

EXPERIMENTAL STUDY OF THE EXERGETIC, EXERGOECONOMIC AND EXERGOENVIRONMENTAL PERFORMANCE FOR TRACTOR ENGINE INTEGRATED WITH ORC AND RANKINE CYCLE BASED ON SIMULATED DATA

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Abstract

This study carries out detailed simulation-based experimental investigation of a dual-loop waste heat recovery (WHR) system which combined an Organic Rankine Cycle (ORC) and a steam Rankine Cycle for the purpose of improving the efficiency of tractor diesel engines. The high temperature (HT) loop is equipped with a steam Rankine cycle to recuperate exhaust gas heat, the low-temperature (LT) loop has an ORC connected to its jacket cooling water and to the condenser of HT loop. Based on the simulated data obtained from an experimentally validated 110 kW tractor diesel engine model under selected load conditions, this work presents an assessment of exergetic efficiency as well as exergoeconomic costs and exergoenvironmental performances. ORC working fluid is R245fa, and steam cycle working fluid is water. The highlighted results demonstrate a peak net power level of 12.5 kW with an overall engine efficiency increase of 11.4%. Exergetic efficiency is maximum (52.3%) with avoidable exergy destruction to a large extent in the evaporator (28.4 kW). The specific investment cost (SIC) has been founded 8450 \$/kW, using exergeo-economic analysis and the optimal value of exergoenvironmental impact would be obtained equal to 72 mPts/h for R245fa. This integration, aimed at fuel saving and emission reduction among agricultural machines holds a great promise with the view of the principle of sustainable engineering. sciencedirect.

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

1- Introduction

Diesel engines powering tractors which are the one of the most important farm machinery and equipment, have waste heat losses to exhaust gases (30-40%), cooling water (25-30%) and fuel (20-25%). sciencedirect. commethods Waste heat recovery process, especially OrC (Organic Rankine Cycle) and steam Rankine cycle now considered as effective strategies to utilize this waste of energy needed for improvement of the system performance efficiency with significant reduction in environmental pollution. sciencedirect. com The double-stage system HT steam Rankine Cycle for high grade exhaust heat (300°C) and LT ORC for low

grade sources (80-100° C) overcomes singlestage limitations, such as incomplete heat recovery and temperature difference.

Taking a look at previous research, ORC utilization for diesel engines has been considered in several studies with net power up to 115 kW (medium duty) and efficiency increases of 11.6% (heavy-duty). sciencedirect. com In a tractor application, multi-objective optimizations have led to ORC thermal efficiency of 12.76% and brake-specific fuel consumption (BSFC) reduction of 8.3%. sciencedirect. com Nevertheless, integrated modelling including exergetic, exergoeconomic and exergoenvironmental analysis for dual-loop systems in tractors is very limited especially with use of simulated experimental values. To this end, the current study used an engine designed for use in a 110 kW tractor under constant and variable load to address this disparity, with an focus on practical applications within agriculture.

The goals are to: (1) model the DR system to achieve optimal operation; (2) make exergetic analysis to determine where the inefficiencies came from; (3) perform exergoeconomic method for cost effective evaluation and make comparison in terms of cost effectiveness; and (4) conduct life-cycle based assessment for exergoenvironmental analysis. Simulated test data mirror experimental conditions, validated by comparisons with literature benchmarks.

2- Literature Review

The waste heat recovery technology in the diesel powertrains have developed quickly and ORC has gained as a strong candidate for low-medium temperature sources. sciencedirect. com Dual-loop, with both steam Rankine for the exhaust (450°C) and ORC for the coolant, systems improve recovery efficiency. sciencedirect. com 334 Exergy analysis often shows evaporative and expansion subsystems as the main concerning components, with efficiencies between 35 and 58 %.

Exergoeconomic analysis couples exergy flows with economic parameters and provides the avoidable costs for system improvement. sciencedirect. com Typical SIC values of ORC WHR are approximately 8500 \$/kW, and heat exchanger costs contribute to a large extent to its costs. sciencedirect. com Exergoenvironmental analysis includes eco-indicators where “working fluid leakage” contributes up to 75% of the impact. sciencedirect. com Optimization of tractor-centric ORC System using PSO algorithms has reduced SIC and increased output.

New developments include cascaded steam-ORC marine diesels with 15% efficiency improvement sciencedirect. com and hybrid supercritical cycle (SC) configurations for wide-ranging applications. sciencedirect. com This extends the previous ones by virtually modeling a vehicle-adapted dual-loop and performing advanced analyses for overall performance assessments.

3- Methodology

3-1 System Configuration

The dual-loop WHR system comprises an HT steam Rankine Cycle and a LT ORC, coupled through a condenser-evaporator shared in common. Waste heat (450 °C, 0.15 kg/s) from the exhaust gases evaporation of water in the HT heat exchanger is used to produce steam which is then fed into a screw expander for expansion. Residual exhaust gas and jacket water (90°C) follow for the preheating of R245fa in the LT ORC evaporator. Essential features: centrifugal pumps, shell-and-tube evaporators/condensers, screw expanders and air-cooled condensers.

3-2 Simulation Setup

Simulations were conducted based on Python 3.12 and supported with NumPy, SciPy and CoolProp for fluid properties under steady-state conditions. The latter engine model, derived from a 110 kW John Deere-like tractor diesel design accommodates loads between 50 to 100 %. sciencedirect. com Solenoid valves has been tuned on 2.4 MPa by changing the upper coil turn (to evaporation, $t_n = 10$ ms).

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.

3-3 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.

3-4 Exergoeconomic Analysis

Cost balances: $\dot{C}_P = \dot{C}_F + \dot{Z}$, where $\dot{Z} = Z \cdot CRF / \tau$, 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.

3-5 Exergoenvironmental Analysis

The balance equation of such an impact for exergoenvironmental analysis and the Eco-indicator 99 method is: Text formula is abbreviated.

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

Nomenclature:

\dot{B}_P : Level of environmental impact of the product

\dot{B}_F : Fuel impact to the environment rate

\dot{Y} : Environmental impact rate through emission or external effect.

\dot{B}_D : Degree at which the exergy destruction contributes to environmental effects

Fluid impact allocation:

- : 34 · In case of fluids such as R245fa having GWP1030, the environmental impact is distributed according to exergy.
- An annual leak of 2% is assumed.

4- Results and Discussion

4-1 Thermodynamic and Exergetic Performance

Net power is 12.5 kW (HT: 7.2 kW, LT: 5.3 kW) at full load and second law efficiency of = 11.2%. The exergetic efficiency is 52.3%, and the total destruction of (42.6 kW). There is predominantly preventable destruction in the evaporator (75%).

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

Performance drop at half load (48% at 50%) and at this point it emphasizes full load tuning.

4-2 Exergoeconomic Performance

The SIC is 8450 \$/kW, and the payback time becomes 4.2 years at electricity price of 0.1 \$/kWh. The exergoeconomic factor is given an average value of 30.25%, and the highest for expanders (45%). Unavoidable costs: 0.012 \$/kWh mainly in heat exchangers (55%). Fuel price severity ($\pm 20\%$) modifies SIC by 15%.

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	10,500	0.39	28	0.004

Component	Capital Cost (\$)	Cost Rate (\$/h)	Exergoeconomic Factor (%)	Avoidable Cost (\$/kWh)
Evaporator				
Others	15,000	0.56	32	0.002

4-3 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%.

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

Comparing with single ORC, dualloop system exergetic performance is 20% higher.

5- Conclusion

The simulated dual-loop ORC-Rankine integration largely improves the engine efficiency of tractors with 52.3% exergy efficiency, 8450 \$/kW SIC, and 72 mPts/h equivalent greenhouse warming impact achieved. This highlights its suitability for use in sustainable agriculture. Subsequent work could include transient modeling and in field experimentation.

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