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Synopsis Of

Thermodynamic Analysis and Economic Assessment of Combined Solar Stirling-Organic Rankine Cycle

A Thesis

To be submitted by

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For the award of the degree

Of

DOCTOR OF PHILOSOPHY

1 Abstract

The designers of solar Stirling engine systems rely primarily on the experimental data and complex mathematical approaches to obtain near optimal performance. A simple and accurate mathematical model needs to be developed to predict the performance of solar Stirling engines at the conceptual design stage. Therefore, the present study combines a non-iterative geometric-optical model with a finite time thermodynamic (FTT) approach for evaluating the performance of Stirling engine. Further, the effect of imperfect regeneration on output power and efficiency of the Stirling cycle has been incorporated. The influence of suitable working fluids and regenerator materials on the output characteristics of LTD Stirling engine has been evaluated. Helium produced better performance characteritics among air, hydrogen, ethane and nitrogen. Copper yielded maximum regenerator effectiveness compared with Monel 400, aluminium and SS-304L. Input parameters such as absorber plate temperature, irradiation, and geometrical features of the solar LTD Stirling engine are taken from Boutammachte and Knorr (2012) and the output findings have been validated with their experimental results.
Further, the quantity and quality of the dissipated thermal energy of the dish Stirling engine (DSE) system operating at $\approx 650°C$ have been predicted by employing the developed modified FTT approach and validated with existing literature. The recoverable waste heat available at sink (cooler end) temperature of 80 to 140°C makes DSE a viable option for combined heat and power (CHP) generation system. An organic Rankine cycle (ORC) is adopted to recover the waste heat available at the DSE heat sink. A novel combined Stirling-ORC prime mover has been investigated thermodynamically for solar CHP applications. An energy-exergy model is also formulated for Stirling-ORC-CHP system and analysed the system's output power and efficiency using real time data. The proposed solar Stirling-ORC-CHP unit increased the energetic and exergetic efficiency by 13.8% and 7.3%, respectively, compared with solar DSE. A detailed sensitivity analysis is performed to elucidate the effect of absorber temperature, waste heat temperature of Stirling cycle, temperature ratio, compression ratio and eight generic ORC working fluids on the overall performance of the solar Stirling-ORC combination. Additionally, an artifical neural retwork (ANN) based multi-objective grey wolf optimization (MOGWO) has been carried out to determine optimal values of five operating parameters and develop a power-efficiency characteristics/pareto frontier of the combined Stirling-ORC-CHP system. The total output power and overall energy efficiency of the solar Stirling-ORC-CHP system, operating at optimal values of the parameters, improved by 10.6% and 22.2%, respectively, compared to the base case. The environmental and economic feasibility of the combined solar Stirling-ORC based CHP system has been evaluated based on carbon dioxide emission reduction (CO_2ER), levelized cost of electricity (LCOE) and simple payback period. The climatic data of six different locations in India viz. Srinagar, Delhi, Jodhpur, Mumbai, Bangalore and Chennai has been used for annual performance prediction of the Stirling-ORC-CHP system in accordance with the national energy policy guidelines Siva Reddy *et al.* (2013). A 3 kW solar Stirling-ORC-CHP system having 25 years life span, costs minimum LCOE Rs 12.2 (0.167$) at an interest rate of 8% and requires a least payback period of 7.5 years at Jodhpur among the cities considered.

2 Objectives

The objectives of the present research are to

- develop simple thermodynamic models of Stirling engine and combined Stirling-ORC incorporating cyclic irreversibilities
- analyise the performance of Stirling engine and combined Stirling-ORC for maximum power output condition at conceptual design stage
- evaluate the effect of optical/heat losses on performance of solar LTD Stirling engine and
- perform 4E analysis and find the optimal operating conditions for maximum energy and exergy efficiency of a solar combined Stirling-ORC based CHP unit

3 Existing Gaps Which Were Bridged

The mathematical models to predict the thermodynamic performance of Stirling engines are classified as 0^{th}, 1^{st}, 2^{nd} and 3^{rd} order based on their accuracy and complexityAhmadi *et al.* (2017). The 0^{th} and 1^{st} order mathematical models are approximate as these are formulated on ideal considerations. Whereas, the 2^{nd} and 3^{rd} order models are accurate and computationally intensive because of inclusion of internal and external losses, and engine's geometrical features. Thus, there is a need for a simple and accurate model to predict the output characteristics of solar Stirling engines at conceptual design stage. The finite time thermodynamic (FTT) method, a nonequilibrium thermodynamic approach, stands between the 1^{st} and 2^{nd} order models as it is uncomplicated and computationally inexpensive Kaushik *et al.* (2017); Tlili (2012); Bejan (2017). It requires only the compression ratio for modelling and does not involve the actual shape unlike the 2^{nd} and 3^{rd} order models. In addition, recent review literatures Wang *et al.* (2016); Zhu *et al.* (2021) suggested that priority should be given to thermal energy applications of solar Stirling engines than using them for electricity generation only. Thus, it is important to consider solar Stirling engines for individual applications like irrigation, grid-independent power generation etc combined with CHP, CCHP. The present study is intented to fill the identified gaps as illustrated in figure 2.

- The existing FTT model of solar Stirling engine Yaqi *et al.* (2011);Ahmadi *et al.* (2013) is improved by incorporating internal irreversibilities, solar collector heat losses and realistic regeneration process. The modified FTT approach, after customization, is applied to both concentrated (DSE) and non-concentrated (LTD) solar Stirling engines.
- The waste heat of Stirling engine is extracted through a bottoming organic Rankine cycle (ORC) Bahari *et al.* (2016). The output characteristics of combined Stirling-ORC are predicted by formulating an FTT model.
- A novel solar CHP unit is evolved by adding a domestic water heat exchanger to combined Stirling-ORC prime mover. The techno-economic viability and environmental feasibility of the solar CHP unit is evaluated.
- The optimal values of the operating parameters of solar Stirling-ORC based CHP system are found through a multi-objective optimization routine.

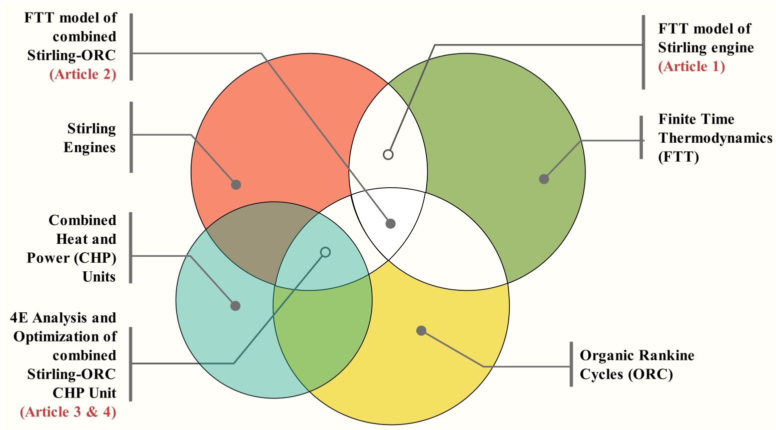

Figure 1: Literature gaps identified

4 Most Important Contributions

A modified FTT model of Stirling engine and combined Stirling-ORC is developed by incorporating cyclic irreversibilities (see figure 2a). The influence of heat capacitance of external fluids, effectivenesses and inlet temperatures of heat exchangers at source, sink and recovery unit on the performance of Stirling-ORC is analysed to obtain their optimum values. The maximum output power was produced by Stirling-ORC when heat capacitance of the external fluids at source and recovery unit were 1.1 kW/K and 1.4 kW/K, respectively, under the operating conditions of Ahmadi *et al.* (2013). The overall performance of combined Stirling-ORC is higher than that of the individual cycles, provided the isothermal heat rejection from Stirling cycle takes place at temperature above 540 K (see figure 2b). Further, an increase in the internal irreversibility parameter by a small amount (say 0.2) from an ideal/reversible condition reduces the maximum output power and the corresponding thermal efficiency of Stirling-ORC by 41.3% and 31.8%, respectively.

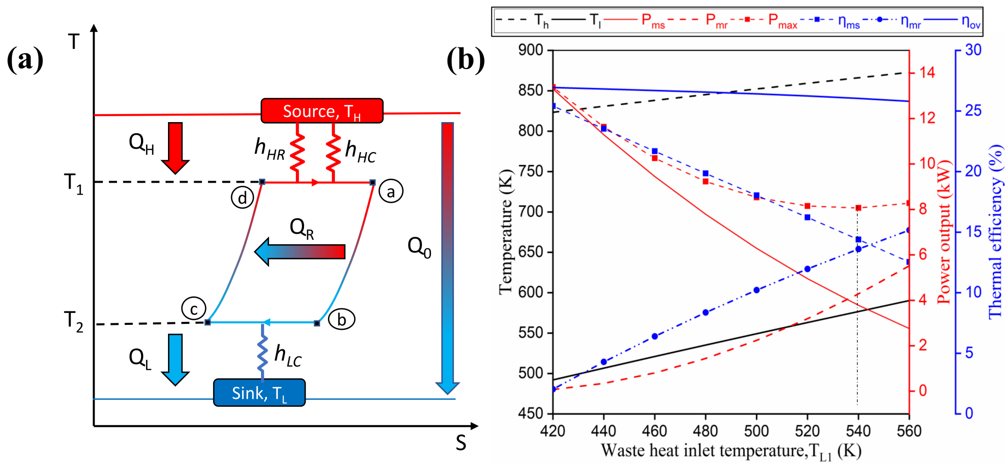

Figure 2: (a) FTT representation of Stirling engine with irreversibilities through T-S diagram, (b) Effect of waste heat temperature on performance of combined Stirling-ORC

The modified FTT model is employed for analysing the performance of solar operated LTD Stirling engine by including a non-iterative correlation for top heat loss of single glazed flat plate collector as illustrated in figure 3a. The effect of imperfect regeneration Dai *et al.* (2018) is incorporated to realise internal imperfections in the thermodynamic Stirling cycle. Input parameters such as absorber plate temperature, irradiation, and geometrical features of the solar LTD Stirling engine are taken from the experimental data of Boutammachte and Knorr (2012). The working fluid temperature predicted using the modified FTT model is found to be inline with the experimental data as depicted in figure 3b. The effect of convective and radiation heat transfer coefficients on maximum power output and thermal efficiency is determined to be significant and marginal, respectively. A comprehensive study of various working fluids and regenerator materials are carried out to investigate their impact on the performance of solar LTD Stirling engine. Helium produced better performance characteritics among air, hydrogen, ethane and nitrogen. Copper yielded maximum regenerator effectiveness compared with monel 400, aluminium and SS-304L.

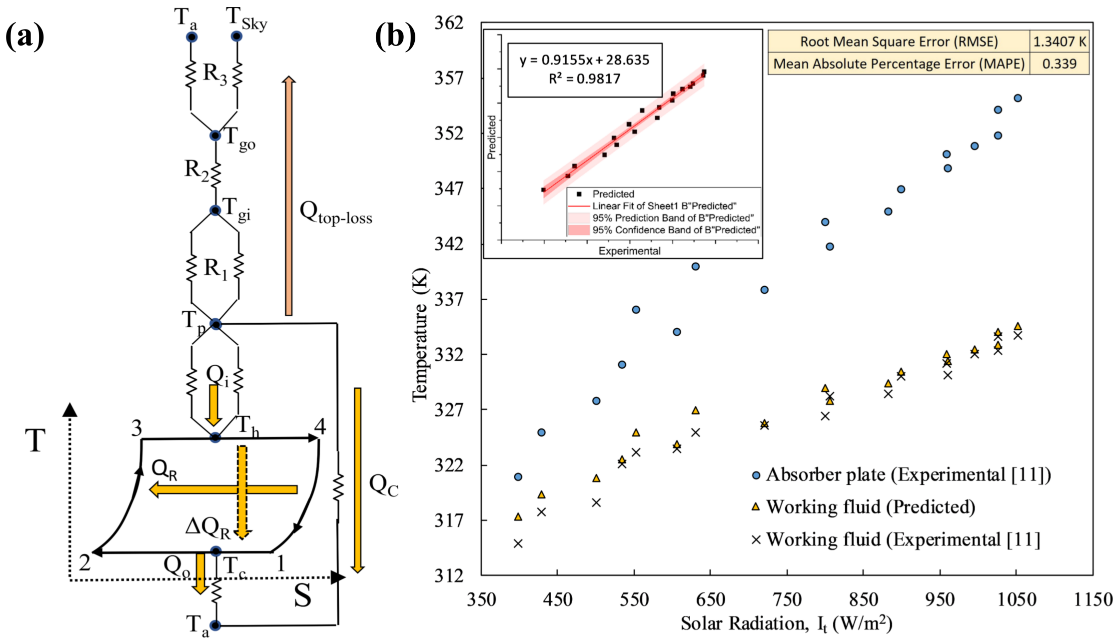

Figure 3: (a) FTT model for solar LTD Stirling engines and its (b) validation

The CHP potential of a novel combination of DSE and ORC (solar Stirling-ORC-CHP) as, illustrated in figure 4a, has been investigated through a detailed 4E (Energy, Exergy, Environmental and Economic) analysis. The modified FTT model of Stirling engine is combined with geometric-optical model of a parabolic dish collector-receiver assembly. The engineering equation solver (EES) is used to predict the energetic (see figure 4b) and exergetic performances of solar Stirling-ORC based CHP unit. The overall energy and exergy efficiencies got increased by 13.8% and 7.3%, respectively, compared with a typical solar DSE (figure 5). A detailed sensitivity analysis was conducted to elucidate the effect of five significant operating parameters and eight generic ORC working fluids on overall performance of the solar Stirling-ORC combination. The CO_2ER parameter value of 36.2% suggests that the solar Stirling-ORC based CHP system is viable environmentally.

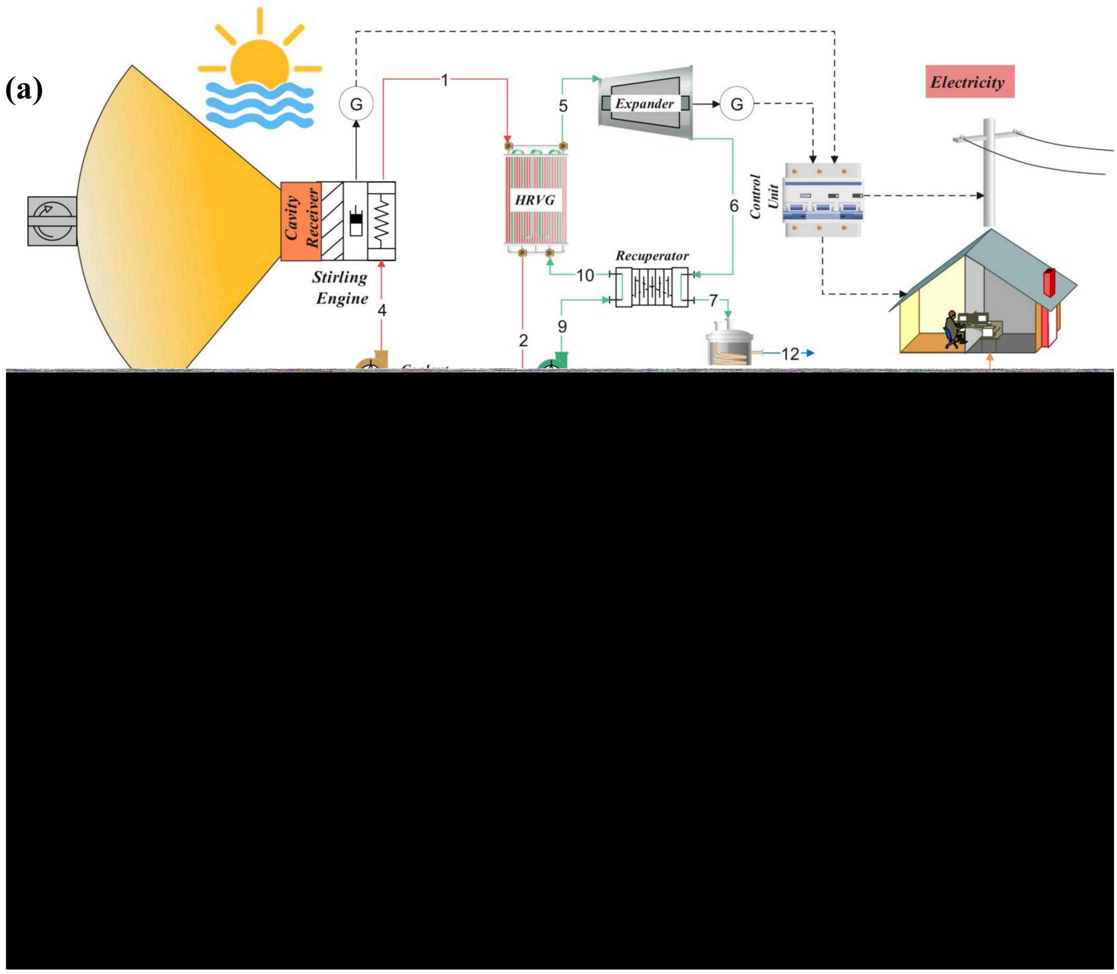

Figure 4: (a) Layout of the propsed solar Stirling-ORC based CHP unit (b) Energy flow diagram of the solar combined Stirling-ORC-CHP unit

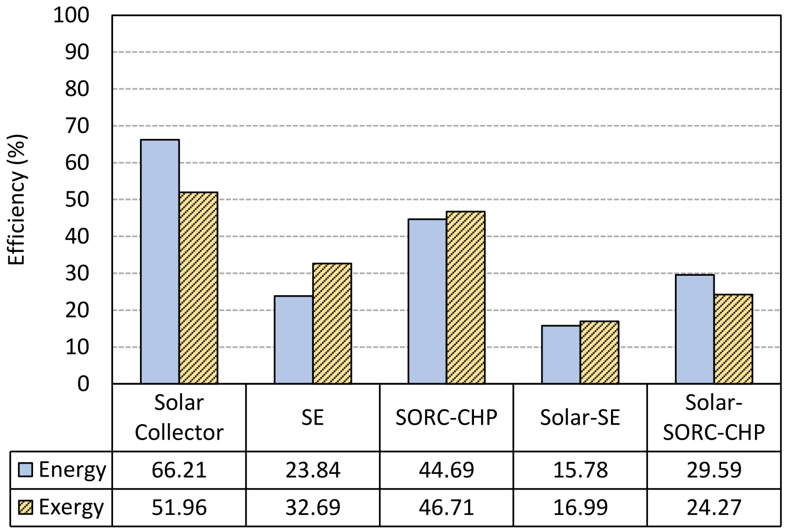

Figure 5: Energy and exergy efficiency comparison between solar SE and solar Stirling-ORC-CHP unit

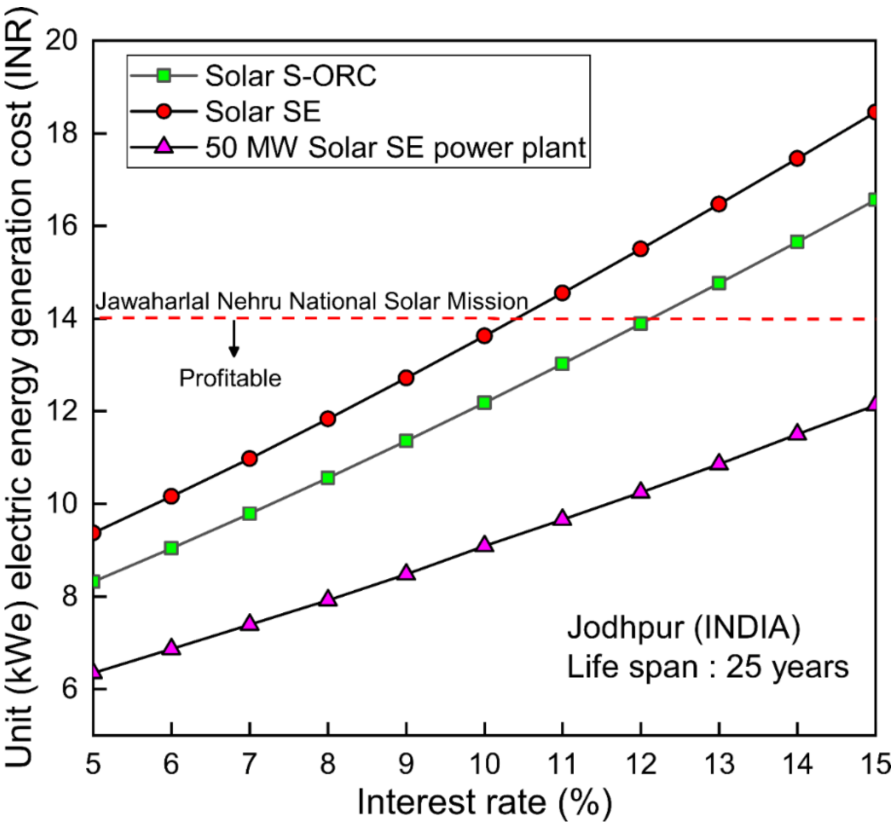

Figure 6: Economic analysis of solar Stirling-ORC-CHP unit

According to the Jawaharlal Nehru national solar mission scheme, the Indian government can purchase unit solar power at Rs 14 for the national grid Siva Reddy *et al.* (2013), which makes the proposed solar Stirling-ORC-CHP system profitable for renewable power generation upto 12% interest rate (see figure 6). A 3 kW solar Stirling-ORC-CHP system with 25 years life span and interest rate of 8% costs minimum LCOE of Rs 12.2 (0.167 \$) with payback period of 7.5 years at Jodhpur, among the Indian cities viz. Srinagar, Delhi, Mumbai, Bangalore and Chennai.

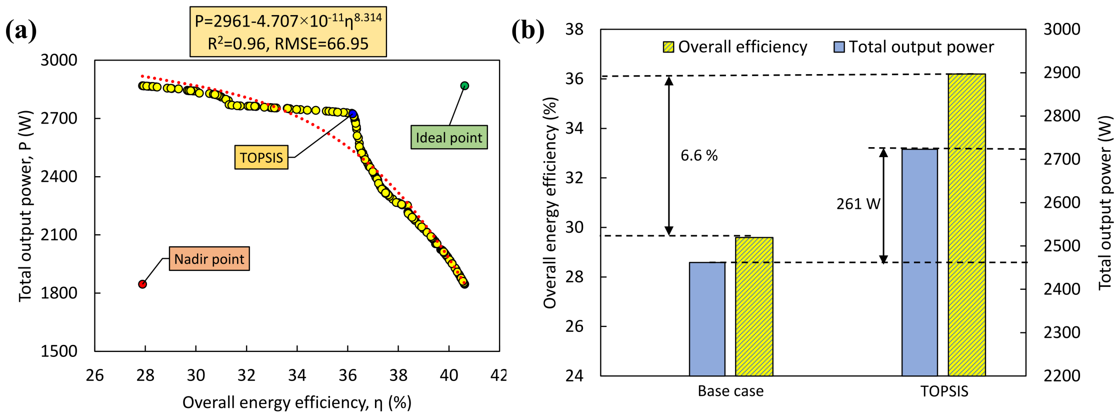

Figure 7: (a) Developed power-efficiency characteristic curve (b) Comparison between base case and TOPSIS (optimal case) on total output power and overall energy efficiency

A multi-objective grey wolf optimization (MOGWO) method Mirjalili *et al.* (2016) based on artificial neural network (ANN) Alirahmi *et al.* (2021) has been adopted to develop a power-efficiency characteristic curve/pareto frontier of the proposed system (see figure 7a). In order to identify the optimal values of five significant operating parameters considered for the optimization study, technique for order of preference by similarity to ideal solution (TOPSIS) Rao *et al.* (2017), well known decision-making method, has been employed. The optimal values of operating parameters improved the total output power and overall energy efficiency of the proposed CHP system by 10.6% and 22.2%, respectively, compared with base case (see figure 7b).

5 Conclusions

- A modified FTT model is developed to predict the performance of Stirling engines and combined Stirling-ORC by incorporating cyclic irreversibilities.
- A thermodynamic analysis of solar LTD Stirling engine revealed better thermal efficiency and output power when helium and copper are employed as working fluid and regenerator material, respectively, among the generally used combinations.
- A detailed 4E analysis of combined Stirling-ORC-CHP system revealed an increase in overall energy and exergy efficiencies by 13.8% and 7.3%, respectively, compared with solar DSE.
- The payback period of a 3 kW solar Stirling-ORC system with a unit electric energy generation cost of Rs 12.2 (0.167$) and an interest rate of 8% is determined to be 7.5 years with additional thermal energy for utility purposes.
- An artifical neural retwork (ANN) based multi-objective grey wolf optimization (MOGWO) revealed an improvement of total output power and overall energy efficiency of the proposed CHP system by 10.6% and 22.2%, respectively, compared with base case.

The generated power-efficiency characteristic curve may be used as a guide for the design of solar Stirling-ORC-CHP system at conceptual design stage. The proposed decentralized renewable CHP system may be considered as an alternate for the existing solar DSE based power unit.

6 Organization of the Thesis

The proposed outline of the thesis is as follows:

(a) Chapter 1: Introduction

(b) Chapter 2: Literature survey

(c) Chapter 3: Finite time thermodynamic modelling of Stirling engine and combined Stirling-ORC

(d) Chapter 4: Thermodynamic analysis of solar LTD Stirling engine

(e) Chapter 5: 4E analysis and optimization of solar Stirling-ORC-CHP unit

(f) Chapter 6: Conclusion and future scope

7 List of Publications

Journal Publications

(a) **Siddharth Ramachandran**, Naveen Kumar, and Venkata Timmaraju Mallina, "Thermodynamic investigation of an irreversible combined stirling-organic rankine cycle for maximum power output condition," Journal of Engineering for Gas Turbines and Power- Transactions of ASME, vol. 143(7) , p. 071016, 2021.

(b) **Siddharth Ramachandran**, Naveen Kumar, and Venkata Timmaraju Mallina, "Thermodynamic analysis of solar low-temperature differential stirling engine considering imperfect regeneration and thermal losses," Journal of Solar Energy Engineering- Transactions of ASME, vol. 142(5), pp. 051012, 2020.

(c) **Siddharth Ramachandran**, Naveen Kumar, and Venkata Timmaraju Mallina, "Energy, Exergy, Environmental and Economic Assessment of a Solar Operated CHP Unit with Combined Stirling-ORC Prime Mover," Sustainable Energy Technologies and Assesment- Elsevier (Under Review).

(d) **Siddharth Ramachandran**, Naveen Kumar, and Venkata Timmaraju Mallina, "Techno-Economic Assessment and Optimization of a Solar Operated CHP Unit with Combined Stirling-ORC Prime Mover" (Under Preparation).

(e) **Siddharth Ramachandran**, Naveen Kumar and Venkata Timmaraju Mallina "Soft computing based optimization of combined solar Stirling-ORC based CHP unit using artificial neural network (ANN)" (Under Preparation)

Conference Publications

(a) **Siddharth Ramachandran**, Naveen Kumar, and Venkata Timmaraju Mallina, "Effect of top losses and imperfect regeneration on power output and thermal efficiency of a solar low delta-t stirling engine", 7th International Conference on Advances in Energy Research (ICAER-2019), IIT,Bombay,Dec-19.

(b) **Siddharth Ramachandran**, Naveen Kumar, and Venkata Timmaraju Mallina, "Parametric study of a low-temperature differential stirling engine for low-grade thermal energy recovery", 25th National and 3rd International ISHMT-ASTFE Heat and Mass Transfer Conference (IHMTC-2019), IIT Roorkee, Dec-2019.

(c) Subodh K.S, **Siddharth Ramachandran**, Naveen Kumar., "Performance Comparison of Solar Thermo-Acoustic Heat Engine with and without using Compliance", July 2019, International Conference on Clean and Renewable Energy (ICCARE-2019) At: NIT Durgapur, India – July 10-12, 2019.

(d) Aravind C.B, **Siddharth Ramachandran**, Naveen Kumar., "Numerical Realization of Thermodynamic Low Delta-T Stirling Engine Cycle by Runge-Kutta (RK4) Method", January 2020,International Conference on Numerical Heat Transfer and Fluid Flow (NHTFF-2020) At: NIT Warangal, India – Jan 17-19, 2020.

(e) Aadithyan T.R, **Siddharth Ramachandran**, Naveen Kumar., "Numerical Study for Estimation of the Solar Irradiance on Dome Shaped Solar Collectors/Stills". . International Conference on Progressive Research in Industrial and Mechanical Engineering (PRIME - 2021), NIT Patna- India, August 2021.

(f) Ashwin M.S, **Siddharth Ramachandran**, Naveen Kumar., "Energy and Exergy Analysis of a Solar Dish Stirling Heat Engine with Bottoming Organic Rankine Cycle". International Conference on Progressive Research in Industrial and Mechanical Engineering (PRIME - 2021), NIT Patna- India, August 2021. (Best Paper Award)

(g) **Siddharth Ramachandran**, Naveen Kumar, and Venkata Timmaraju Mallina, "A comprehensive perspective of waste heat recovery potential from solar stirling engines", 19th International Stirling Engine Conference (ISEC-2021), Sapienza University of Rome, Italy, Sep-2021.

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