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The influence of fuel composition on a heavy-duty, natural-gas direct-injection engine

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ABSTRACT

This work investigates the implications of natural-gas composition on the combustion in a heavy-duty natural-gas engine and on the associated pollutant emissions. In this engine system, natural gas is injected into the combustion chamber shortly before the end of the compression stroke; a diesel pilot that precedes the natural-gas injection provides the ignition source. The effects of adding ethane, propane, hydrogen, and nitrogen to the fuel are reported here. The results indicate that these additives had no significant effect on the engine's power or fuel consumption. Emissions of unburned fuel are reduced for all additives through either enhanced ignition or combustion processes. Black carbon particulate matter emissions are increased by ethane and propane, but are virtually eliminated by including nitrogen or hydrogen in the fuel.

1. Introduction

Natural gas is a potential alternative to conventional liquid fuels for use in automotive internal combustion engines. While predominantly methane (CH_4), natural gas also contains heavier hydrocarbons and inert diluents. The levels of these species vary substantially with geographical source, time of year, and treatments applied during production or transportation. The addition of unconventional and bio-derived gases to fossil natural gas can have an even greater effect on fuel composition [1]. Natural-gas fuelling can reduce greenhouse gas (GHG) emissions compared to diesel; adding hydrogen to the natural gas offers even further GHG reductions from transportation applications [2]. When considering the use of natural gas, it is vital to understand the influences of fuel composition on the combustion system. This work evaluates the implications of natural-gas composition on the combustion process and pollutant emissions for a heavy-duty pilot-ignited engine fuelled with directly injected natural gas.

1.1. Directly injected natural-gas engine

One technology for natural-gas fuelling of heavy-duty engines, developed by Westport Power Inc., uses natural gas injected directly into the combustion chamber late in the compression stroke, retaining the performance and efficiency of an equivalently-sized diesel engine [3]. A small amount of diesel fuel is injected late in the compression stroke, prior to the natural-gas injection. The auto-ignition and combustion of this pilot fuel provides the ignition source for the gaseous fuel; the latter then burns in a predominantly non-premixed combustion event. Compared to diesel fuelling, the main fuel's lower carbon:energy ratio reduces carbon dioxide (CO_2) emissions; its lower adiabatic flame temperature reduces oxides of nitrogen (NO_x) emissions; and, its lower sooting tendency reduces fine particulate matter (PM) emissions. As the natural gas is not premixed in the combustion chamber, emissions of unburned fuel are significantly lower than from many other natural-gas fuelling technologies [4]. Using exhaust gas recirculation (EGR) can achieve substantial further reductions in NO_x emissions; however, a lack of oxidizer at high levels of EGR degrades the combustion and increases the emissions of unburned hydrocarbons (HC), carbon monoxide (CO), and PM [5]. At the EGR levels required to achieve low NO_x levels, more than 90% of the PM originates from the natural gas [6].

2. Natural-gas composition

Natural gas is a mixture of various hydrocarbon molecules. Commercial-grade natural-gas compositions vary from 70% to 95% CH_4, with the balance composed of heavier hydrocarbons (primarily ethane, C_2H_6, and propane, C_3H_8) as well as diluents such as

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molecular nitrogen (N_2) and CO_2. There are also trace levels of sulphur compounds, often added as odorants, and other hydrocarbon species.

The effect of fuel composition on the combustion process and on the emissions from natural-gas fuelled engines has been addressed in both fundamental and applied studies. The majority of research has focused on premixed-charge spark-ignition engines, which are currently the predominant form of natural-gas engines [4]. These results, along with studies of non-premixed flames in laboratory-scale burners, provide insight into the effects of natural-gas composition. However, there has been relatively little work on the complex combustion seen in a non-premixed compression-ignition engine, as investigated here.

2.1. Effect of heavy hydrocarbons

The principal heavy hydrocarbons found in natural gas are ethane and propane. For premixed auto-ignition combustion, the greatest influences of these species are in the ignition and early combustion phases, where they enhance the ignitability of the mixture; this is primarily a result of increases in the concentration of reactive radicals. At high temperatures, increases in the concentrations of H, OH, HO_2 and H_2O_2 radicals enhanced the natural-gas ignition process [7,8]; at temperatures below ~1200 K, it is the methylperoxy (CH_3O_2H) radical that fills this role [9]. The heavier hydrocarbons also promote the formation of hydrocarbon radicals, including C_2 species such as the ethyl radical (C_2H_5) and acetylene (C_2H_2) [9].

Ethane and propane also influence the combustion event and pollutant emissions. Enhanced radical formation extends the lean combustion limit [10,11]. In premixed-charge spark-ignition engines, ethane addition increases the flame propagation rate [12]. No significant effects on CO emissions are reported in most engine studies; however, some researchers report increases in HC emissions with increased ethane and propane concentrations [13], although these results are not consistent across all reported studies. Fuel quality sensors [14] and closed-loop control engines [15] have permitted spark-ignition engines to run successfully on a wide range of fuel compositions.

The presence of heavy hydrocarbons also affects the ignition process in non-premixed natural-gas combustion. At temperatures >1400 K, fuel additives have little effect as this process is mixing limited [16]. At lower temperatures, the addition of either ethane or propane is found to reduce ignition delay times by as much as 0.7 ms [16]. However, there is a limit to the effectiveness of improved kinetics, especially at higher temperatures; beyond a certain point mixing limitations dominate the ignition processes. The shorter ignition delay time has also been identified as a potential source for increased NO_x emissions with ethane addition to the fuel [17]; however, substantially more work is required to understand the effects of the heavier hydrocarbons on the ignition and pollutant formation mechanisms of a natural-gas engine using a non-premixed direct-injection combustion system.

2.2. Fuel dilution with nitrogen

Small quantities of nitrogen may be found in natural gas, often added as a diluent to maintain a specified heating value. Other than reducing the mass- or volume-specific energy content (heating value) of the fuel, small levels of an inert diluent like N_2 are unlikely to significantly influence the combustion event. However, higher dilution levels may have a greater impact; these influences have been studied in various combustion systems. For a natural-gas fuelled, premixed-charge engine, adding N_2 to the fuel reduces NO_x emissions but impairs efficiency [18]. In a low pressure non-premixed combustion system (an industrial boiler), gaseous-fuel dilution reduces NO_x emissions more effectively than does oxidizer dilution; fundamental studies attribute this to more rapid quenching of the NO-forming reactions [19]. In laminar counter-flow diffusion flame studies, N_2 dilution is used to reduce fuel concentrations; no significant effects are observed until the fuel stream contains more than 80% N_2 (by volume) [20]. These results indicate that the principal influence of nitrogen addition manifests itself by reducing the heating value of the fuel. There is no evidence of direct participation in the reaction kinetics, even at very high N_2 concentrations.

The effects of N_2 addition on a heavy-duty engine fuelled with directly injected natural gas have been studied previously [21]. The key findings from this work indicated that diluting the natural gas (while increasing the injection mass to retain the same total fuel energy) resulted in a slower initial combustion but faster and more stable late-stage combustion. This is attributed to the higher kinetic energy of the gas jet and resulting improvement in mixing. The current work compares these effects with those of other fuel additives.

2.3. Hydrogen addition

The most important effect of blending natural gas and hydrogen for use in homogenous-charge, spark-ignition engines is extension of the lean combustion limit [22]. Combustion bomb studies demonstrate that hydrogen's enhanced diffusivity results in a higher turbulent flame propagation rate for lean mixtures [23]. The hydrogen also increases the flame's resistance to stretch [24], reducing local extinction events. At a constant air–fuel ratio, NO_x emissions are increased due to a higher adiabatic flame temperature while CO and HC emissions are reduced [25]. Flame stability in the presence of EGR is also improved [26].

For non-premixed combustion of hydrogen/methane blends in a co-flowing jet diffusion flame, non-premixed flame stability is enhanced with increasing hydrogen content [27]. In a non-premixed steady flow burner, hydrogen addition reduces prompt NO formation due to a reduction in CH, but increases thermal NO due to higher flame temperatures and higher H, O, and OH radical concentrations [28,29]. In a direct-injection natural-gas engine, replacing the natural gas with a hydrogen/methane blend increases the ignitability of the gaseous fuel and improves combustion stability, leading to significant reductions in emissions of combustion by-products including CO, HC, and PM, while higher temperatures increase NO_x emissions [30]. The current work compares these effects with those of other fuel additives.

3. Experimental apparatus and procedures

A single-cylinder research engine equipped with a prototype fuelling system was used to investigate the effects of gaseous-fuel composition on a pilot-ignited, directly injected natural-gas engine. The engine used is a Cummins ISX series modified for single-cylinder operation (Table 1); the experimental facility has been described in detail previously [31,32]. The diesel and natural-gas injection processes are controlled electronically using a single multi-fuel injector. The engine is also equipped with a custom air-exchange system to ensure that the charge conditions are independent of variations in fuel composition and injection timing. A cooled high-pressure EGR loop controls intake charge dilution.

The engine facility is fully instrumented, with measurements of air and fuel flow (both diesel pilot and natural gas) as well as exhaust gas composition. The gaseous-fuel flow measurement uses a coriolis-force mass flow sensor, and hence is insensitive to changes in gaseous-fuel composition. The combustion process is monitored using a high-speed water-cooled in-cylinder pressure