type Stirling engines.

One of the cylinders in the Gamma-type Stirling engine performs the expansion and compression of the working fluid by means of a power piston, and the other performs the heating and cooling of the working fluid through the displacer piston. The two cylinders are connected to each other by means of a pipe. The regenerator can be placed inside or outside the displacer cylinder as in Beta-type engines. The displacer piston operates with a gap between the hot and cold volume. The up and down movement of this piston carries the working fluid flowing between the cylinder and the piston between the heater, the regenerator and the cooler. The cold volume contains the cylinder with the power piston and the cooler side of the displacer piston. Gamma-type Stirling engines can have kinematic and free-piston arrangements. The Gamma-type Stirling engine and its basic parts are shown in Figure 18.

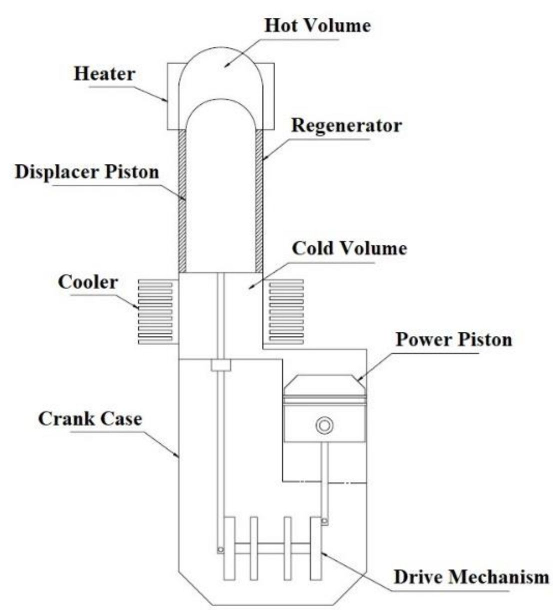

Figure 18. The Gamma-type Stirling engine

Cyclic heating and cooling of the working fluid causes it to expand and compress, as in other Stirling engines. Thus, while being transported between hot-cold cylinders, it transfers its energy to the power piston in the cold cylinder. Gamma-type engines, which are generally seen in multi-cylinder examples, have some disadvantages although they have a simple mechanical structure. The fact that the power piston and the displacer piston are in separate cylinders increases the dead volumes in these engines, thus reducing their compression ratio and efficiency. Its advantages are ease of design, it does not require sealing on the displacer piston rod, as in Beta-type engines, so only the power piston is sealed.

Finally, Gamma-type Stirling engines consist of four different groups called Lauberau-Schwartzkopff, Heinrici, Rainbow and Robinson. In the Lauberau-Schwartzkopff Gamma-type Stirling engine, the regenerator area is located on the displacer piston. In Heinrici-type engines, the power and displacer cylinders are in parallel position, and the cold and hot volumes are connected to each other by the use of external regenerators. In Robinson-type Stirling engines, there is a 90° phase difference between the power and displacer cylinders [10,52]. The advantages and disadvantages of these cylinder arrangements used in Stirling engines are shown in Table 1.

Table 1. Comparison of the cylinder arrangements

	Advantages	Disadvantages
Alpha	-High power to volume ratio. -Simplest mechanical structure [53]. -It has a compact structure and high specific power, with the double-acting piston design [3,23].	-Both power pistons operating in different cylinders must be sealed [54]. -For high engine volumes, system weight is a problem.
Beta	-It has a more compact structure. The system weight is low [54]. -Only one power piston and displacer piston rod must be sealed. -The amount of dead volume is low and can be designed at high compression ratio.	-It has a more complex mechanical structure. -Its design and production is quite laborious.
Gamma	-It has a simpler mechanical structure. It is more effortless to design and manufacture [23,55]. -It is quite suitable for operation at low temperature differences. -It is the best cylinder configuration for sealing.	-The high amount of dead volume reduces efficiency and power. It also works at low compression ratios [3,55].

5. Drive Mechanisms

In Kinematic Stirling engines, many different drive mechanisms are used for motion transmission and control. The most preferred ones are rhombic, wobble plate, slider crank, swash plate, ross-yoke, scotch-yoke drive mechanisms. The amplitudes and phases of the movements of the power piston and the displacer piston are determined by these connections. These mechanisms are mechanically complex, but their analysis is relatively simple compared to other types of Stirling engines. Many different types of drive mechanisms have been designed throughout the development of Stirling engines. With different mechanisms, high cost, wear, vibration, noise, sealing, lubrication and imbalance problems were tried to be eliminated, and it was aimed to improve power output and efficiency. Today, the development of these drive mechanisms continues to be an important field of study. The advantages and disadvantages of these drive mechanisms used in Stirling engines are shown in Table 2.

Table 2. Comparison of the drive mechanisms

	Advantages	Disadvantages
Rhombic	-Low lateral forces, low vibration, small engine size, good sealing, suitable for high pressure and high power, suitable for single and multi-cylinder engines [8,10,19,52,57].	-Mechanically complex, high number of parts [8,10,19,52,57].
Wobble Plate	-Low cost [57].	-High friction, lubrication problem [57].
Slider Crank	-Easy to manufacture, low resistance forces [10].	-There is a balance problem, lateral friction is high [10,57]
Swash Plate	-Suitable for high pressure and high power, compact structure, small engine size, suitable for mass production and good sealing [10,14].	-It has lubrication and friction problems, not economical, difficult to manufacture, only suitable for multi-cylinder engines [14,65].
Ross-Yoke	-Balanced, low friction, low vibration, low noise, low wear, easy to manufacture and economic [10,57].	-Only suitable for small engines [10].
Scotch-Yoke	-Low wear, low lateral forces [10].	-Only suitable for small engines [71,72].

5.1 Rhombic drive mechanism

The rhombic drive mechanism was first designed by Meijer in 1953. This motion transmission mechanism, which was designed for Stirling engines, was started to be used in Philips engines in 1954 [7,10,32,55]. The rhombic drive mechanism consists of two gears rotating in opposite directions and a rod mechanism combined with a crankshaft. The power piston rod connects to the upper link and the displacer piston to the lower link. With the help of this connection type and gears, 90° phase difference is created between the pistons [56,57]. With the use of rhombic drive mechanism in Stirling engines, lateral forces and vibrations are reduced, sealing problems are eliminated and engine dimensions are reduced [7,58]. It also allows operation at higher pressures for higher specific power generation. This mechanism, which is generally used in single-cylinder Beta-type Stirling engines, can also be used in multi-cylinder engines side by side or opposite. [7,10,19,57] Beta-type Stirling engine with rhombic drive mechanism and drive mechanism parts are shown in Figure 19.

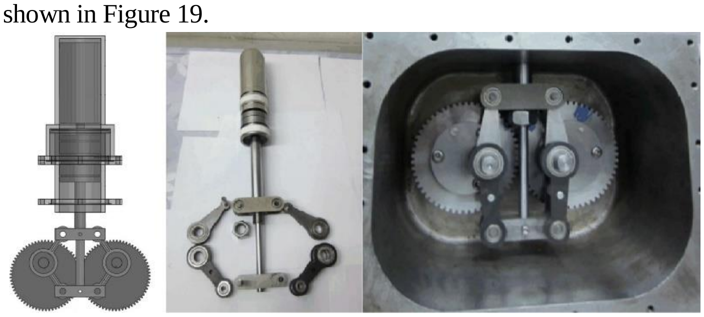

Figure 19. β-type Stirling engine with rhombic drive mechanism [59,60]

5.2 Wobble plate drive mechanism

The wobble plate drive mechanism was first used by Siemens in 1860 in Stirling engines [57]. In the wobble plate drive mechanism, two pistons are placed side by side and connected to each other by a rocker mechanism. The mechanism oscillates, giving movement to the piston connecting rods at both ends. Generally used in double-acting Stirling engines, this mechanism is also used in compressors and internal combustion engines [61]. The main advantage of the wobble plate drive mechanism is its low cost. As a disadvantage, it can be said that the high amount of wear and friction losses caused by lubrication problems [10]. Detailed views of the wobble plate drive mechanism are shown in Figure 20.

Figure 20. Wobble plate drive mechanism [62,63]

5.3 Slider crank drive mechanism

The slider crank drive mechanism has been used extensively since the invention of internal combustion engines. It is also widely used in Stirling engines thanks to its ease of manufacture advantage. Since the displacer piston is supported through the power piston rod, the resistance forces are minimized. However, the power piston is driven by the connecting rod, which makes an oscillating movement. This increases the frictional forces in the lateral direction.

Especially in Alpha and Gamma-type Stirling engines, the cylinders are placed in a V shape. Ease of manufacture is provided by connecting the piston-piston or piston-displacer piston to the same rod journal [3,23]. The disadvantage of this mechanism is difficulties in balancing. Beta-type Stirling engine with slider crank drive mechanism is shown in Figure 21.

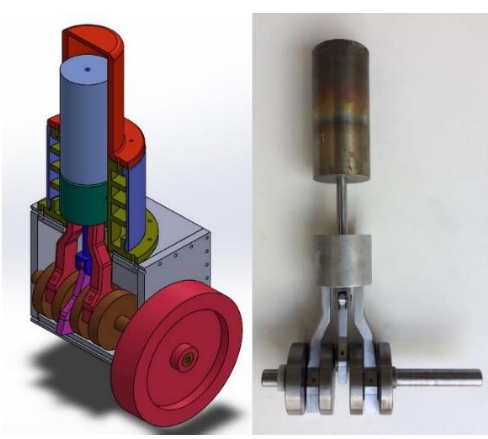

Figure 21. Slider crank drive mechanism [64]

5.4 Swash plate drive mechanism

The swash plate drive mechanism, which is widely used in hydraulic pumps and compressors, was produced in Stirling engines in the 1970s with the license of Philips for use in automobiles and was tested by Ford and General Motors companies. Stirling engines with swash plate drive mechanism have been also manufactured by United Stirling, Malmo and MAN-MWM companies independently of Philips license for underwater power systems [7]. This mechanism is used in multi-cylinder engines. It is preferred in Stirling engines, which aim high power output, thanks to its more compact structure compared to the rhombic drive mechanism [10]. The swash plate drive mechanism has several advantages such as reducing engine dimensions, suitability for mass production, good sealing and providing desired torque characteristics. As disadvantages, it is difficult to produce, not economical, hydrodynamic lubrication and friction problems at low speeds [14]. As the number of cylinders increases, the balance problem decreases in engines using swash plate drive mechanism. It is suitable for use in at least three-cylinder engines [65]. A Stirling engine with swash plate drive mechanism is shown in Figure 22.

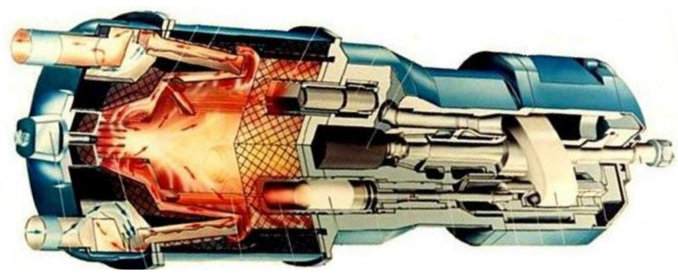

Figure 22. Stirling engine with swash plate drive mechanism [32]

5.5 Ross-Yoke drive mechanism

Ross-yoke drive mechanism, designed by Ross for Stirling engines in 1976, is used in small Stirling engines [10]. In the ross-yoke drive mechanism, two parallel pistons are connected to the crankshaft by a triangle mechanism. Since the lateral forces are mutually balanced in this mechanism, friction, wear, vibration and noises are reduced [57]. Its design is easy and its production cost is very low. A small Stirling engine for hobby with ross-yoke drive mechanism is shown in Figure 23.

Figure 23. Stirling engine with ross-yoke drive mechanism [66]

5.6 Scotch-Yoke drive mechanism

In the scotch-yoke drive mechanism, which was designed for the first time by Parsons, the alternative movement of the piston is converted into circular movement by the journal moving in the slot [67,68]. In this mechanism, which has fewer moving parts compared to other systems, as in the rhombic drive mechanism, the wear on the parts is minimized since the lateral frictional resistance is reduced [10]. Scotch-yoke drive mechanism is used in small Stirling engines without the use of any lubricating element [54,69]. The schematic representation of a Stirling engine with Scotch-yoke drive mechanism is shown in Figure 24.

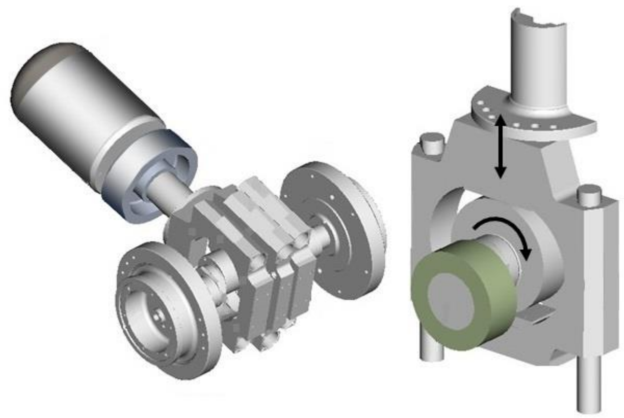

Figure 24. Stirling engine with scotch-yoke drive mechanism [70]

6. Conclusions

Stirling engines, invented by Robert Stirling in 1816, can work with many alternative energy sources thanks to the external heat supply. The rapid development of internal combustion engines over time has reduced the interest in Stirling engines. However, the problems caused by fossil fuels and their impact on the environment have brought Stirling engines back to the agenda in recent years. These engines, which can operate at medium and low temperature differences with all kinds of heat sources, are especially promising in the recovery of solar energy, geothermal energy and waste heat.

Stirling engines have some advantages and disadvantages compared to internal combustion engines. The advantages of Stirling engines are that the combustion is continuous, the absence of intake and exhaust valves, the low noise emissions and pollutant gas emissions, the easy and cheap maintenance thanks to having fewer parts, and the ability to be designed with many different mechanical arrangements. The disadvantages of Stirling engines are low power/weight ratios, slow acceleration and deceleration responses, requiring experimental knowledge as it is still under development, and sealing problems.

The basic working principle of Stirling engines is the compression of the cooled working fluid and the expansion of the heated working fluid. The theoretical Stirling cycle consists of two isothermal processes and two constant volume processes. In the isothermal compression process, the increasing temperature during compression is kept constant by cooling the working fluid. In the isothermal expansion process, the decreasing temperature during the expansion is kept constant by giving heat to the working fluid from an external source. In the constant volume regeneration process, heat transfer takes place from the regenerator to the low temperature working fluid or from the high temperature working fluid to the regenerator. By giving heat to and removing heat from the regenerator between compression and expansion processes, system efficiency is increased and dead volumes are reduced.

Since the invention of Stirling engines, many engine types, cylinder arrangements and drive mechanisms have been developed for reasons such as increasing thermal efficiency, reducing costs, improving power output and reducing dead volumes. Although the working principles are the same, these configurations are structurally quite different from each other. Stirling engines can be classified according to their mechanical configuration or operating principles.

Engines classified according to their mechanical arrangement are kinematic Stirling engines and free-piston Stirling engines. In kinematic Stirling engines, the crankshaft, power piston and displacer piston are connected by mechanical connections. In free-piston engines, there is no mechanical connection between the power piston and the displacer piston. There is a phase difference between these pistons working in the same cylinder and usually the power piston is controlled by a linear alternator.

Low temperature differential (LTD) Stirling engines, double-acting Stirling engines, thermoacoustic Stirling engines and liquid piston Stirling engines can be given as examples of engines classified according to their working principle. Low temperature differential (LTD) Stirling engines, as the name suggests, can operate at very low temperature differences between the hot and cold ends. In double-acting Stirling engines, the number of parts is reduced by half, thanks to the fact that the heater, cooler and regenerator are located between the expansion volume of one cylinder and the compression volume of the other cylinder. In thermoacoustic Stirling engines, work is produced by creating pressure changes with high amplitude acoustic waves caused by temperature difference. On the other hand, liquid piston Stirling engines have no moving mechanical parts and the liquid columns act as pistons. Oscillatory movements occur in the liquid columns with the temperature difference. This situation creates pressure changes and provides work to be obtained.

Stirling engines are divided into three types according to their cylinder arrangements: Alpha, Beta and Gamma types. In Alpha and Gamma-type Stirling engines, the power piston and the displacement piston work in separate cylinders with a phase difference. In Beta-type Stirling engines, the power piston and the displacer piston are in the same cylinder.

Finally, different drive mechanisms are used in kinematic Stirling engines. Commonly used among these are rhombic, wobble plate, slider crank, swash plate, ross-yoke and scotch-yoke drive mechanisms. Studies on the drive mechanisms in Stirling engines are still continuing intensively. With the use of different drive mechanisms in Stirling engines, it is aimed to prevent problems such as sealing, wear, noise, lubrication and balance, and to improve power output.

Nomenclature

CO	Carbon Monoxide
CO_2	Carbon Dioxide
C_v	Specific heat in constant volume
HC	Hydrocarbon
k	Heat capacity ratio of working fluid
LTD	Low Temperature Differential
m	Mass of working fluid
MAN-MWM	Maschinenfabrik Augsburg-Nürnberg and Motoren Werke Mannheim
MSI	Micro Star International
NO_X	Nitrogen Oxides
P	Pressure
Q	Heat transfer
Q_R	Heat transfer regenerator
R	Gas constant of working fluid
S	Entropy
T	Temperature

T_H	High temperature
T_L	Low temperature
U	Internal energy
UKAEA	United Kingdom Atomic Energy Authority
V	Volume
W	Work
ε	Compression ratio
η_{Th}	Thermal efficiency

Conflict of Interest Statement

The authors declare that there is no conflict of interest in the study.

CRediT Author Statement

Turan Alp Arslan: Writing-original draft, Conceptualization, Investigation. **Tolga Kocakulak:** Writing-review & editing, Visualization.

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