Applied Energy 146 (2015) 335–343

Contents lists available at ScienceDirect

Applied Energy

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

Extending the environmental benefits of ethanol–diesel blends through DGE incorporation

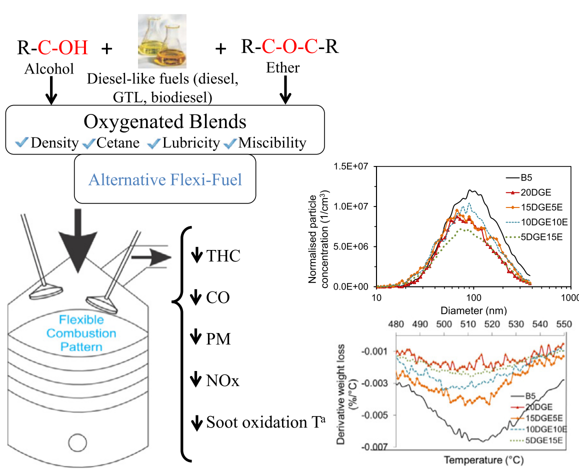
J.M. Herreros, K. Schroer, E. Sukjit, A. Tsolakis *

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

HIGHLIGHTS

- DGE addition to diesel-like fuels significantly reduces PM number concentration.
- DGE incorporation to ethanol–diesel blends enhances blend miscibility and auto-ignition.
- DGE–ethanol blends' soot is easier to be oxidised than conventional diesel soot.
- Partially renewable fuel blends can be designed to simultaneously reduce PM and NO_x.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 10 February 2014
Received in revised form 30 January 2015
Accepted 20 February 2015
Available online 7 March 2015

Keywords:
Diesel combustion
Ether
Ethanol blends
NO_x–soot trade-off
Soot oxidation

ABSTRACT

The research focuses on the potential use of DGE (diethylene glycol diethyl ether), as a high-cetane number oxygenated additive to diesel-like fuels. Apart from evaluating its individual effects an investigation of how DGE can facilitate the use of bio-ethanol in diesel engines was conducted; which faces many technical difficulties, but can provide environmental advantages over biodiesel and conventional diesel fuel. Four partly renewable fuel blends with varying contents of DGE and ethanol were designed with overall diesel-replacement rate of 20%.

DGE was found to reduce gaseous emissions, achieving a simultaneous reduction in both soot and NO_x which highlighted the beneficial effects of its high cetane number and oxygen content. In ethanol–diesel blends small additions of DGE significantly enhanced blend stability and blend auto-ignition properties. Improvements in the NO_x/soot trade-off characteristics were obtained for all blends. All tested blends produced lower particulate matter number concentrations and soot with characteristics that reduced their oxidation temperatures, hence providing benefits for diesel particulate filter (DPF) regeneration. Overall it was found that DGE fuel provides considerable energy and environmental benefits if used both as a single oxygenate with diesel or in multicomponent blends with ethanol and diesel.

* Corresponding author. Tel.: +44 (0) 121 414 4170; fax: +44 (0) 121 414 7484.
E-mail address: a.tsolakis@bham.ac.uk (A. Tsolakis).

http://dx.doi.org/10.1016/j.apenergy.2015.02.075
0306-2619/

Acronyms and abbreviations

CAD	crank angle degree
CO	carbon monoxide
CO_2	carbon dioxide
DGE	diethylene glycol diethyl ether
DGM	diethylene glycol dimethyl ether
DPF	diesel particulate filter
E	ethanol
EGR	exhaust gas recirculation
FTIR	Fourier-Transform Infrared Spectroscopy
HC	hydrocarbon
HFRR	High Frequency Reciprocating Rig
IETE	indicated engine thermal efficiency
IMEP	indicated mean effective pressure
ISFC	indicated specific fuel consumption
LHV	lower heating value
NO_x	oxides of nitrogen (NO, NO_2)
PM	particulate matter
RME	Rapeseed methyl ester
ROHR	rate of heat release
SOF	soluble organic fraction
SOM	soluble organic material
TDC	top dead centre
THC	total hydrocarbon
TGA	thermogravimetric analyser
ULSD	ultralow sulphur diesel
B5	ultralow sulphur diesel +5% RME
VOM	volatile organic material

1. Introduction

There is an increased interest in searching for alternatives energy carriers in the transportation and energy generation sectors over the past decade. The motivations for that are the reduction of the fossil fuels dependence (energy sustainability), a desire to reduce greenhouse gas emissions (especially CO_2 in the transportation sector) and human health concerns related to other pollutant emissions (particulate matter, NO_x, CO, etc.). In fact, in a recent press release, the International Agency for Research on Cancer (IARC) classified diesel exhaust as carcinogenic to humans (Group 1). Due to these issues new legislation is being introduced to promote the use of biofuels in the transportation sector and strict pollutant emission regulations must be fulfilled demanding the incorporation of aftertreatment systems. These short and medium term scenarios indicate the ideal timeliness for research aiming to design new energy alternatives able to overcome those energy and environmental issues taking into account the interaction between some of the vehicle systems (e.g. the effect of alternative fuels in the diesel particulate filter).

Efforts to tackle these challenges have been based on both engine and fuel-focused techniques. Diesel reformulation using sustainably sourced biofuels seems to be a promising field of research. The focus now lies on biofuels obtained from non-edible feedstock leading to several publications critically assessing the production and environmental implications of energy alternatives derived from algae [1,2], triglycerides [3], lignocellulose [4,5], etc. A feasible and common alternative could be the use of primary alcohols such us methanol [6], ethanol [7], butanol [8] and/or pentanol [9]. Traditionally, ethanol fuel is the one which has received the most attention as can be produced from non-edible feedstock and it has some advantages over biodiesel in terms of availability, price and emission characteristics. Its oxygen content is about three times higher than biodiesel resulting in further improvements in PM emissions [10,11] and it has been demonstrated to reduce NO_x emissions under certain operating conditions [12]. However various limitations in the use of ethanol in compression ignition (CI) engines exist due to its adverse effects on some key fuel properties in particular flash-point [13], blend stability with diesel-like fuels, viscosity, lubricity and cetane number [12–15]. For high ethanol content in diesel blends (i.e. e-diesel) cetane-enhancing and stability-improving components must be utilised [16] such as biodiesel [17,18].

Diethylene glycol diethyl ether (DGE) could be a promising fuel additive for compression ignition engines based on its high cetane number and its high amounts of fuel-born oxygen. These properties also qualify DGE as a potential cetane-enhancing additive to e-diesel blends. A review of the limited literature suggests that DGE may have similar effects to DGM, a well-studied [19–22] but about three-times more expensive oxygenate. When combusting pure DGE under EGR conditions in a diesel engine, Cheng et al. obtained reductions in all regulated emissions as compared to neat diesel [23] which was confirmed in two other studies by Upatnieks et al. who attributed this to the high oxygen content and low soot formation potential of DGE [24,25]. Yet the available literature on DGE fails to give a detailed account of the additive's real-world potential in diesel combustion as there are no in-depth studies on its combustion pattern and detailed emission characteristics. The factual novelty of this work, however, is the enhancement of ethanol–diesel blends through the incorporation of DGE which has so far not been attempted.

The aim of this investigation is to evaluate the potential of DGE in replacing part of the diesel with a view in designing new feasible fuel blends composed of different hydrocarbon constituents to partly replace diesel fuel while obtaining energy efficiency improvements and environmental benefits. In doing so the effects of various fuel blends on engine performance, combustion patterns, exhaust emissions and aftertreatment systems are investigated.

2. Material and methods

2.1. Test engine and instrumentation

For this research a natural aspirated single-cylinder diesel engine was utilised. The research engine employs a pump-line nozzle direct injection system with mechanical injection timing. The injector has 3 holes with 0.25 mm diameter each, while the opening injection pressure is 180 bar. Injection timing was not optimised for the different fuel blends. A Thrige Titan DC electric dynamometer with a load cell and a thyristor controlled Shackleton System Drive was used to load and motor the engine.

Each fuel was tested at constant engine speed (1500 rpm) and two different load conditions of 3 bar and 5 bar indicated mean effective pressure (IMEP) representing ∼30% and ∼70% of the engine's power capacity respectively. Additionally exhaust gas recirculation (EGR) of 0%, 10% and 20% was introduced for both loads to study its effect on emissions. The results and error bars showed in the graphs are calculated from three measurements for every studied fuel blend and engine operating condition. Due to the small quantity of fuel used in this study a calibrated glass bulb, connected in parallel with the fuel tank, was used to determine the liquid fuel flow by timing the consumption of a known