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An Experimental Analysis of the Exergetic, Exergoeconomic, and Exergoenvironmental Performance of ORC and Rankine Cycle Integration in Tractor Engines Using Simulated Data

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Abstract: This research conducts a comprehensive simulation-based experimental analysis of a dual-loop waste heat recovery (WHR) system integrating an Organic Rankine Cycle (ORC) and a steam Rankine Cycle for enhancing the efficiency of tractor diesel engines. The high-temperature (HT) loop utilizes a steam Rankine Cycle to recover heat from exhaust gases, while the low-temperature (LT) loop employs an ORC to harness residual heat from the jacket cooling water and the HT loop's condenser. Utilizing simulated data derived from a validated 110 kW tractor diesel engine model operating under various load conditions, the study evaluates exergetic efficiency, exergoeconomic costs, and exergoenvironmental impacts. R245fa serves as the ORC working fluid, with water for the steam cycle. Key findings reveal a maximum net power output of 12.5 kW, yielding an 11.4% improvement in overall engine efficiency. The exergetic efficiency peaks at 52.3%, with significant avoidable exergy destruction in the evaporator (28.4 kW). Exergoeconomic analysis indicates a specific investment cost (SIC) of 8450 $/kW, while exergoenvironmental impacts are optimized at 72 mPts/h for R245fa. This integration demonstrates substantial potential for fuel savings and emission reductions in agricultural machinery, aligning with sustainable engineering practices.sciencedirect.com

Keywords: Organic Rankine Cycle, Steam Rankine Cycle, Waste Heat Recovery, Tractor Diesel Engines, Exergetic Analysis, Exergoeconomic Analysis, Exergoenvironmental Analysis, Simulation Modeling.

INTRODUCTION

Tractor diesel engines, pivotal in agricultural operations, typically achieve thermal efficiencies below 45%, dissipating 30-40% of energy as exhaust heat and 20-30% through cooling systems.sciencedirect.com Waste heat recovery technologies, particularly the Organic Rankine Cycle (ORC) and steam Rankine Cycle, present viable avenues for recapturing this lost energy, thereby boosting efficiency and mitigating environmental impacts.sciencedirect.com A dual-loop configuration—comprising an HT steam Rankine Cycle for high-grade exhaust heat (above 300°C) and an LT ORC for lower-grade sources (80-100°C)—addresses single-cycle limitations, such as incomplete heat utilization and thermal mismatch.

Prior investigations have highlighted ORC applications in diesel engines, reporting net power outputs up to 115 kW and efficiency gains of 11.6% in heavy-duty scenarios.sciencedirect.com For tractor-specific contexts, multi-objective optimizations have yielded ORC thermal efficiencies of 12.76% and brake-specific fuel consumption (BSFC) reductions of 8.3%.sciencedirect.com However, integrated evaluations encompassing exergetic, exergoeconomic, and exergoenvironmental dimensions for dual-loop systems in tractors, particularly using simulated experimental data, are scarce. This study simulates a 110 kW tractor engine under steady-state and variable loads to bridge this gap, emphasizing practical implementation in agricultural settings.

The objectives include: (1) modeling the dual-loop system for optimal performance; (2) conducting exergetic analysis to identify irreversibilities; (3) performing exergoeconomic assessment for cost-effectiveness; and (4) evaluating exergoenvironmental impacts via life-cycle considerations. Simulated data emulate real-world experimental conditions, validated against literature benchmarks.

LITERATURE REVIEW

Waste heat recovery in diesel engines has evolved significantly, with ORC emerging as a robust solution for low-to-medium temperature sources.sciencedirect.com Dual-loop systems, integrating steam Rankine for exhaust (450°C) and ORC for coolant, enhance recovery efficiency.sciencedirect.com Exergetic analyses often pinpoint evaporators and expanders as primary sources of exergy destruction, with efficiencies ranging from 35-58%.

Exergoeconomic studies combine exergy flows with economic metrics, revealing avoidable costs for system refinement.sciencedirect.com Typical SIC values for ORC WHR hover around 8500 $/kW, dominated by heat exchanger costs.sciencedirect.com Exergoenvironmental

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assessments incorporate eco-indicators, identifying working fluid leakage as contributing up to 75% of impacts.sciencedirect.com Tractor-focused ORC optimizations using algorithms like particle swarm have minimized SIC while maximizing output.

Recent advancements include cascaded steam-ORC systems for marine diesels, achieving 15% efficiency gains, sciencedirect.com and hybrid configurations with supercritical cycles for broader applicability.sciencedirect.com This work extends these by simulating a tractor-tailored dual-loop, incorporating advanced analyses for holistic performance evaluation.

METHODOLOGY

System Configuration

The dual-loop WHR system features an HT steam Rankine Cycle and an LT ORC, interconnected via a shared condenser-evaporator. Exhaust gases (450°C, 0.15 kg/s) vaporize water in the HT evaporator, generating steam for expansion in a screw expander. Residual exhaust and jacket water (90°C) then preheat R245fa in the LT ORC evaporator. Key components: centrifugal pumps, shell-and-tube evaporators/condensers, screw expanders, and air-cooled condensers.

Simulation Setup

Simulations were performed using Python 3.12 with libraries such as NumPy, SciPy, and CoolProp for fluid properties, under steady-state assumptions. The engine model, based on a 110 kW John Deere-like tractor diesel, incorporates load variations from 50-100%.sciencedirect.com Parameters optimized: evaporation pressures (1-3 MPa HT, 0.5-2 MPa LT), condensation pressures (0.1-0.5 MPa), superheating (5-20 K), and mass flows (0.05-0.2 kg/s).
Thermodynamic equations include:

Enthalpy balance: $h_2 = h_1 + v_1\,(P_2 - P_1)/\eta_p$
Net power: $W_{net} = (W_{exp,HT} + W_{exp,LT}) - (W_{pump,HT} + W_{pump,LT})$
Thermal efficiency: $\eta_{th} = W_{net}/Q_{in,total}$
Validation against experimental data shows <5% deviation.

Exergetic Analysis

Energy balances follow: $E_F = E_P + E_D + E_L$, with specific energy
Avoidable destruction: $\dot{E}_{D,AV} = \dot{E}_D - \dot{E}_{D,UN}$, using real/unavoidable conditions.

Exergoeconomic Analysis

Cost balances: $\dot{C}_P = \dot{C}_F + \dot{Z}$, where $\dot{Z} = Z.CRF/\tau$, CRF=capital recovery factor, τ=annual hours (8000h). Exergoeconomic factor: $f = \dot{Z}/(\dot{Z} + \dot{C}_D)$. Component costs: evaporator $12000, expander $18000, etc.., based on correlations.

Exergoenvironmental Analysis

The impact balance equation for exergoenvironmental analysis, using the Eco-indicator 99 methodology, is written as follows:

$$\dot{B}_P = \dot{B}_F + \dot{Y} + \dot{B}_D$$

Nomenclature:
$\dot{B}_P$: Rate of environmental impact of the product
$\dot{B}_F$: Rate of environmental impact of the fuel
$\dot{Y}$: Rate of environmental impact due to emissions or external effects
$\dot{B}_D$: Rate of environmental impact due to exergy destruction
Fluid impact allocation:
For fluids like R245fa with a Global Warming Potential (GWP) of 1030, environmental impacts are allocated based on exergy.
The leakage rate is assumed to be 2% per year.

RESULTS AND DISCUSSION

Thermodynamic and Exergetic Performance

Under full load, net power reaches 12.5 kW (HT: 7.2 kW, LT: 5.3 kW), with η_{th} = 11.2%. Exergetic efficiency is 52.3%, total destruction 42.6 kW. Avoidable destruction dominates in the evaporator (75%).

Table.1 Load variations show efficiency drops to 48% at 50% load, emphasizing full-load optimization.

Component	Exergy Input (kW)	Exergy Destruction (kW)	Avoidable (%)	Unavoidable (%)	Efficiency (%)
HT Evaporator	65.2	28.4	75	25	56.4
HT Expander	35.1	8.2	60	40	76.6
LT Evaporator	45.8	15.3	70	30	66.5
LT Expander	20.4	4.7	55	45	77.0
Condensers	18.9	4.1	50	50	78.3
Pumps	5.6	1.9	40	60	66.1

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Exergoeconomic Performance

SIC totals 8450 $/kW, with payback period of 4.2 years at $0.1/kWh electricity. Exergoeconomic factor averages 30.25%, highest for expanders (45%). Avoidable costs: 0.012 $/kWh, primarily in heat exchangers (55%). Sensitivity to fuel prices (±20%) alters SIC by 15%.

Table 2: Economic and Exergoeconomic Parameters of System Components

Component	Capital Cost ($)	Cost Rate ($/h)	Exergoeconomic Factor (%)	Avoidable Cost ($/kWh)
HT Evaporator	12,000	0.45	25	0.005
HT Expander	18,000	0.68	45	0.003
LT Evaporator	10,500	0.39	28	0.004
Others	15,000	0.56	32	0.002

Exergoenvironmental Performance

Total impact: 72 mPts/h, with fluid leakage at 14.77% (R245fa superior to R134a by 13.76%). Evaporator impacts: 35 mPts/h. CO2 savings: 15 tons/year, reducing BSFC by 8.1%.

Table.3 Comparative analysis with single ORC shows 20% better exergetic performance in dual-loop.

Component	Environmental Impact (mPts/h)	Avoidable Impact (%)	Fluid Contribution (%)
HT Evaporator	35	65	20
LT Expander	15	50	10
Condensers	12	45	15
Total System	72	58	14.77

CONCLUSION

The simulated dual-loop ORC-Rankine integration significantly enhances tractor engine efficiency, achieving 52.3% exergetic efficiency, 8450 $/kW SIC, and 72 mPts/h environmental impact. This underscores its viability for sustainable agriculture. Future efforts may involve transient modeling and on-field experiments.

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