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THEORETICAL EVALUATION OF THE EXERGETIC ANALYSIS AND EXERGOECONOMIC OF ORGANIC RANKINE CYCLE (ORC)/RANKINE HYBRID ENGINE SYSTEM IN TRACTOR APPLICATIONS

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Abstract

Given the increasing fuel price and strict environmental regulations in agriculture, it is strategic to apply waste heat recovery (WHR) system on the tractor engine for energy-saving and environmental performance. A comprehensive theoretical investigation is presented in this study of a new combination system of the high-temperature steam Rankine Cycle (RC) absorbing the waste heat from exhaust gas and the low-temperature Organic Rankine Cycle (ORC) utilising supplement waste heat coming from cooling water towards a more efficient way at recovering energy in heavy duty diesel engine. The system has been modelled thermodynamically, analyzed exergetically and evaluated in terms of exergo-economics through optimizing multi-objective genetic algorithms to obtain the highest exergy efficiency with lowest specific electricity cost. Novelties include the combination of a regenerative preheater in the ORC loop and green refrigerants like R1233zd(E) for the ORC and water-steam for the RC carefully selected according to global warming potential (GWP) and ozone depletion potential criteria. The results show that the net power output, exergy efficiency and brake-specific fuel consumption (BSFC) of 38.7 kW, 42.8% and 12.5% are obtained in this cycle respectively. Unit electricity cost of 16.85 USD/GJ is obtained based on exergoeconomic analysis with a payback period of 3.5 years at varying load conditions. Sensitivity analysis demonstrates the resistance to variations in exhaust temperature (400-550°C) and environmental impact assessment indicates the annual reduction of 15.2tons of CO_2 emission per tractor. The cascade topology attains 18-22% higher system efficiency compared with the single-loop, which is an evidence for its novelty in off-highway applications. Experimental validation in the future is suggested to relate theoretical analysis and practical use.

Keywords: Waste heat recovery; Organic Rankine Cycle; Rankine cycle; Exergy analysis; Exergoeconomic analysis A B I 1Io V t e Trac Practor]; engnes d iesel rdf olo fan motiroduction to the system 1.

1- Introduction

Agricultural tractors are equipped with heavy-duty diesel engines and work in high-load conditions for long time, which mean that large a mount of thermal energy is lostOutdoor. In general, the fraction of the chemical energy in fuel converted to work is between 35-45%,

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while 40% of this remains being lost in the exhaust gases at a temperature ranging from 400-600°C and 20-30% of it through coolant systems [13]. In European Union, tractors use approximately 10-15% of total diesel fuel in farming and cast aside greenhouse gases up to 50 million tons CO2 per year [10]. With the introduction of IMO Tier III and EU Stage V emission requirements, it is imperative to have alternative WHR solutions that can enhance vehicle fuel economy and alleviate environmental burdens [10]. Rankine cycle (RC) predominates for high-grade heat recovery by steam, and the Organic Rankine Cycle (ORC) is more suitable at low temperature sources with organic fluids having lower boiling temperatures and better thermal matching [11]. RC and downstream ORC allows sequential heat utilization, suitable for several temperature waste heat profile in diesel engine. Some studies have shown that ORCs are likely to be successful in tractors with potential BSFC gains of up to 10% [18], but this integrated cascading system is at an early stage, especially when exergoeconomic views could compare thermodynamic benefits versus the investment on equipment [1]. This paper promotes an evolutionary analysis in which a regenerative cascade RC-ORC plant layout applying advanced working fluid selection, GAs-based optimization and exergoenvironmental considerations for a tractor 302 kW engine has well been examined. Several real-world energy recovery systems are implemented, and exercises involving exergy calculations and the design of a waste heat recovery device are included with these machines.

2- Literature Review

The recovery of waste heat in internal combustion engines has made great progress and at present, ORC or Rankine cycle (RC) systems are the most widely used ones. Early works were on single loop ORC for diesel waste heat recovery, which can achieve a thermal efficiency of 10-15% using refrigerants such as R245fa [10]. For example, an exergetic investigation of ORC system for marine diesel engines showed that exergy efficiencies can reach up to 57.3% under optimized conditions [14]. Dual-loop systems mixing high and low-temperature cycles are achieving the best results, a work on cascading ORC to recover engine surplus heat obtained 33-40 kW of net power at exergy efficiencies circa 40% [6]. Exergetic study shows that for 50-70% of the total exergy destruction, there is a possibility to reduce by even 80 % of this avoidable part [4]. Advanced exergy analysis which separates the destruction damage into endogenous/exogenous and avoidable/unavoidable has been also used for ORC systems, revealing that improvements in the turbines represent the most important modification towards efficiency increase [4]. Exergoeconomic analyses involve cost flows and may rely on techniques like SPECO to develop unit costs; as an example, utilizing the ORC linked with geothermal produced electricity around 0.035-0.045 USD/kWh in less than 4 years payback [7]. In the tractor application, simulations for a RC with exhaust recovery were made focusing on fluid dynamics and pressure ratios [18]. A computational calculation on WHR potential of tractor engine indicated that power of 15-20 kW can be recovered from the exhaust only [10]. Combined systems, for instance ORC-ejector cycles, show that even multipurpose operation (power g cooling or heating) can be well-executed with exergy efficiencies more than 50% [9]. Such results are furthermore expanded in

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exergoenvironmental analyses, where ecologic impacts are expressed quantitatively, with the result that ORCs decrease in CO2 equivalent between 10% and 20% [3]. Other recent developments are transcritical-subcritical parallel ORC arrangements for better heat matching [20]. Genetic algorithms based multi-objective optimization have optimized evaporation pressure and superheat degree as parameters to balance performance and cost [8]. For diesel applications combined RC-ORC cascades have been exergoeconomically tested for two working fluids and ORGanics have been found to be suitable for low-grade heat recovery [1]. Thermoeconomic analyses of ORC-series HHX also highlight the importance of regenerative preheaters in enhancing system performance [7]. Tractor applications are no exception, where a lesser emphasis is seen on variable loads, and environmental performance, which in turn strengthens the novelty of the present study by incorporating regenerative elements and using AI based optimization.

3- System Description and Modeling

High-temperature exhaust (450–550 °C) is recovered by the steam RC in a proposed cascade system, and the residual heat on both the RC condenser and engine coolant streams (80–150 °C) is recovered using regenerative ORC. The RC circuit is through water-steam, it evaporates in a shell-and-tube heat exchanger then allows expanding in turbine, compressing and pumping back. The ORC uses R1233zd(E) with a regenerative preheater for rescue of turbine exhaust heat and increased cycle efficiency. System limits are an assumption of steady-state conditions, isentropic efficiencies of 85% for turbines and 80% for pumps, and a lack of kinetic/potential exergies. The ambient temperature is 25 °C, and the pressure is 101.3 kPa.

3-1 Thermodynamic Model

The description of each part is subject to mass and energy balances. 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 formulated in Engineering Equation Solver (EES) apps and validated against an engine giving 180 kW of exhaust heat and 120 kW of coolant heat.

3.2 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: $\psi = 1 - \frac{\sum \dot{E}_{D,k} + \sum \dot{E}_{L,k}}{\sum \dot{E}_{F,k}}$

Exogenous interactions are minimally isolated in optimization (innovative).

3.3 Exergoeconomic Analysis

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

Where $\dot{Z}_k$ comprises investment, maintenance and operational costs, which are estimated as follows:

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

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

3.4 Multi-Objective Optimization

04-17 An iterative genetic algorithm (IT-GA) in MATLAB is used to optimize evaporation pressures, superheat degrees and pinch points with objectives: * maxψ* min. Pareto fronts are obtained and knee points Linmap method. The novelty is the inclusion of exergoenvironmental costs to penalize high-GWP fluids.

4. Results and Discussion

The net power output of the optimized system is 38.7 kW (22.4 kW for RC and 16.3 kW for ORC). The corresponding exergy efficiency is 42.8%, which is higher than non-regenerative base-point by a factor of 15%. Avoidable exergy destruction is maximal in the evaporator (45%, 12.5 kW) and condenser (35%, 9.8 kW), with finned-tube improvements recommended. The exergoeconomic results indicate: USD/GJ, the (70%) investment priority for turbines. It has a play-back period of 3.5 years at 0.8 USD/L for diesel. Exhaust temperature (Sensitivity to last gas temp: ψ= 38-46% from 400-550°C.

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

By juxtaposition with literature, the system is superior to single ORC (34% ψ) and RC (29% ψ) when they combine cascade synergy [1]. Environmental advantages are the reduction in CO_2 equivalent of 15.2 ton/year which complies with sustainable agriculture [3].

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5- Conclusion

It is found that, the regenerative cascade RC-ORC system of NGH for tractor WHR achieves high performance levels in terms of both exergetic (42.8%) and exergoeconomic potential (16.85 USD per GJ). Modifications in optimization and fluid choice increase viability, decreasing BSFC by the 12.5% as well as pollutions. Recommendations are for the dynamic modeling of tractor transients and prototype testing for theoretical losses.

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