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A Theoretical Assessment of the Exergetic and Exergoeconomic Potential of Integrating Organic Rankine Cycle (ORC) and Rankine Cycle in Tractor Engine Systems

Atheer Fadhil Radhi

The General Directorate of Education in Babil, Ministry of Education in Iraq.

Abstract: In the context of escalating fuel costs and stringent environmental regulations in agriculture, integrating waste heat recovery (WHR) systems into tractor engines represents a pivotal strategy for enhancing energy efficiency and sustainability. This study conducts a comprehensive theoretical assessment of a novel cascade system that combines a high-temperature steam Rankine Cycle (RC) with a low-temperature Organic Rankine Cycle (ORC) to harness exhaust and coolant waste heat from a 302 kW heavy-duty diesel engine typical in modern tractors. Employing thermodynamic modeling, advanced exergy analysis, and exergoeconomic evaluation, the system is optimized using multi-objective genetic algorithms to maximize exergy efficiency while minimizing specific electricity costs. Innovative aspects include the incorporation of a regenerative preheater in the ORC loop and the use of environmentally benign working fluids such as R1233zd(E) for the ORC and water-steam for the RC, selected based on global warming potential (GWP) and ozone depletion potential (ODP) criteria. Results indicate a net power output of 38.7 kW, an exergy efficiency of 42.8%, and a brake-specific fuel consumption (BSFC) reduction of 12.5%. Exergoeconomic analysis yields a unit cost of electricity at 16.85 USD/GJ, with a payback period of 3.5 years under variable load conditions. Sensitivity analysis reveals robustness against exhaust temperature fluctuations (400-550°C), and environmental impact assessment shows a CO2 emission reduction of 15.2 tons annually per tractor. Compared to single-loop systems, the cascade configuration improves overall efficiency by 18-22%, underscoring its innovative potential for off-highway applications. Future experimental validation is recommended to bridge theoretical insights with practical deployment.

Keywords: Waste heat recovery; Organic Rankine Cycle; Rankine Cycle; Exergy analysis; Exergoeconomic analysis; Tractor engines; Diesel engine integration.

INTRODUCTION

Agricultural tractors, powered by heavy-duty diesel engines, operate under high-load conditions for extended periods, resulting in significant waste heat dissipation. Typically, only 35-45% of the fuel's chemical energy is converted to mechanical work, with 30-40% lost via exhaust gases at 400-600°C and 20-30% through coolant systems (Majewski, W. A., & Khair, M. K). In the European Union, tractors consume approximately 10-15% of total diesel fuel in agriculture, contributing to greenhouse gas emissions equivalent to 50 million tons of CO2 annually (Varshil, P., & Deshmukh, D. 2021). With the advent of IMO Tier III and EU Stage V emission standards, there is an urgent need for innovative WHR technologies to improve fuel economy and reduce environmental footprints (Varshil, P., & Deshmukh, D. 2021).The Rankine Cycle (RC) excels in recovering high-grade heat using steam, while the Organic Rankine Cycle (ORC) is adept at low-grade sources with organic fluids offering lower boiling points and better thermal matching (Sprouse III, C., & Depcik, C. 2013). Cascading RC and ORC enables sequential heat utilization, addressing the multi-temperature waste heat profile in diesel engines. Prior studies have demonstrated ORC viability in tractors, achieving up to 10% BSFC improvements (Koronaki, I. P. *et al.*, 2012), but integrated cascade systems remain nascent, particularly with exergoeconomic perspectives that balance thermodynamic gains against capital costs (Fierro, J. J. *et al.*, 2022).This paper innovatively assesses a regenerative cascade RC-ORC system for a 302 kW tractor engine, incorporating advanced fluid selection, genetic algorithm-based optimization, and exergoenvironmental analysis. The objectives are to quantify exergetic potential, evaluate economic feasibility, and propose design enhancements for real-world tractor applications, filling a gap in off-highway WHR literature.

LITERATURE REVIEW

Waste heat recovery in internal combustion engines has evolved significantly, with ORC and RC systems at the forefront. Early works focused on single-loop ORC for diesel exhaust recovery, reporting thermal efficiencies of 10-15% using fluids like R245fa (Varshil, P., & Deshmukh, D. 2021). For instance, a thermodynamic analysis of ORC in marine diesel engines highlighted exergy efficiencies up to 57.3% under optimized conditions (Koroglu, T., & Sogut, O. S. 2017). Dual-loop configurations, combining high and

***Corresponding Author:** Atheer Fadhil Radhi

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low-temperature cycles, have shown superior performance; a study on cascade ORC for engine waste heat achieved net powers of 33-40 kW with exergy efficiencies around 40% (Real, A. C. *et al.*, 2024).Exergetic analyses reveal that evaporators and condensers account for 50-70% of total exergy destruction, with avoidable portions up to 80% amenable to optimization (Fergani, Z., & Morosuk, T. 2023). Advanced exergy methods, splitting destruction into endogenous/exogenous and avoidable/unavoidable, have been applied to ORC systems, identifying turbine improvements as key for efficiency gains (Fergani, Z., & Morosuk, T. 2023). Exergoeconomic evaluations integrate cost flows, using methods like SPECO to derive unit costs; for example, an ORC coupled to geothermal sources yielded electricity costs of 0.035-0.045 USD/kWh with payback periods under 4 years (Ambriz-Díaz, V. M. *et al.*, 2022).In tractor-specific contexts, RC applications for exhaust recovery have been modeled, emphasizing fluid dynamics and pressure ratios (Koronaki, I. P. *et al.*, 2012). A numerical study on tractor engine WHR potential estimated recoverable power of 15-20 kW from exhaust alone (Varshil, P., & Deshmukh, D. 2021). Integrated systems, such as ORC with ejector cycles, have demonstrated multi-generation capabilities (power, cooling, heating) with exergy efficiencies exceeding 50% (Hai, T. *et al.*, 2024)**.** Exergoenvironmental analyses extend this by quantifying ecological impacts, showing ORC reductions in CO2 equivalents by 10-20% **(**Chen, S. *et al.*, 2022).Recent innovations include transcritical-subcritical parallel ORC configurations for enhanced heat matching (Zhi, L. *et al.*, 2025)**.** Multi-objective optimizations using genetic algorithms have optimized parameters like evaporation pressure and superheat degree, balancing efficiency and cost (Kaur, N. *et al.*, 2023). For diesel engines, combined RC-ORC cascades have been exergoeconomically compared, favoring organic fluids for low-grade recovery (Fierro, J. J. *et al.*, 2022). Thermoeconomic studies on series heat exchangers in ORC underscore the role of regenerative preheaters in boosting performance (Ambriz-Díaz, V. M. *et al.*, 2022). However, tractor applications lag, with limited focus on variable loads and environmental metrics, motivating this study's novel integration of regenerative elements and AI-driven optimization.

SYSTEM DESCRIPTION AND MODELING

The proposed cascade system integrates a steam RC for high-temperature exhaust recovery (450-550°C) and a regenerative ORC for residual heat from the RC condenser and engine coolant (80-150°C). The RC loop uses water-steam, evaporating in a shell-and-tube heat exchanger, expanding in a turbine, condensing, and pumping back. The ORC employs R1233zd(E), incorporating a regenerative preheater to recover turbine exhaust heat, enhancing cycle efficiency. System boundaries assume steady-state operation, isentropic efficiencies of 85% for turbines and 80% for pumps, and negligible kinetic/potential exergies. Ambient conditions are 25°C and 101.3 kPa.

Thermodynamic Model

Mass and energy balances govern each component. For the RC evaporator:

$$m_{exh,in}\left(h_{exh,in} - h_{exh,out}\right) = m_{steam}\left(h_{steam,out} - h_{steam,in}\right)$$

Network output: $\dot{W}_{net} = \left(\dot{W}_{t,RC} + \dot{W}_{t,ORC}\right) - \left(\dot{W}_{p,RC} + \dot{W}_{p,ORC}\right)$

Thermal efficiency: $\eta_{th} = \frac{\dot{W}_{net}}{\dot{Q}_{exh}+\dot{Q}_{cool}}$

Models are developed in Engineering Equation Solver (EES), validated against engine data yielding 180 kW exhaust heat and 120 kW coolant heat.

Exergy Analysis

Exergy balance for component k: $\dot{E}_{D,k} + \dot{E}_{L,k} = \dot{E}_{F,k} - \dot{E}_{P,k}$

Advanced analysis splits $\dot{E}_{D,k}$ into avoidable $\left(\dot{E}_{D,k}^{AV}\right)$ and unavoidable $\left(\dot{E}_{D,k}^{UN}\right)$ parts, and endogenous/exogenous. Exergy efficiency: $\psi = 1 - \frac{\sum \dot{E}_{D,k}+\sum \dot{E}_{L,k}}{\sum \dot{E}_{F,k}}$

Innovatively, exogenous interactions are minimized through component isolation in optimization.

Exergoeconomic Analysis

Cost balance: $\sum \dot{C}_{out,k} + \dot{C}_{w,k} = \sum \dot{C}_{in,k} + \dot{C}_{q,k} + \dot{Z}_k$

Where $\dot{Z}_k$ includes capital, maintenance, and operational costs, calculated via:

$$\dot{Z}_k = \frac{Z_k.CRF.\phi}{N}$$

CRF is the capital recovery factor, ϕ maintenance factor (1.06), N annual hours (8000).

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Exergoeconomic factor: $f_k = \frac{\dot{Z}_k}{\dot{Z}_k + \dot{C}_{D,k} + \dot{C}_{L,k}}$ Unit product cost c_p is minimized.

Multi-Objective Optimization
A genetic algorithm (GA) in MATLAB optimizes evaporation pressures, superheat degrees, and pinch points, with objectives: maximize ψ\psiψ and minimize c_p. Pareto fronts are generated, selecting knee points via LINMAP method. Innovation lies in incorporating exergoenvironmental costs, penalizing high-GWP fluids.

RESULTS AND DISCUSSION

The optimized system delivers 38.7 kW net power, with RC contributing 22.4 kW and ORC 16.3 kW. Exergy efficiency reaches 42.8%, a 15% improvement over non-regenerative baselines. Avoidable exergy destruction is highest in the evaporator (45%, 12.5 kW) and condenser (35%, 9.8 kW), suggesting finned-tube enhancements. Exergoeconomic results show c_p=16.85c_p = 16.85c_p=16.85 USD/GJ, with turbines exhibiting high f_k (70%), indicating investment priority. Payback period is 3.5 years at 0.8 USD/L diesel. Sensitivity to exhaust temperature: ψ= 38-46% from 400-550°C.

Table: 1 Compared to literature, the system outperforms single ORC (34% ψ) and RC (29% ψ) by leveraging cascade synergy (Fierro, J. J. *et al.,* 2022). Environmental benefits include 15.2 tons CO2 savings/year, aligning with sustainable agriculture goals (Chen, S. *et al.,* 2022)

Component	Exergy Destruction (kW)	Avoidable (%)	Cost Rate (USD/h)	Exergoeconomic Factor (%)
Evaporator (RC)	18.2	65	0.45	55
Turbine (RC)	8.5	40	0.32	72
Condenser (RC/ORC Interface)	14.3	70	0.38	60
Evaporator (ORC)	10.1	55	0.28	58
Turbine (ORC)	6.2	35	0.25	68
Preheater (ORC)	4.8	50	0.18	62

CONCLUSION

This theoretical study demonstrates the superior exergetic (42.8%) and exergoeconomic (16.85 USD/GJ) potential of a regenerative cascade RC-ORC system for tractor engine WHR. Innovations in optimization and fluid selection enhance viability, reducing BSFC by 12.5% and emissions significantly. Recommendations include dynamic modeling for transient tractor operations and prototype testing to validate theoretical gains.

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