Journal of Natural Gas Science and Engineering 21 (2014) 524–531

Contents lists available at ScienceDirect

Journal of Natural Gas Science and Engineering

journal homepage: www.elsevier.com/locate/jngse

Application of Grey–Taguchi based multi-objective optimization strategy to calibrate the PM–NHC–BSFC trade-off characteristics of a CRDI assisted CNG dual-fuel engine

Sumit Roy*, Ajoy Kumar Das, Rahul Banerjee

Department of Mechanical Engineering, NIT Agartala, Tripura, India

A R T I C L E I N F O

Article history:
Received 4 August 2014
Received in revised form
13 September 2014
Accepted 15 September 2014
Available online

Keywords:
CRDI
CNG
Grey relational analysis
Taguchi method

A B S T R A C T

The present work attempts to simultaneously reduce the BSFCeq, NHC and PM emissions of a CRDI assisted diesel engine under CNG-diesel dual-fuel mode. Load, fuel injection pressure and CNG energy share were chosen as input parameters with NHC, PM and BSFCeq as the response variables. To reduce the experimental effort the experiments have been performed by employing Taguchi's L_{16} orthogonal array. In order to search for the optimal process response, the Grey relational analysis is employed for solving the optimization problem. The optimal combination of the input parameters was obtained using the Grey relational grade and signal-to-noise ratio as a performance index, which achieved the desired response characteristics. The optimal combination so obtained was further confirmed through experimentation. Among the three, load was found to be the most influencing factor.

1. Introduction

Diesel engine based technology in the present millennium has undergone a paradigm shift in its perspectives to meet the increasingly stricter emission directives on one hand and consumer expectations of superior fuel economy on the other. Such a state of responsiveness to the present day requirements is necessitating an unprecedented increase of dependence on control of the several new degrees of freedom that are being called into play simultaneously by virtue of the significant increases in the mechanical and electronic complexity of engine hardware and after treatment systems dictated by the incorporation of new technologies such as VVT, VGT, CRDI, GDI, VIS, exhaust after-treatment add-ons of SCR, DPF etc. together with the shift towards newer and innovative low temperature combustion technology concepts such as HCCI (Homogeneous Charge Compression Ignition), DCCS (Dilution Controlled Combustion System), HPLI (Highly Premixed Late Injection), HCLI (Homogeneous Charge Late Injection), Premixed Charge Compression Ignition (PCCI) and Reactivity Controlled Compression Ignition (RCCI) offer the promise of improved engine efficiencies along with markedly reduced emission footprints from conventional engines (McGeehan et al., 2005; Johnson, 2008, 2010, 2011; Zhao, 2010). Common Rail Diesel Injection systems have led the technological renaissance (Badami et al., 1999; Suh, 2011) in diesel injection characteristics of the present day due to its efficacy in drastically reducing BSFC and the conventional PM emission precursors as compared to conventional diesel operation (Balusamy and Marappan, 2010; Nagata et al., 2004; Shimazaki et al., 2003; Pickett and Siebers, 2004; Minato et al., 2005). That said the very ability of the CRDI systems to decrease PM emissions has been found to be a penalizing precursor for NOx formation which have been observed to paradoxically increase (Badami et al., 1999; Desantes et al., 2004; Pierpont and Reitz, 1995; Payri et al., 2006) on account of higher peak temperature arising out of very lean and homogenous conditions which provide impetus for attaining close-to adiabatic flame temperatures during the ensuing combustion. To contain the consequence of NOx emissions while retaining the incentives of lower PM and fuel consumption on CRDI systems, EGR (Reitz, 1998; Ladommatos et al., 1998; Hountalas

Abbreviations: BDO, baseline diesel operation; BP, brake power; BSFCeq, brake specific fuel consumption equivalent; BTDC, before top dead centre; CI, compression ignition; CNG, compressed natural gas; CRDI, common rail diesel injection; DI, direct injection; FIP, fuel injection pressure; GRG, Grey relational grade; HC, hydrocarbon; IC engine, internal combustion engine; NOx, oxides of nitrogen; PM, particulate matter; ppm, parts per million.

* Corresponding author. Tel.: +91 9402108135; fax: +91 3812346360.
E-mail addresses: sumitroy@hotmail.de, sam.roy4u@gmail.com (S. Roy).

http://dx.doi.org/10.1016/j.jngse.2014.09.022
1875-5100/

et al., 2008; Maiboom et al., 2008; Roy et al., 2014a; Bose et al., 2013) and pilot injection strategies (Buyukkaya and Cerit, 2008; Thurnheer et al., 2011) have been widely investigated.

Comparing the context of the present day insecurities of convention fossil fuel based energy resources, air pollution, and climate change that are collectively calling into question the fundamental sustainability of the current energy system, alternative fuels, are destined to be a dominant stake holder in the transition of the energy sector in the immediate future. Of all the existing alternative fuel resources, CNG with its inherent synergy of its cheap availability and its projected sustainability till the immediate future (Kvenvolden, 1994; Dyntar et al., 2002) along with its potential of reducing the regulated emission footprint of conventional IC engines (Fritz and Egbuonu, 1992; Carlucci et al., 2008; Kusaka et al., 2000; Cascetta et al., 2008; Maji et al., 2008; Kalam and Masjuki, 2011; Liu et al., 2013), provides itself as a desirable and potent/alternative energy transition vector to the ultimate hydrogen based economy.

It is thus apparent from the discussion that the PM–NOx–BSFC trade-off problem requires increased design space to explore the possibility of obtaining possible solutions to satisfy the conflicting objectives. Such extended design space is provided by the increase in control/design variables which can be suitably explored for attaining the desired objectives. That said, increase of parametric variability on conventional diesel platforms as provided by the CRDI and CNG dual-fuel systems needs to be suitably attuned to obtain the desired optimal responses. Though a full factorial approach would have been the ideal methodology to explore the entire design space with one at a time variation of the input variables, such efforts are constrained by the penalty of unviable experimental cost and time. Thus a methodology is needed to be adopted wherein the optimal exploration of the design space can be performed with reduced yet experimentation. To this end the Taguchi methodology provides an effective and established (Saravanan et al., 2010, 2013; Wu and Wu, 2013; Lee et al., 2013; Ganapathy et al., 2009) statistical tool derived from the theory of design of experimentation. Though, the Taguchi platform has been utilized as a very popular process optimization technique, it has been observed to be unsuitable to solve multi-objective optimization problems (MOOPs) (Tarng and Yang, 1998; Ross, 1988). To overcome this limitation, Grey relation analysis (GRA) theory has been employed successfully in conjunction with the Taguchi method (Datta et al., 2008; Tarng et al., 2000) to solve the MOOPs in diverse engineering domains including the IC engine paradigm (Pohit and Misra, 2013; Karnwal et al., 2011). The main objective of the present work was to find an optimal combination of load, fuel injection pressure (FIP) and CNG energy share (CES) for the simultaneous reduction of BSFCeq, NHC (NOx + HC) and PM emissions.

2. Instrumentation

The experiment was conducted on an existing single cylinder four-stroke CI engine coupled to a Common Rail Direct Fuel Injection system as detailed in Table 1. The engine was coupled to an air-cooled eddy current dynamometer of PowerMag® make. The CRDI setup is an attachment to the experimental engine. It consists of a high-pressure fuel pump, rail, high-pressure fuel injector and the heart of the system being the electronic injection controller (EIC). The description of the fuel injection system is given in Table 2. The CNG was stored in a 25 lit cylinder compressed at 210 bar. The CNG was inducted into the Vidhata make VL-8 single cylinder four stroke diesel engine through the manifold of the engine intake. An open loop Electronic Control Unit (OPECU) was provided with the CNG manifold injection kit to decide the injection start angle and the induction duration. Technical Specification CNG Injector Rail is given in Table 3. The CNG energy share was calculated as per Equation (1) (Roy et al., 2014c). The exhaust gases were sampled by a *5 Gas analyzer* and an *AVL smoke meter (415S)* was used to measure the soot content, present in the exhaust. The specifications of the emission measuring apparatus are detailed in Tables 4 and 5. The layout of the experimental setup used to conduct the experiments is shown in Fig. 1.

Table 1
Experimental engine specification.

Specification	Resources
Make	Vidhata
No of cylinder	One (1)
Bore	120 mm
Stroke	139.7 mm
Displacement	1580 cc
Cooling	Water
Compression ratio	18:1
Valve timing	
Exhaust valve opening	35° before BDC
Exhaust valve closing	4° after TDC
Inlet valve opening	4° before TDC
Inlet valve closing	35° after BDC

$$\text{CES}_i = \frac{\left[(\dot{m}_\text{D})_\text{BD} \times \text{LHV}_\text{D}\right]_i - \left[(\dot{m}_\text{D})_\text{Dual} \times \text{LHV}_\text{D}\right]_i}{\left[(\dot{m}_\text{D})_\text{BD} \times \text{LHV}_\text{D}\right]_i} \tag{1}$$

2.1. Methodology

In the present experimental work, the fuel injection methodology was undertaken for 25%, 50%, 75% and full load characteristics of the engine. The experimental engine when subjected to progressive higher loads then demanded a higher injection rail pressure. Consequently for each variation of injection duration at the given load, the injection rail pressure would adjust automatically as per the specification of the CRDI setup to maintain the constant speed set. The initial injection duration for each load was set to approximately 225 bar which was the designed fuel nozzle opening pressure of the experimental engine. The start of injection angle was set to 5° BTDC for all the cases. The injection duration on the CRDI platform for each load was then reduced at particular intervals specific to each case of loading. Such reduction of injection duration was accompanied by a complementary increase of pressure needed to maintain the set constant speed of 800 rpm. The reduction in fuel injection duration was continued in steps until a minimum injection duration was reached at that given load, beyond which the stability of engine operation was compromised.

The effect of drastic increase in FIP has been observed to stimulate a significant reduction in the spray droplet diameter distribution of the injected fuel due to better atomization characteristics obtained due to the drastic increase in the pressure drop experienced by the liquid fuel during injection. This enhances a better

Table 2
Specification of the fuel injector.

Specification	Resources
Type	Common rail injection system
Make	Bosch
Injection pressure	10–120 MPa
Number of holes	5 (Symmetric)
Nozzle diameter	0.15 mm
Injection angle	120°