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Combined effect of injection timing and exhaust gas recirculation (EGR) on performance and emissions of a DI diesel engine fuelled with next-generation advanced biofuel – diesel blends using response surface methodology

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A B S T R A C T

Advanced biofuels like dimethyl-carbonate (DMC), isobutanol and *n*-pentanol can be derived from non-food based biomass feedstock without unsettling food supplies and biodiversity. An experimental and statistical investigation was carried out to analyze the effects of injection-timing and exhaust gas recirculation (EGR) on performance and emissions of a DI diesel engine using advanced biofuel/diesel blends (containing 8 wt% oxygen). Engine characteristics were measured under high-load condition using moderate EGR (up to 30%) and injection-timing modification (up to ±2°CA bTDC) for controlling charge-dilution and combustion-phasing. Multiple regression models developed using response surface methodology (RSM) for measured responses like nitrogen oxides (NOx), smoke opacity and brake specific fuel consumption (BSFC) were found to be statistically significant by analysis of variance (ANOVA). Interactive effects between injection timing and EGR for all blends were analyzed using response surface plots that were fitted using developed models. Optimization was performed using desirability approach of the RSM to minimize NOx and smoke emissions simultaneously with minimum BSFC. Isobutanol/diesel blend injected at 22°CA bTDC without EGR was predicted to be optimum for the tested engine. Confirmatory tests validated that the models developed using RSM are adequate to describe the effects of the injection timing and EGR on performance and emissions characteristics using all blends as the error in prediction is within 5%.

1. Introduction

Diesel engines are the most preferred in major global sectors like industry, transport, agriculture and power generation because of its unique combination of higher torque capability, higher fuel conversion efficiency, higher durability and reliability when compared to gasoline engines [1]. However, diesel engines emit high NOx and smoke emissions due to their lean burning nature and fuel-rich local regions in the diffusion controlled combustion. To add to the woes, the inherent trade-off relation between NOx and smoke remains as a main challenge in modern diesel engine research and development. NOx is acknowledged to be the major cause for smog [2], ground-level ozone [3] and acid rain [4]. Smoke is found to be carcinogenic [5,6] and its continuous exposure can cause allergy [7], asthma [8], hypertension [9], cardio-respiratory diseases [10] and lung cancer [11] to human.

In view of the threats to both environment and human race, government agencies across the world are piling up pressure by imposing rigorous emission standards. Diesel engine researchers often resort to emission reduction by (i) engine design modifications, (ii) diesel fuel reformulation, (iii) employing new combustion strategies and (iv) using after-treatment devices like diesel oxidation catalysts, diesel particulate filters and selective catalytic reduction. Various methods that were specifically employed to reduce NOx emissions include exhaust gas recirculation (EGR),

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Nomenclature

Abbreviations

A(B)BDC	after (before) bottom dead centre
A(B)TDC	after (before) top dead centre
ANOVA	Analysis of Variance
BMEP	brake mean effective pressure
ASTM	American Society for Testing and Materials
BSFC	brake specific fuel consumption
BTE	brake thermal efficiency
CA	crank angle
CAS	Chemical Abstract Service
CO	carbon monoxide
CO_2	carbon dioxide
CRDI	common rail direct ignition
DI	direct injection
DMC	di-methyl carbonate
DMC15	15% dimethyl carbonate + 85% ULSD blend
EGR	exhaust gas recirculation
EPA	Environmental Protection Agency
HC	hydrocarbons
HRR	heat release rates
ISB38	38% isobutanol + 62% ULSD blend
NOx	nitrogen oxides
PEN45	45% *n*-pentanol + 55% ULSD Blend
PM	particulate matter
RFS	Renewable Fuel Standard
RIN	Renewable Identification Numbers
ROPR	rate of pressure rise
RSM	Response Surface Methodology
SOI	start of injection
TDC	top dead centre
ULSD	ultra-low sulfur diesel

Symbols

vol%	blending percentage per volume of diesel
wt%	blending percentage per weight of diesel
wt	weights assigned for a response
Adj-R^2	adjusted R^2 value
d_i	desirability value of the response
e	EGR
F	value of Fisher-statistic test
f	fuel as a *categoric factor*
high	upper limit of a response
i	response
low	lower limit of a response
P	percentage contribution
Pred-R^2	predicted R^2 value
p	probability value
R^2	coefficient of determination
r	relative importance of a response
T_i	target value of a response
t	injection timing
Y_i	value of the response

retarding fuel injection timing, low injection pressure, split injection, modifying combustion chamber geometry, water injection and excessive cooling of intake air [12]. Employing EGR suppresses peak combustion temperatures of fuel/air mixtures which reduces NOx formation and controls the combustion phasing [13]. As documented earlier in several studies, the effects of EGR include the thermal effect (that lowers peak combustion temperature by the way of recirculating non-reacting high specific heat gases, CO_2 and H_2O), the dilution effect (as a result of low O_2 concentration) and chemical effect (as a result of dissociation of CO_2 and H_2O during combustion). The combined results of these effects are low combustion temperature and long ignition delay [14]. On the flipside, it can deteriorate combustion and eventually decrease the performance of the engine due to high levels of HC and CO emissions. Retarding the injection timing also affects the ignition delay and could result in further reduction of NOx emissions with a slight penalty in smoke and fuel consumption [15,16].

Diesel reformulation with biofuels is an attractive option because (i) it reduces fossil diesel dependence and improves the renewable fraction in the fuel and (ii) it reduces smoke emissions due to the presence of fuel-bound oxygen. Bio-diesel or bio-alcohol addition to diesel alters diesel fuel properties like cetane number, calorific value, viscosity, density and air/fuel ratio which influences the combustion, emissions and performance characteristics of the engine. NOx emissions generally increased with bio-diesel addition to diesel [17]. Bio-alcohols (like ethanol and methanol) have low energy content and low cetane number [18]. Hence, bio-alcohol addition to diesel lowers the cetane number of diesel which directly influences NOx emissions and engine performance [19].

This study proposes the use of three advanced biofuels with low cetane number that includes two higher alcohols (isobutanol and *n*-pentanol) and a carbonyl ester (di-methyl carbonate) as blending components with diesel. Advanced biofuels are derived from non-food based sources such as stalks, leaves and husks that are left behind after cultivation of food crops, non-food crops like switch-grass, water-hyacinth, agave, algae, duckweed and industrial wastes like paper, wood chips and crude glycerine. Currently, industrial microorganisms (like *Escherichia coli* and *Saccharomyces cerevisiae*) and photosynthetic organisms like cyanobacteria are engineered to act upon these non-food-based sources and secrete molecules similar to fossil fuels, called 'advanced' or 'drop-in' biofuels [20]. Isobutanol and *n*-pentanol can be both synthesized from cellulose by modern fermentation processes using new strains of Clostridium species [21] and by biosynthesis using genetically engineered micro-organisms like *E. Coli* [22,23], Cyanobacteria [24] and *S. Cerevisiae* [25]. Di-methyl carbonate (DMC) is a green advanced biofuel produced by using a feedstock of methanol and waste CO_2 obtained from power stations [26,27].

There are some difficulties in using fuels like gasoline, DMC and alcohols in compression ignition engines owing to their low cetane number (low reactivity and long ignition delay), low calorific value (less energy content), high volatility, high latent heat of vaporization and high HC, CO emissions [28]. However, these low reactive biofuels can be suitable for reducing smoke and NOx emissions simultaneously because when blended with diesel they offer (a) high resistance to auto-ignition, (b) extend the ignition delay period (due to low cetane number) for sufficient fuel-air mixing and (c) faster vaporization (due to high volatility) for faster mixing rate [29].

In general, low NOx and smoke emissions can be realized by using moderate EGR rates, early or late injection, and diesel fuel reformulation [30]. Tornatore et al. [31] used 20% *n*-butanol/diesel blend at retarded injection timing coupled with an EGR rate of 50% in an optically accessible diesel engine and achieved substantial reductions in smoke and NOx emissions with a slight drop in efficiency. They found that a good compromise between performance and emissions can be obtained using early injection timing. Valentino et al. [32] reported the effects of injection timing, intake oxygen concentration (*via* EGR) and injection pressure on the