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Integrating compressed air energy storage with a diesel engine for electricity generation in isolated areas

Yongliang Li *, Adriano Sciacovelli, Xiaodong Peng, Jonathan Radcliffe, Yulong Ding

School of Chemical Engineering, University of Birmingham, Birmingham B15 2TT, UK

HIGHLIGHTS

- Diesel fuel consumption decreases significantly due to system integration.
- Waste heat of the diesel genset can be recovered effectively in the integrated system.
- The effectiveness of an integrated system is determined by 'Normalized standard deviation'.

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ABSTRACT

This paper reports an integrated system consisting of a diesel genset and a Compressed Air Energy Storage (CAES) unit for power supply to isolated end-users in remote areas. The integration is through three parts: direct-driven piston-compression, external air turbine-driven supercharging, and flue gas waste recovery for super-heating. The performance of the integrated system is compared to a single diesel unit and a dual-diesel unit with a capacity of electricity supply to a village of 100 households in the UK. It is found the fuel consumption of the integrated system is only 50% of the single-diesel unit and 77% of the dual-diesel unit. The addition of the CAES unit not only provides a shift to electrical energy demand, but also produces more electricity due to the recovery of waste heat.

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1. Introduction

The use of diesel generators is a preferred option for electricity production in remote areas where the cost of national grid extension is prohibitively expensive [1–4]. While diesel power generating unit requires relatively little investment, the fuel costs increase by up to a multiple of six to ten when the associated transportation charges are taken into account [2,5]. Therefore operating a diesel power generator at a higher efficiency is critical for saving fuel cost, which also brings environmental benefits. A typical load pattern for remote area power supplies (especially for village scales) is characterized by a small to medium base load, and several periods of high electricity demand during a day [1,6]. In addition with the intermittent renewable electricity generation such as wind power, in most cases diesel generators have to be operated at a low load factor for most of the time. Fig. 1 shows fuel consumption and efficiency characteristics of a typical diesel engine operated at different load factors (as described in details in Section 3.1). It can be seen that, for a low- and medium-penetration system, the diesel fuel consumption even at zero load, is approximately 35% of that at the rated power output. Moreover, operating a diesel generator at light loads (<30–50% of rated load) can accelerate carbon deposits of wear and tear and thus shorten the lifetime of the equipment, leading to a high maintenance cost [7,8]. As a consequence, interests in the integration of diesel engine with energy storage technologies have been growing enormously over the past decades. Studies have been done on enabling diesel generators to be operated above a certain minimum level of load in order to maintain an acceptable efficiency and to reduce the rate of premature failures [9–12].

Attention has also been paid to the recovery of diesel engine waste heat to enhance the overall performance. An inspection of the energy balance of internal combustion engines indicates that the input energy can be roughly divided into three equal parts: energy converted to useful work, energy transferred to coolant and energy lost through exhaust [13,14]. Thermal energy loss from the exhaust can be regarded as a high grade, which has a temperature ranging approximately from 400 to 600 °C [15]. Recent work has shown a potential increase in the overall efficiency by up to

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* Corresponding author. Tel.: +44 (0)121 414 5135.
E-mail address: y.li.1@bham.ac.uk (Y. Li).

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Nomenclature

A	constant Eq. (8) (K)
h	specific enthalpy (J kg^{-1})
h_v	volumetric heat transfer coefficient (W m^{-3} K^{-1})
$\dot{m}$	mass flow rate (kg s^{-1})
m	mass (kg)
n	polytrophic factor
N	number of stages (–)
P	pressure (Pa)
R	universal gas constant (J kg^{-1} K^{-1})
T	temperature (K)
t	time (s)
V	volume (m^3)
W	power (W)

Superscripts

rated	rated conditions
max	maximum

Subscripts

a	air
AT	air turbine
am	ambient conditions
ex	exhaust
f	fuel
DE	diesel engine
EU	end user
IC	inlet compressor
LHV	lower heating value
PC	piston compressor
PCM	phase change material
s	storage
SD	supercharged diesel engine

Greek letters

γ	adiabatic index (–)
η	diesel engine thermal efficiency (–); isentropic efficiency (–)
λ	air to fuel ratio (–)
ξ	constant parameter Eq. (2)
ρ	density (kg m^{-3})
σ	normalized standard deviation (–)

30% through efficient recovery of waste heat [16]. Technologies proposed for the recovery of waste heat include Organic Rankine Cycle (ORC) [17], thermoelectric generation [18] and the use of heat pumps [19]. However, when a diesel engine is used for remote electricity generation, the temperature of the exhaust gas changes frequently as does the load factor [20]. Thermoelectric power generation is expensive and has a low efficiency. The unsteady exhaust gas temperature is disadvantageous for the operation of an ORC engine or a heat pump. Compressed Air Energy Storage (CAES) presents an alternative solution to the issue, which can store excessive shaft power, and recover the waste heat of the diesel engine in the energy extraction process. Using CAES to deal with the stochastic fluctuations of wind power in wind–diesel hybrid systems has been examined numerically, and the results are promising in enhancing the wind energy penetration [2,21]. In this paper, an integrated diesel-CAES power system is proposed and investigated. The aim is to reduce fuel consumption and production costs for electricity generation in rural areas. Specific attention is paid to the operating principle and the influence of demand patterns of end-users. This may lead to a real system to be developed accordingly to demonstrate the advantages.

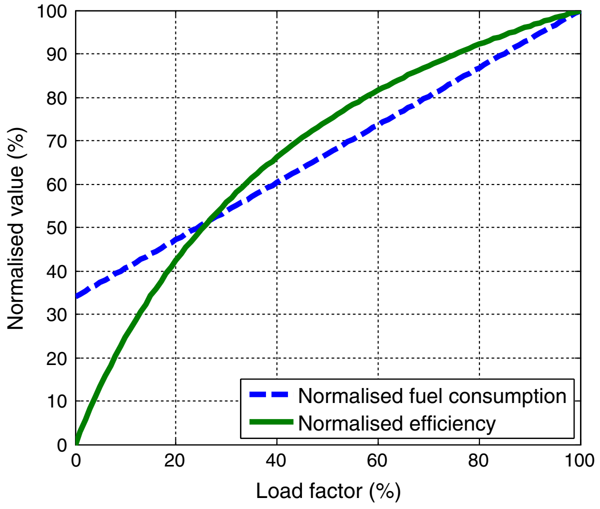

Fig. 1. Diesel engine characteristics as a function of load.

2. System configuration and operating principle

Most modern diesel engines are turbocharged or even supercharged. A turbocharger or a supercharger is made up of a coupled compressor-turbine unit aiming to increase the density of the engine air intake. This results in the engine producing significantly more power than a naturally aspirated engine with the same combustion-chamber volume. The difference between the turbocharger and supercharger is that the supercharger has a compressor driven mechanically by external power such as the engine's crankshaft, while a turbocharger is powered by the engine exhaust, therefore does not require any mechanical power.

This paper focuses on an integrated diesel-CAES system in which the diesel engine could be supercharged by a CAES unit, as illustrated in Fig. 2. The diesel engine used in such an integrated system differs from the traditional engine in the air intake method: the atmospheric air can either be naturally aspirated or forcibly compressed into the combustion-chamber depending on the switch conditions of a 3-way valve located at the engine inlet. The CAES unit is made up of a piston compressor, a compressed air reservoir, two heat exchangers and a two-stage air turbine. The diesel engine and the CAES unit are integrated by three parts: first the diesel engine shaft and the piston compressor shaft could be mechanically connected or disconnected through using Clutch 1. Second, the air turbine shaft in the CAES unit and the compressor shaft in the diesel engine can be mechanically connected or disconnected by the use of Clutch 3. Third, the flue gas from the diesel engine and the compressed air from the reservoir are both fed into Heat exchangers 1 and 2 for waste heat recovery. It is worth mentioning that two heat exchangers are used not only for the heat transfer between the flue gas and compressed air, but also for the storage of thermal energy in cases where the engine and air turbine operate at different times. Phase Change Materials (PCMs)

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