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A practical multi-objective design approach for optimum exhaust heat recovery from hybrid stand-alone PV-diesel power systems

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A B S T R A C T

Integration of solar power and diesel generators (DGs) together with battery storage has proven to be an efficient choice for stand-alone power systems (SAPS). For higher energy efficiency, heat recovery from exhaust gas of the DG can also be employed to supply all or a portion of the thermal energy demand. Although the design of such heat recovery systems (HRSs) has been studied, the effect of solar power integration has not been taken into account. In this paper, a new approach for practical design of these systems based on varying engine loads is presented. Fast and elitist non-dominated sorting genetic algorithm (NSGA-II) equipped with a novel local search was used for the design process, considering conflicting objectives of annual energy recovery and total cost of the system, and six design variables. An integrated power system, designed for a remote SAPS, was used to evaluate the design approach. The optimum power supply system was first designed using the commercial software Hybrid Optimization of Multiple Energy Resources (HOMER), based on power demand and global solar energy in the region. Heat recovery design was based on the outcome of HOMER for DG hourly load, considering different power scenarios. The proposed approach improves the annual heat recovery of the PV/DG/battery system by 4%, PV/battery by 1.7%, and stand-alone DG by 1.8% when compared with a conventional design based on nominal DG load. The results prove that the proposed approach is effective and that load calculations should be taken into account prior to designing HRSs for SAPS.

1. Introduction

In the past few decades a growing interest in renewable energy, particularly wind and solar, has been observed, as these sources do not pollute the environment and are available in abundance. Between solar and wind energy, the former has a much lower investment cost and hence is more desirable in small systems [1]. In particular, a hybrid energy power system is preferable in stand-alone power systems (SAPS) that are not connected to the main grid. Diesel generators (DGs) are normally used in such systems to meet peak load demands whenever a deficit in available renewable energy exists. Diesel engines have higher thermal efficiency than their counterpart spark-ignition (SI) engines, which results from their higher compression ratios and operation on lean fuel mixtures. High compression ratios are essential to provide the required high temperatures to achieve auto-ignition. Consequently, less thermal energy is wasted though the exhaust as a result of this high expansion ratio [2].

Nevertheless, around 30% of fuel energy is wasted through exhaust gases alone. Therefore, considerable efforts have been dedicated to harvesting at least a portion of this waste energy through heat recovery systems (HRSs) [2]. For the case of diesel engines, many studies have been conducted considering the design of these exchangers and their effect on the engine performance. Hatami et al. [3] experimentally compared the effect of different heat exchangers on the performance of a diesel engine by exergy analyses. They considered five engine loads ranging from 20% to 80% of the engine's full load and four mass flow rates in an attempt to determine the most suitable HRS with the least effect on the engine performance. It was concluded that the exhaust gas pressure drop needs to be kept as low as possible to decrease the HRS's

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Nomenclature

a_1, a_2, a_3	cost parameters in Eq. (28)
O & M	operational and maintenance cost (USD)
AHT	heat transfer area (m^2)
B	baffle spacing (mm)
c_k	boundaries for histogram generation
CI	clearance
C_p	specific heat capacity (kJ/kg·K)
CE	electricity price ($/kW h)
COE	cost of electricity ($/kW h)
DG	diesel generator
D_e	hydraulic diameter (m)
D_s	shell diameter (m)
f	Darcy friction factor
f(*i*)	frequency of the *i*th interval
GA	genetic algorithm
H	annual working hours of the heat recovery system
HTF	heat transfer fluid
h	convection heat transfer coefficient (W/m^2·k)
k_H	number of class intervals for load histogram
k	thermal conductivity (W/m·k)
L	tube length (m)
m	mass flow rate (kg/s)
NPC	net present cost (USD)
NSGA-II	fast and elitist non-dominated sorting genetic algorithm
Nu	Nusselt number
N_t	number of tubes
ny	operational years of the heat recovery system
AER	annual energy recovery (kW h)
P	power (kW)
Pr	Prandtl number
Pt	Pitch
Q	heat transfer rate (kW)
Re	Reynolds number
STHE	shell-and-tube heat exchanger
TC	total cost (USD)
SC	power scenario in HOMER

Greek symbols

ρ	density (kg/m^3)
μ	viscosity (kg/m s)
ΔP	pressure drop (kPa)
N	gas or fluid velocity (m/s)

Subscript

F	fluid
o	operational
S	shell side
T	tube side

effect on the engine performance thus the heat exchanger should be optimally designed for the task.

Experimental and numerical analyses were done on a finned-tube heat recovery exchanger mounted on an OM314 diesel exhaust recovery in [4]. Artificial neural network (ANN) and genetic algorithm (GA) were employed on the numerical outcome of a heat exchanger utilized for exhaust heat recovery task. The study was mainly focused on the optimum fin design where thirty heat exchangers with different fin length, thickness and fin numbers were modeled considering three engine loads. The results showed that the maximum exergy could be recovered in higher engine loads.

Hatami et al. [5] considered designing an optimum heat exchanger for the heat recovery from a diesel engine by using central composite design (CCD) and computational fluid dynamics (CFD). A single working condition of an OM314 diesel engine, obtained from experiment, was used for the design task. Similar to [4], the primary focus of the heat exchanger design was the selection of optimum fin configuration.

The potential of heat recovery from exhaust gas of a diesel passenger car was experimentally studied in [6] where the new European driving cycle was followed to record the relevant operating variables of the engine. Using the real-world operating conditions of the engine helped a practical understanding of the heat recovery system. It was concluded that while the maximum engine load provides a higher recovery potential, the environmental considerations regarding the exhaust temperature had to be taken into account as well. Nevertheless, the optimum design of the HRS was not the focus of this study.

In another experimental study, Ghazikhani et al. [7] presented the effect of engine load and torque on the performance of a HRS from a turbocharged OM314 DIMLER diesel engine. Similar to [6], it was concluded that a higher exergy recovery potential is achievable by increasing the load and engine speed.

Yang et al. [8] studied the issue from a different angle and adopted an Organic Rankine Cycle (ORC) for recovering the exhaust waste energy from a diesel engine. The ORC was modeled and optimal operating regions of the ORC system were identified by multi-objective GA. They considered several working fluids for the ORC system and found out that a multi-objective optimization of the system is most suitable as the thermodynamic performance was improved at the expense of the economic performance. Similarly in [9], the design optimization of an ORC waste heat recovery for a marine diesel engine was studied. The heat recovery from both exhaust gas and jacket cooling water was considered to design an economically feasible HRS for the marine applications. Thermal performance as well as system structure and economic feasibility were investigated to determine the optimal preheating temperature of the system.

In any HRS, regardless of the method in which the recovered energy is utilized, the heat exchanger design is crucial to achieve the best possible recovery performance. The heat recovery exchanger needs to be optimally designed for a specific condition, considering one or more objective functions, while normally a number of restrictions have to be met by the design. Thus, the design of heat exchangers is a cumbersome task which was traditionally based on a trial-and-error process. In the past decade, the application of evolutionary algorithms (EAs) for this task has gained considerable attention. EAs can easily explore a multi-variable search space without requiring much mathematical knowledge of the system. The only requirement for designing a heat exchanger with an EA is to model a proper fitness function based on the required objective and the variables of the problem. Among various types of heat exchangers, shell-and-tube heat exchanger (STHE) has been recommended for exhaust heat recovery task as the imposed back pressure on the engine is relatively low and thus the engine performance remains less intact when the HRS is mounted [6].

For STHE design, both single- and multi-objective EAs have been studied extensively in the literature. For the case of single-objective optimization, Selbas et al. [10] proposed the first application of genetic algorithm for design optimization of STHEs from economic point of view. Other EAs have been also employed for