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A comparative investigation into cold-start and hot-start operation of diesel engine performance with oxygenated fuels during transient and steady-state operation

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ABSTRACT

Using a six-cylinder turbocharged common rail compression ignition engine, this study investigated the effect of oxygenated fuels on transient and steady-state performance. This paper considers the effect of oxygenated fuels on both cold- and hot-start operation. A range of fuel oxygen contents between 0% and 13.57% was derived from diesel, waste cooking biodiesel and two other blends, containing triacetin as a fuel additive. A custom test was designed to investigate engine performance parameters using acceleration, load increase and steady-state modes of operation. For each fuel, the cold-start test was conducted after an overnight engine-off time. In this study, different parameters related to engine performance were studied, such as engine coolant and lubricant temperatures and their rise rate, boost pressure, injected fuel, turbocharger lag, engine speed and torque, start of injection, maximum in-cylinder pressure, maximum rate of pressure rise, cyclic variability, FMEP, mechanical and thermal efficiencies, and BSFC. In comparison with hot-start, the cold-start results indicated a higher injected fuel, indicated torque, maximum in-cylinder pressure, maximum rate of pressure rise, FMEP, BSFC and CoV of IMEP, and a lower SOI, ME and BTE. During cold-start, using oxygenated fuels, instead of diesel, resulted in a lower rate of lubricant temperature rise and a higher BSFC, while decreasing the FMEP. Using oxygenated fuels, instead of diesel, during the idle and transient modes resulted in lower indicated torque and maximum in-cylinder pressure under cold-start whilst, under hot-start, it resulted in higher indicated torque and maximum in-cylinder pressure, because during hot-start, the fuel oxygen is significantly influential in torque build-up during turbocharger lag. While, during cold-start there are some other influential factors. In addition, oxygenated fuels—compared to diesel—experienced higher CoV of IMEP during cold-start while, during hot-start, they had lower values.

1. Introduction

Currently, a high portion of new diesel engines are turbocharged [1], giving them advantages such as lower CO_2 emission, better fuel economy and higher brake power [2]. However, turbocharger lag in this type of engine can cause some disadvantages, such as overshoot in emissions and slow acceleration rates which lead to poor drivability. However, these factors could potentially be improved by the use of alternative fuels, such as biofuels. For example, Rakopoulos et al. [3] reported that during transient operation, where smoke opacity had an overshoot, biofuel blends showed lower smoke opacity than diesel. Regarding the potential effect of biofuels on drivability, it can be mentioned that the slow acceleration rate in turbocharged diesel engines is due to the low air-to-fuel ratio (lack of oxygen in the combustion) during turbocharger lag. Since diesel has no oxygen content, the fuel oxygen content in biodiesels can potentially improve combustion during turbocharger lag, thereby leading to improved acceleration response.During the last decade a significant quantity of research has focused on the adverse health effects of fossil fuels, their role in environmental degradation and impact on global warming [4–6]. Limiting fossil fuel use was emphasized by the Paris agreement (December 2015, at the Paris climate conference, COP21), where 195 nations agreed to

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Nomenclature

LHV	lower heating value
BSFC	brake specific fuel consumption
IMEP	indicated mean effective pressure
ME	mechanical efficiency
CO	carbon monoxide
CO_2	carbon dioxide
HC	hydrocarbon
SET	supplemental emissions test
SOI	start of Injection
HHV	higher heating value
BTE	brake thermal efficiency
FMEP	friction mean effective pressure
AFR	air-to-fuel ratio
NOx	nitrogen oxides
NO_2	nitrogen dioxide
PM	particulate matter
ESC	European stationary cycle
CoV	coefficient of variation

limit global warming. EU Directive 2009/28/EC, issued by the European Union, requires all member countries to increase the share of renewable sources in their transport fuels to 10% by 2020 (EU Directive 2009/28/EC).Among the different biofuels introduced by industry and academic research, waste cooking biodiesel has attracted attention due to its close properties to diesel, low price and global availability [7]. The benefits and disadvantages of using waste cooking oil biodiesel have been discussed in the literature [8]. Di et al. [9] studied waste cooking oil and reported that the use of this fuel decreased PM, mainly due to the higher oxygen content, and increased NOx, mainly due to the higher combustion temperature and increased oxygen level of combustible mixtures. Doroda et al. [10] used waste olive oil in their research and reported that its use led to lower CO and CO_2 and higher NO_2 and brake specific fuel consumption. Another report showed that brake thermal efficiency with 40% waste cooking oil blended with diesel was higher in comparison with diesel only [11]. Different properties of this fuel were used to interpret its effect on engine performance and exhaust emissions. For example, its heating value, which is lower than diesel, was used to explain the increased BSFC [12–14] and decreased brake power [11,12].In biodiesel, the presence of long-chain alkyl esters, which have two oxygen atoms per molecule, is an effective factor that differentiates them from diesel. This is related to the oxygen content of fuel, which is derived from the fatty acid ester profile, such as carbon chain length and unsaturation level [15]. Among different fuel properties, oxygen content has been reported as a significant factor that affects engine performance and reduces exhaust emission [16–19]. Accordingly, in terms of the emission reduction, a low volume of highly-oxygenated fuel additives can enhance emission reduction.The high oxygen content of triacetin [$C_9H_{14}O_6$] makes it a potential additive to fuels [20]. Triacetin is a triester of glycerol acetic acid, and glycerol is a byproduct of the biodiesel transesterification process. The availability of glycerol increases as the production of biodiesel increases. In contrast to the global availability of glycerol, which could affect its price, the physical and chemical properties of glycerol are the limitations for using it as a fuel [21]. However, the production of glycerol-derived fuels could be a solution [22]. Triacetin is the product of the acetylation process of glycerol and acetic acid. However, the literature reveals only limited research on triacetin as a potential fuel or fuel-additive [23–29]. Casas et al. [20] reported that adding triacetin to biofuels increased fuel oxygen content, viscosity and density and decreased the heating value and cetane number.Owing to the increasing share of oxygenated fuels in combustion engines, the use of these alternative fuels should be studied under different engine operating conditions; such as cold-start and hot-start, under steady-state and transient operation, to quantify their advantages and disadvantages, as such quantification is essential to evaluate the possibility of using these alternative fuels in the market.A significant proportion of driving starts when the engine is cold, either after an overnight soak or at the end of a work day. The main engine block, engine coolant and lubricant are three thermal masses that interact during cold-start. Since the engine is operating at a sub-optimal temperature, the inefficient temperature (lower than steady-state) of these thermal masses affects engine performance and emissions. For example, low engine cylinder wall temperature leads to poor combustion, higher fuel consumption, higher emissions and increased piston/liner friction [30]. Because engine lubricant operates most efficiently between 100 °C and 110 °C [31], the higher viscosity of lubricant oil results in higher friction losses and lower thermal efficiency during cold-start [30]. Frictional losses during the early stage of cold-start operation can be up to 2.5 times higher than hot-start operation [32]. Another study predicted that, during cold-start, the fuel consumption would increase by up to 13.5% in comparison with hot-start [33]. Cao [34] reported that, during the first minute of engine operation, emissions are significantly higher than during regular engine operation. This is due to incomplete combustion because of the cold engine block.The definition of cold-start in the literature, including official documents, varies [35]. Reiter and Kockelman [35] reviewed definitions of cold-start and its duration to identify synergy among the various interpretations. Based on the literature [35], this study considers cold-start to be when the engine starts after an overnight soak (engine-off time) and continues until the engine coolant temperature reaches 70 °C (according to EU Directive 2012/46/EU). This study also investigates conditions in which the engine coolant temperature is above 70 °C, but the engine lubricant temperature is sub-optimal.Many vehicle journeys start and finish within a short period, before the engine reaches regular operating temperature [35]. Andre [36] studied the driving pattern of 55 French vehicles under real conditions, recording 10,000 trips over 71,000 km, which represented 1260 h of driving. The study revealed that, during one third of the trips, the engine coolant and lubricant did not exceed 70 °C, and that the journeys were completed before the engine was fully warm. Based on a survey among 39 European laboratories (data from 1766 vehicles), Andre and Joumard [37] estimated that 5.2 km was the cold-start distance at 20 °C. This refers to the distance in which CO, CO_2, HC and NOx stabilised. The 1995 Nationwide Personal Transportation Survey indicated that about 50% of all person-trips were less than three miles [38]. The 2009 National Household Travel Survey from the U.S Department of Transportation reported that the median journey of a light-duty vehicle is four miles.In addition to cold-start and hot-start conditions, the use of oxygenated fuels should be studied under steady-state and transient engine operation.Only a small proportion of daily driving schedules involve steady-state operation: engines are mostly used under transient conditions [39]. Therefore, the study of transient operation, where engine speed or fuel injection change [4], may lead to results which are more reflective of reality than investigation conducted during steady-state operation alone.There is limited research on transient engine operation compared to the steady-state operation in the literature [4]. This could be due to difficulties such as the availability of automatically-controlled test-beds and high-tech fast response measuring instruments. Most of the transient engine studies presented their results as mean and cumulative values over the cycle, as dictated by legislated drive cycle procedures, consequently concealing the influence of transient discrete modes such as acceleration and load acceptance. Accordingly, it is important to investigate engine behaviour under individual acceleration and load increases to reveal transient operation mechanisms. Studies on the effect of load increase and acceleration on engine performance have been, to date, limited