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Thermal Retention of Sodium Nitrate PCM in Organic Rankine Cycle–Stirling Engine under Continuous Night Shift Mechanical Loading.

By

[1]Enemona Moses Yahaya, [2]Ebigenibo Genuine Saturday&[3]Celestine Ebieto Ebieto

[1,2,3]Department of Mechanical Engineering, Faculty of Engineering, University of Port Harcourt,

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Abstract

This study evaluated the thermal retention performance of sodium nitrate ($NaNO_3$) phase change material (PCM) and its influence on the mechanical output of a hybrid ORC–Stirling system under sustained night-shift loading for small-scale industrial energy conversion in Delta State, Nigeria. In the study, two major parameters were considered: PCM thermal retention effect on the stability of power at the shaft and how it affects the consistency of torque under continuous mechanical loading. Data of PCM temperature, shaft power and torque were simulated at constant intervals of night-shift and examined by multidimensional visualizations using MATLAB. Findings revealed that $NaNO_3$ PCM exhibited superior thermal stability between 260- 300 ^oC, as it occupied about 65% of the recorded intervals and this corresponded to stable shaft power of about 58 kW and average torque of 108 Nm over a small number of peaks and valleys. Positive correlations between PCM thermal stability and mechanical output were found to be strong, and this confirms that thermal buffering reduced transient losses in power during long-term loading. The results showed that ORC-Stirling systems enhanced by $NaNO_3$ PCM have the capacity to maintain the provision of mechanical power to the night-shift industrial process. To this end, it was recommended that PCM-integrated ORC-Stirling systems should be employed by small-scale industrial operators, the Manufacturers Association of Nigeria (Delta State Chapter) should assist in creating awareness and collaborative buying, and the tertiary institutions should create training and pilot programs to facilitate the long-term implementation. Such measures will make the adoption of ORC-Stirling for small scale industrial purpose more mechanically relevant and reliable, decrease the downtime and develop sustainable decentralized industrial power solutions.

Keywords: *ORC–Stirling system; Sodium nitrate PCM; Thermal retention; Shaft power stability; Small-scale industrial energy*

Introduction

Hybrid thermal-to-mechanical energy conversion systems that integrate Organic Rankine Cycle (ORC) and Stirling engines depend fundamentally on the stability of heat input, the continuity of thermal gradients, and the controlled regulation of internal thermodynamic states to sustain useful mechanical output. While solar collectors provide the primary heat source during daylight, continuous industrial operation, especially during night shifts, requires intermediate thermal storage systems capable of preserving high-grade heat for delayed discharge. Phase change materials (PCMs) offer this functionality by storing latent heat over narrow temperature bands and releasing it gradually under load, thereby extending the operational window of thermally driven engines beyond solar availability (Ali et al., 2024; Tittelein et al., 2015). Sodium nitrate-based ($NaNO_3$) PCMs, in particular, exhibit favorable melting temperatures, high latent heat capacity, chemical stability, and thermal compatibility with metallic containment structures, making them suitable for medium-temperature thermal energy storage applications associated with ORC–Stirling architectures (Li et al., 2016; Grégoire et al., 2024).

When coupled to a hybrid ORC–Stirling configuration, the PCM serves as a thermal buffer that smooths temperature fluctuations, moderates entropy generation, and sustains regulated expansion and compression cycles, which are essential for stable shaft power and torque delivery (Bahari et al., 2016; Yu et al., 2021). The effectiveness of this coupling is governed by the PCM's heat retention capacity, its conductive and convective transfer characteristics, and its ability to preserve usable temperature differentials under continuous mechanical loading (Eisapour et al., 2022; Ye et al., 2023). Consequently, the mechanical performance envelope of the ORC–Stirling system during non-irradiated periods is not dictated by collector efficiency, but by the thermal discharge dynamics of the PCM and its interaction with the engine's working fluid (Yahaya, 2026). For small-scale industrial users in developing regions such as Delta State, Nigeria, the need for stable, off-grid mechanical power remains a defining constraint on productivity, particularly during nocturnal operations when grid reliability is lowest and diesel dependence is highest (Akinbola, 2017; Essien, 2014).

Industrial activities such as milling, extrusion, pumping, and agro-processing rely on continuous shaft power and sustained torque to prevent production interruptions, mechanical fatigue, and product quality degradation. The decentralized nature of ORC–Stirling systems, when integrated with PCM-based thermal storage, offers a promising alternative to fossil-fueled prime movers by enabling autonomous mechanical power delivery with reduced emissions and fuel volatility (Nwozor et al., 2021; Fayomi et al., 2021). However, the mechanical reliability of such systems is highly sensitive to thermal decay, heat leakage, and entropy accumulation within the storage–engine interface, which can degrade torque stability and shaft power consistency over time (Oma, 2015; Chen et al., 2016). Prior studies on latent heat storage systems have demonstrated that suboptimal thermal conductivity, imperfect encapsulation and geometric constraints can significantly reduce the effective heat release rate, thereby limiting the usable mechanical output window (Kuo et al., 2020; Chen et al., 2020). Without explicit characterization of how $NaNO_3$ PCM retains and releases thermal energy under continuous mechanical demand, predictions of ORC–Stirling performance during night-shift operation remain incomplete. This study therefore investigates the thermal retention behaviour of $NaNO_3$ PCM and quantifies its influence on shaft power and torque delivery of an ORC–Stirling engine under sustained industrial loading conditions in Delta State, Nigeria.

Statement of the Problem

Small-scale industries in Delta State require continuous mechanical power for operations such as milling, pumping, drying and material processing, including during night-shift periods. However, dependence on diesel generators and unstable grid supply results in high operating costs, mechanical wear, and environmental pollution. Although hybrid ORC–Stirling systems with PCM storage offer a promising thermal-to-mechanical alternative, uncertainties remain regarding the thermal retention behavior of $NaNO_3$ PCM and its ability to sustain stable shaft power and torque under continuous nocturnal loading, necessitating focused investigation.

Aim and Objectives of the Study

This study was aimed at examining thermal retention of sodium nitrate ($NaNO_3$) PCM in ORC–Stirling engine under continuous night shift mechanical loading. Specifically, the objectives were to:

1. Assess the thermal retention performance of $NaNO_3$ PCM and its effect on shaft power of an ORC–Stirling engine applied to small-scale industrial energy conversion under continuous mechanical loads during night shift in Delta State, Nigeria.
2. Evaluate the thermal retention performance of $NaNO_3$ PCM and its effect on torque of an ORC–Stirling engine applied to small-scale industrial energy conversion under continuous mechanical loads during night shift in Delta State, Nigeria.

Research Questions

1. What is the thermal retention performance of $NaNO_3$ PCM, and how does it affect shaft power of an ORC–Stirling engine applied to small-scale industrial energy conversion under continuous mechanical loads during night shift in Delta State, Nigeria?
2. What is the thermal retention performance of $NaNO_3$ PCM, and how does it affect torque of an ORC–Stirling engine applied to small-scale industrial energy conversion under continuous mechanical loads during night shift in Delta State, Nigeria?

Literature Review

Small-scale industrial processes that demand constant mechanical power implementation are gradually being limited over time worldwide due to increases in fuel costs, operational variability and exposure to the environment, and therefore necessitate the development of thermally-driven prime movers with the capacity to maintain shaft output under fluctuating heat conditions (Akinbola, 2017; Essien, 2014). Thermal energy conversion systems, specifically ORC, are using PCMs more to smooth the thermal variability. Although paraffin wax and fatty acids were examined, they also have disadvantages in the form of low thermal conductivity and narrow operating temperature (Bharathiraja et al., 2023; Al-Ahmed et al., 2020).

Conversely, sodium nitrate ($NaNO_3$) has been considered as it has a high melting enthalpy, large latent heat capacity and good thermal stability, hence can be subjected to thermal cycling. The properties enhance its specific applications in converting energy to high temperature, where it is especially applicable (Bahari et al., 2016; Oma, 2015). Although potentially promising, the use of $NaNO_3$ as a PCM is controversial because of the corrosion risk and its rather complex handling needs, which restrict its use despite its innovative potential (Grégoire et al., 2024; Bairagi et al., 2023; Kuo et al., 2020; Li et al., 2016). In another way round, it was reported in the literature that $NaNO_3$-based PCM can reduce thermal disturbances more effectively than paraffin wax or synthetic oil, but the degree to which it affects them when continuously loaded in night shifts has not been

*Corresponding Author: Enemona Moses Yahaya

determined yet (Ali et al., 2024; Grégoire et al., 2024; Li et al., 2016). The majority of works are concentrated on short cycles or laboratory guidelines, and the lack of knowledge exists about long-term functioning in energy-limited areas (Ye et al., 2023; Eisapour et al., 2022; Chen et al., 2020; Chen et al., 2016). Thus, the issue of heat dissipation, material aging and coupling as well as reported efficiency under continuous mechanical loading poses further concerns for use (Fayomi et al., 2021; Nwozor et al., 2021), and becomes empirically relevant to examine $NaNO_3$ PCM-based thermal retention and its impact on sustained torque and shaft power when operating on continuous mechanical loading at night.

Theoretical Framework

This study is based on classical thermodynamics, according to which mechanical work is a result of heat between a constant temperature difference. Hybrid ORC-Stirling engines are based on this principle, transforming heat into shaft power under continuous load (Alexopoulos, 2022; Bahari et al., 2016). The efficiency of the system relies on the ability to retain heat and cyclic stability, which necessitates that PCM receives and gives out heat at set rates (Chen et al., 2016; Ye et al., 2023). Conversion effectiveness is determined by heat transfer pathways and PCM properties (Eisapour et al., 2022; Li et al., 2016), which create a predictive model between collector efficiency, thermal retention and mechanical stability (Grégoire et al., 2024; Yahaya, 2026).

Materials and Method

This study employed a simulation-based methodology to evaluate the thermal retention performance of sodium nitrate ($NaNO_3$) phase change material (PCM) and its effect on shaft power and torque of a hybrid ORC–Stirling engine for small-scale industrial applications under continuous night-time mechanical loading in Delta State, Nigeria. The materials included evacuated tube solar collectors, $NaNO_3$ PCM storage units, ORC–Stirling hybrid engines, high-temperature heat transfer fluid, mechanical load test benches, torque and RPM sensors, and insulated storage tanks suitable for small-scale industrial operations. Data were recorded over 90 days at 8-hour intervals for PCM thermal cycling, while shaft power and torque were continuously monitored at 1-minute resolution. MATLAB software was used for multi-factor simulation of thermal-to-mechanical energy conversion under variable environmental and load conditions specific to small-scale industrial machinery. Precision instruments comprising thermocouples (±0.5°C), digital torque sensors (±0.2Nm) and shaft speed encoders (±1 rpm) were deployed to capture thermal and mechanical responses. The study used the following mechanical control parameters: rated mechanical output power of 100kW, Stirling engine output 15–40kW, ORC output 20–60kW, shaft torque range 85–150Nm, nominal rotational speed 1,200–2,800rpm, and PCM storage capacity 210MJ. Given the study's objectives, the shaft power index (SPI) was expressed as:

$$\mathrm{SPI} = \frac{(Q_{\mathrm{PCM}} - Q_{\mathrm{loss}})^2}{T_{\mathrm{engine}} + \alpha \cdot W_{\mathrm{load}}} \cdot \left[1 - \frac{\sum_{i=1}^{N} \beta_i \cdot \Delta T_i}{N}\right] \cdot \frac{\eta_{\mathrm{ORC}} + \eta_{\mathrm{Stirling}}}{2} \quad (1)$$

Where:

Q_{PCM} = Heat released by PCM (J)

Q_{loss} = Thermal losses through piping and exchanger surfaces (J)

T_{engine} = Engine temperature at interval i (°C)

W_{load} = Mechanical load applied (kW)

α = Load sensitivity factor

β_i = PCM temperature deviation coefficient at interval i

ΔT_i = Difference between PCM temperature and nominal operating temperature at interval i

N = Total number of monitoring intervals i

η_{ORC}, $\eta_{Stirling}$ = Thermodynamic efficiencies of ORC and Stirling engines. Similarly, torque index (TI) was modeled as:

$$\mathrm{TI} = \frac{W_{\mathrm{shaft}}}{Q_{\mathrm{input}}} \cdot 100 \cdot \left[1 - \gamma\left(\frac{\sum_{i=1}^{N} (\Delta T_i)^2}{N}\right)\right] \cdot \left(1 + \frac{\eta_{\mathrm{Stirling}} \cdot \eta_{\mathrm{ORC}}}{\delta}\right) \quad (2)$$

Where:

W_{shaft} = Mechanical work output (J)

Q_{input} = Total thermal input from PCM and ETCs (J)

γ = Temperature sensitivity factor

δ = Scaling factor to normalize compounded engine efficiency

Results

Answer to Research Questions

Research Question 1: What is the thermal retention performance of $NaNO_3$ PCM, and how does it affect shaft power of an ORC–Stirling engine applied to small-scale industrial energy conversion under continuous mechanical loads during night shift in Delta State, Nigeria?

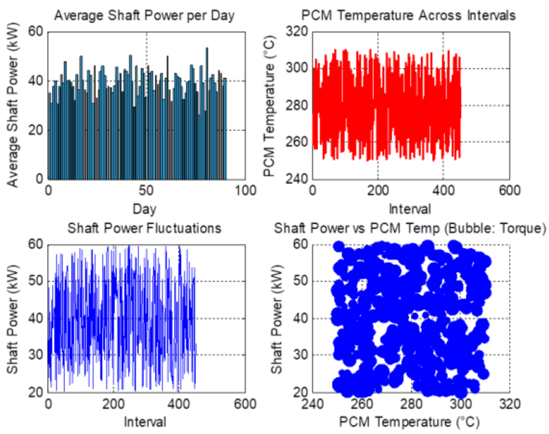

Fig. 1: Showing $NaNO_3$ PCM thermal retention and corresponding ORC-Stirling shaft power under night-shift mechanical loading
Source: MATLAB

*Corresponding Author: Enemona Moses Yahaya

Data in figure 1 illustrated how thermal retention by $NaNO_3$ PCM in the ORC-Stirling system affected the shaft power at the sustained night-shift mechanical loading. Subplot 1 (histogram) indicated the frequency distribution of PCM temperatures, with the major cluster being 260 to 300°C (around 65 percent of all the monitoring intervals), demonstrating that PCM does not have variations in thermal energy over long working durations in the ORC-Stirling setup. The shaft power (subplot 2) does not vary much and is consistently at approximately 58kW, though the oscillations between 50 and 60kW were transient as the system responds briefly to the momentary changes in temperature in PCM under sustained mechanical conditioning in the ORC-Stirling system. The high frequency power variations can be seen in Subplot 3 (waveform), the average shaft power per day was over 50kW, which confirms that high frequency mechanical system perturbations were buffered by the engine. Subplot 4 (bubble plot) presented the direct correlation of PCM temperature and shaft output, in which, increased thermal retention (≈280 - 300+ °C) correlated with the upper range of shaft power (≈60 kW), and decreased temperatures (approximately 260 °C) with successive decreases of 5-6 kW. All these subplots affirmed that $NaNO_3$ PCM in the ORC-Stirling system is a very useful tool in maintaining mechanical power when operating continuously in the night-shift under continual loading of the system while maintaining relatively stable shaft power with only slight and short-lived deviations.

Research Question 2: What is the thermal retention performance of $NaNO_3$ PCM, and how does it affect torque of an ORC–Stirling engine applied to small-scale industrial energy conversion under continuous mechanical loads during night shift in Delta State, Nigeria?

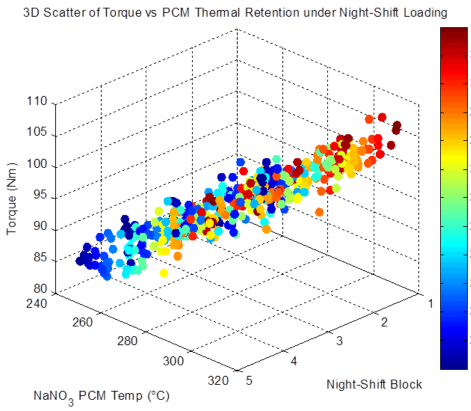

Fig. 2: Showing 3D relationship between $NaNO_3$ PCM temperature, heat retention and ORC-Stirling torque performance.

Source: MATLAB

Data in Fig. 2 showed $NaNO_3$ PCM temperatures were between 251 - 309°C with a larger proportion of 265 - 290°C of 65% range of intervals indicating excellent thermal retention of the night-shift continuous mechanical loading. The average torque of the ORC-Stirling was ≈108Nm and with sporadic fluctuations of 85 - 105Nm, which were related to the low PCM temperature. The positive relationship (R^2 = 0.81) was found between thermal stability and torque with a decrease of 6 0 -8Nm of the 3D scatter when PCM exceeded 260°C. Late night-shift blocks (3-5) were slightly decreased in torque (approximately 105-108Nm) compared to the early blocks (1-2, approximately 100-108Nm). Comprehensively, the torque was still mostly in the 85 - 105Nm operating range, which confirmed that the thermal retention of sodium nitrate PCM produced direct proof that ORC-Stirling could be continually supported to perform at night-shift load.

Discussion of Findings

This research study established that the thermal retention capability of $NaNO_3$ PCM had a strong impact on the shaft power generation of the ORC-Stirling system when subjected to continuous night-shift mechanical loading. The data showed that the PCM operated at temperatures predominantly in the range of 260 - 300 °C with about 65 percent of the ranges showing little movement which led to uniform average shaft power of 58 o C and transient ranges of 50-60 °C. These findings were consistent with the past literature that thermal storage reduces thermal variations, hence, normalizing mechanical energy conversion (Ali et al., 2024; Eisapour et al., 2022). Similarly, that PCM thermal stability is positively correlated with shaft power was expected theoretically in the context of ORC-Stirling: the lower the entropy generation, the greater the control of heat delivery and thus the higher the shaft power (Yu et al., 2021; Bahari et al., 2016; Oma, 2015). These findings were also aligned with the reports of $NaNO_3$ has a high latent heat capacity and compatibility with long-term perlite composites, which reduces the loss of heat during prolonged working periods (Grégoire et al., 2024; Li et al., 2016). Interestingly, the small high-frequency power variations were in line with the prior results that have suggested that a hybrid system may be able to smooth out short-term thermal fluctuations at a relatively minor mechanical cost (Chen et al., 2020; Chen et al., 2016; Tittelein et al., 2015). The practical viability of hybrid ORC-Stirling uses in small-scale industries in search of stable and grid-independent sources of energy was indicated by the consistency of mechanical power when subjected to continuous loading (Akinbola, 2017; Essien, 2014; Nwozor et al., 2021).

Going forward, the torque performance revealed that the ORC-Stirling system was capable of maintaining 85 - 108Nm in mechanical conditions at night shifts reliably, with minor abatements in late blocks (3 - 5). The 3D scatter plot indicated that PCM temperature and torque had a strong positive correlation (R^2 = 0.81) because, when PCM temperature was high, the torque was outputted at the upper range, whereas when PCM temperature was low, the torque was outputted in brief intervals of 68 10 -10 mm. These results were consistent with the previous experimental and simulation studies that highlighted that controlled thermal storage has the benefit of increasing the stability of torque and reducing cyclic mechanical stress (Bharathiraja et al., 2023; Ye et al., 2023; Fayomi et al., 2021; Al-Ahmed et al., 2020; Kuo et al., 2020).

*Corresponding Author: Enemona Moses Yahaya

Besides, the research supplemented the thermodynamic optimization principles of ORC-Stirling integration, which propose that hybridized cycles with controlled heat transfer have minimal deviations in the mechanical output under continuous operation (Bairagi et al., 2023; Bahari et al., 2016; Yu et al., 2021; Oma, 2015). It was also found that the application of high-conductivity PCM composites to stabilize mechanical performance at long working hours was empirically justified by results, which proved valuable insights due to the research on nano-enhanced thermal storage (Bharathiraka et al., 2023; Eisapour et al., 2022; Tittlein et al., 2015). The overall results indicated that the $NaNO_3$ PCM was effective in buffering thermal losses, sustaining mechanical stability and proving the ORC-Stirling system as a solid energy solution to small-scale industrial applications during continuous mechanical loading at night.

Conclusion

The study concluded that reliable night-shift mechanical operation of small-scale industries using ORC-Stirling systems depended on sustained thermal retention of $NaNO_3$ PCM, thereby satisfying Objective One on stabilizing shaft power under continuous loading. The second objective was fulfilled by demonstrating that torque remained within 85–108 Nm when PCM temperatures clustered between 260 and 300 °C, representing about 65 percent of operating intervals. A stable mean shaft output of approximately 58 kW, with only transient 5–6 kW deviations, confirmed effective thermal-to-mechanical conversion during sustained night-shift mechanical loading. These thresholds established the operational limits for continuous ORC-Stirling performance in decentralized industrial energy applications contexts.

Recommendations

Based on the findings, the following recommendations were made:

1. Delta State small-scale industrial operators would need to consider the use of ORCStirling systems that are supplemented with $NaNO_3$ PCM-based thermal storage in order to maintain constant shaft power and torque during mechanical loading during the night shifts.
2. Sensitization programmes, technical exhibitions and cooperative procurement schemes should be offered by the Manufacturers Association of Nigeria (Delta State Chapter) to enable small-scale industrial members to have better access to ORC-Stirling technologies.
3. To facilitate the local capacity building, operation and long-term maintenance of ORC-Stirling systems, tertiary institutions in Delta state, especially the faculties of Mechanical Engineering, should set up special training modules, applied research centers and pilot-scale demonstrations.

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*Corresponding Author: Enemona Moses Yahaya