Fuel 196 (2017) 154–168

Contents lists available at ScienceDirect

Fuel

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

Full Length Article

Effect of ethanol blending on particulate formation from premixed combustion in spark-ignition engines

Stephen Sakai [a,*], David Rothamer [b]

[a] University of Wisconsin-Madison, 1500 Engineering Dr, ERB 140, Madison, WI 53706, USA
[b] University of Wisconsin-Madison, 1500 Engineering Dr, ERB 127, Madison, WI 53706, USA

ARTICLE INFO

Article history:
Received 25 October 2016
Received in revised form 11 January 2017
Accepted 13 January 2017
Available online 4 February 2017

Keywords:
Gasoline
Ethanol
Particulate
Soot
Size distribution
Combustion
Premixed

ABSTRACT

Particulate formation due to combustion of a wide range of ethanol-gasoline blends were investigated in an internal combustion engine. The engine used for this study is a single-cylinder research engine, the architecture of which is representative of a modern spark ignited direct injected (SIDI) engine. Instead of direct injection, the engine was fueled using a premixed prevaporized (PMPV) mode, which supplied the fuel to the engine in a well-mixed, gas-phase air-fuel mixture in order to isolate physical effects of the fuel. This created a completely homogenous air-fuel mixture with no pockets of significantly differing equivalence ratio, liquid fuel droplets, or wetted surfaces, ensuring that particulate formation was due to homogenous, gas-phase combustion. The engine was operated at a fixed load and phasing so that the effects of varying equivalence ratio and ethanol content could be examined. The results in this work show that the addition of ethanol results in a consistent decrease in engine-out particulate proportional to ethanol content. Moreover, the critical equivalence ratio, the equivalence ratio at which significant sooting begins, increases in a linear fashion with ethanol addition. It was also shown that the shape of the particulate size distribution (PSD) is affected by ethanol content, with increased ethanol leading to more nucleation-mode dominated distributions.

1. Introduction

Renewable energy standards in the US have positioned ethanol addition to gasoline squarely into the long-term view. Currently, gasoline in the United States contains up to 10% ethanol by volume (E10); however, the United States Environmental Protection Agency (EPA) has already begun allowing E15 to be sold to consumers [1] and this allowance has opened the door for future increases. With stricter particulate matter (PM) regulation in Europe and the US putting more focus on PM emissions from spark-ignited (SI) engines, and increasing ethanol content in gasoline, it is important to understand how ethanol blending influences the sooting tendency of gasoline in a comprehensive way.

Engine-out PM emissions from ethanol-blended gasoline are still not nearly as well understood as those for diesel or gasoline. Most gasoline-ethanol PM research in the literature has focused on low ethanol blend percentages (<20 vol.%). Laboratory flame studies have concentrated on the formation of soot precursors. Ethanol was shown to reduce aromatic species in an ethylene premixed flame for concentrations up to 10% by mass [2–5]. However, in non-premixed ethylene flames it was found that ethanol addition increased soot production for the same concentrations [6,7]. Salamanca et al. found similar increases in soot for low concentration ethanol blends with ethylene in a counter-flow diffusion flame but saw a decrease when the ethanol content exceeded 20% by mass [8]. Similar results were found with higher hydrocarbons. Rubino et al. found increased benzene in a counter-flow diffusion propane flame with 10% ethanol addition by volume, followed by a decrease when ethanol concentration was increased to 15% [9]. Experiments with toluene, isooctane, *n*-heptane, and gasoline showed similar trends [10–14].

The differences in laboratory flame results show that the effect of small concentrations of ethanol will depend on the mode of combustion: premixed or diffusion controlled burning. Conversely, larger fractions of ethanol consistently show decreases in soot and soot precursors. This has been attributed to both the dilution of a more sooting fuel with less sooting ethanol [13,15,16], as well as the chemical effect of the oxygen in the fuel reducing the available pathways for soot formation [3,4,17].

Engine studies in the literature which include ethanol generally have also focused on low ethanol blend percentages. Much like flame studies, there is not always a consistent trend. Some studies

* Corresponding author.
E-mail addresses: ssakai@wisc.edu (S. Sakai), rothamer@engr.wisc.edu (D. Rothamer).

http://dx.doi.org/10.1016/j.fuel.2017.01.070
0016-2361/

showed little to no sensitivity to ethanol content up to 10% by volume, indicating that engine operating conditions played a more critical role in reducing engine PM [18–20]. Price et al. showed little change in PM for ethanol concentrations up to 30% but indicated a large reduction for E85 [21]. Other work showed a consistent decrease in PM with ethanol content [22–24]. In contrast, Catapano et al. and Di Iorio and coworkers indicated that E50 and E85 made more particulate than neat gasoline [25,26]. Nearly all studies cite engine operation as a significant factor in the results due to the operating condition's effect on parameters such as air-fuel mixture preparation, fuel vaporization, and wetting of surfaces.

The purpose of this study is to examine the effect of ethanol addition to gasoline on particulate formation in a spark-ignition engine while minimizing the effects of mixture preparation and engine operating condition. To accomplish this, a previously reported operation method was utilized in which fuel was introduced to the intake air stream far upstream of the engine [27]. This method, called premixed prevaporized (PMPV) operation, ensures that the fuel is completely premixed and prevaporized before reaching the engine. Changes in fuel physical properties due to ethanol addition can directly affect mixture preparation. By premixing and prevaporizing the fuel in advance, the majority of physical effects of the fuel can be removed. This allows for an air-fuel mixture which is completely homogenous, eliminating any pockets of significantly differing equivalence ratio, liquid fuel droplets, or wetted surfaces which could easily occur under direct-injection operation. Also removed is the effect of evaporative cooling from the fuel which can create different in-cylinder conditions. Thus, any soot formed in this operating mode can only be attributed to the combustion of homogenously-mixed gas-phase fuel components under comparable in-cylinder conditions.

2. Experimental setup

2.1. Engine

The engine used for these experiment is a single-cylinder engine which has been configured to be representative of a modern spark-ignited direct injection (SIDI) engine. The cylinder head features a 4-valve pent-roof combustion chamber with a centrally mounted spark plug and a side-mounted fuel injector. Table 1 lists the specifications for the engine. It should be noted that all engine timings are listed with 0 crank angle degree (CAD) referenced to top dead center (TDC) of the compression stroke, times before TDC are negative and times after TDC are positive. In-cylinder pressure was measured using a high-speed piezo-electric pressure transducer (Kistler 6125C). An average of 50 cycles of measured pressure was used to set the operating condition based on gross indicated mean effective pressure ($IMEP_g$) and location of 50% cumulative heat release (CA50). Pressure data was acquired for 500 cycles and averaged. A MATLAB post-processor was used to calculate cumulative heat release, heat release rate, and mass averaged in-cylinder temperature.

For this work, the in-cylinder fuel injector was replaced with a plug and was moved to a premixing chamber upstream of the intake surge tank. As mentioned before, under PMPV operation, fuel is injected far upstream of the intake such that it is premixed and vaporized by the time it enters the engine. Complete vaporization is verified by shining a laser through an observation window just upstream of the engine. Laser light is scattered by any droplets present, indicating the presence of liquid fuel. This method isolates liquid fuel and spray effects from the particulate formation process, enabling the investigation of fuel chemistry impacts on PM, specifically the effect of the fuel-bound oxygen for

Table 1
Engine geometric parameters.

Parameter	Value	Unit
Bore	85.96	mm
Stroke	94.6	mm
Displacement	549	cm^3
Compression ratio	11.97	
Connecting rod length	152.4	mm
Intake valve open	+350	CAD
Intake valve close	−140	CAD
Exhaust valve open	+150	CAD
Exhaust valve close	−355	CAD
Intake/exhaust valve lift	9.9	mm

Table 2
Nominal engine operating parameters corresponding to EEE $\Phi = 0.98$ baseline condition.

Parameter	Value	Unit
Engine speed	2100	RPM
$IMEP_g$	334	kPa
CA50	+8.0	CAD
Spark timing	−25	CAD
Intake pressure	35	kPa
Exhaust pressure	101.5	kPa
Intake temperature	60	°C
Exhaust sample temperature	250	°C
Fuel pressure	9	MPa
Indicated power	3.2	kW

ethanol-gasoline blends. For all test conditions, the engine was held at constant speed, load, and combustion phasing as listed in Table 2.

2.2. Particulate sampling system

Engine out particle size distributions (PSDs) were measured using a particulate sampling system composed of a dilution system (Dekati FPS 4000) and a scanning mobility particle sizer (SMPS). The SMPS utilizes an electrostatic classifier (EC, TSI model 3080), a differential mobility analyzer (LDMA, TSI model 3081), and a condensation particle counter (CPC, TSI model 3010). A diagram of the exhaust sampling system is shown in Fig. 1. Exhaust is sampled at a location downstream of the exhaust surge tank. The dilution

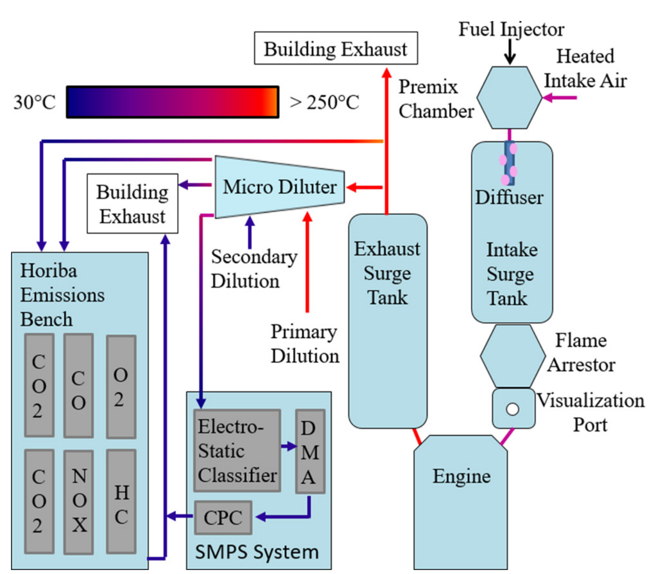

Fig. 1. Experimental setup schematic showing the exhaust sampling system.