Do all gas engines respond the same way to varying fuel composition?

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Introduction and method

The globalization of the gas supply and the desire to incorporate renewable fuels into the energy supply are changing the composition of natural gas being supplied to end users. Thus, the hydrocarbon mix in natural gases is changing, and renewable fuels, such as hydrogen from excess renewable power, are being added to pipeline natural gas. A parallel development is the use of liquefied natural gas (LNG) as a land and sea transportation fuel, intended as a less polluting alternative for fuels like diesel and heavy fuel oil. As is well known, engine knock in gas-fueled engines is very sensitive to the fuel composition, and the occurrence of knock must be avoided: diminished performance, engine shutdown and even physical damage can result from knock. To define the limits of fuel composition guaranteeing knock-free performance for engine owners, it is essential to be able to predict the impact of composition on knock, accurately.

Engine knock is caused by autoignition of the unburned fuel gas mixture, the so-called end gas, ahead of the propagating flame in the engine cylinder. The tendency of the mixture to autoignite depends on the fuel gas composition, equivalence ratio and the temperature and pressure of the end gas. To characterize the effects of changes in the composition of gaseous fuels on engine knock, the autoignition process during the compression and burn periods of the engine cycle must be analyzed and predicted. While the correct prediction of autoignition behavior of fuel mixtures is a clear prerequisite for predicting knock, it is furthermore essential to account for the effects of fuel composition on the in-cylinder pressure and temperature history relevant for knocking. These are caused by changes in thermophysical properties, primarily the heat capacity, of the air-fuel mixture and in the phasing of the combustion process, governed by the burning velocity of the mixture [1]. Different engine platforms, e.g., stoichiometric vs. lean-burn, can have different in-cylinder conditions that can directly impact the autoignition behavior, thermophysical properties and burning velocity of the combustible mixture. Consequently, these different types of engine may respond differently regarding the effect of varying fuel composition on engine knock. Substantial differences in engine response are a complicating factor when characterizing the knock resistance of the fuel for the end user and must be considered. Here, we discuss modeling results for three different 4-stroke engine types: a spark-ignited, lean-burn engine, a dual-fuel (diesel-pilot), ultra-lean-burn engine and preliminary results for a spark-ignited, stoichiometric truck engine. The results are based on a method [1] that incorporates changes in thermophysical properties, combustion phasing (i.e., the burn rate) and autoignition, which uses detailed chemistry to predict autoignition and a two-zone model to predict combustion phasing. The method scales different fuel mixtures as an equivalent methane/propane mixture (so-called Propane Knock Index, PKI), and then converts the results into a 0-100 Methane Number scale [1], analogous to the Octane Number for gasoline. After a brief review of the method used, we present the results on combustion

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phasing and knock behavior as a function of fuel composition. The analysis indicates that the differences in behavior observed are directly related to fundamental differences in physical and chemical processes caused by the extant in-cylinder conditions.

Results and Analysis

Before describing the results of the computations, we first discuss an important insight into the differences in autoignition behavior between the conditions in the spark-ignited lean-burn and dual-fuel, ultra-lean-burn engines. The former engine (6 cylinder, 208 kW [1]) operates at 1500 rpm and excess air ratio, λ=1.55, while the latter engine (6 cylinder, 6 MW) operates at 750 rpm and λ=2.07. For the latter engine, ~1% of the full-load energy input to the cylinder is supplied by the diesel pilot used for ignition. We remark that the differences in peak pressures, from 70-80 bar for the spark-ignited engine up to ~150 bar for the dual-fuel engine, result in different peak temperatures. Using adiabatic compression to estimate the maximum temperatures in the two engines, we see that there is a substantial difference. As illustrated in Fig. 1, below, we see that the spark-ignited engine has a peak temperature of roughly 1050 K when close to knock, while that of the dual-fuel engine is generally below 950 K. In the figure, we also illustrate the trends in computed autoignition delay time with temperature for pure methane, and methane with 20% ethane or 10% propane at 120 bar and λ=2. In addition to a substantial difference in the ignition delay time at the different temperatures, we observe that the behavior of ethane in the mixture changes with temperature: above ~1050 K, 20% ethane has roughly the same impact on ignition delay time as 10% propane, but below ~950 K, this ethane fraction has a substantially smaller ignition promoting effect. Anticipating the results presented below, we expect a difference between these two engine types with varying ethane fraction.

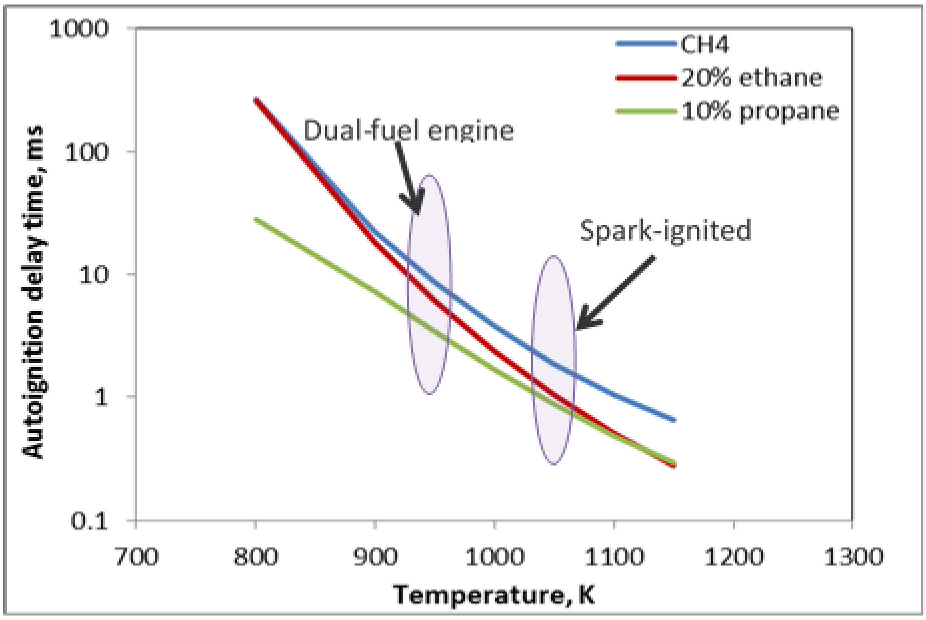

Fig. 1 Calculated autoignition delay times for CH_4, CH_4+20 mole% C_2H_6 and CH_4 + 10 mole% C_3H_8 mixtures as a function of temperature at 120 bar and λ=2; indicated are the temperature regimes of the two engines.

We further remark that this behavior of ethane as a function of temperature resembles that of hydrogen reported previously [2].

The modeling of the combustion phasing, needed to determine the pressure and temperature history of the end gas, revealed that the in-cylinder performance of the dual-fuel engine had an additional component arising from the fuel composition. In contrast to the spark-ignited engine, with an ignition timing that is independent of fuel composition, the ignition of the diesel pilot was either accelerated or delayed depending on the heat capacity of the combustible mixture. A higher heat capacity means that the mixture reaches the ignition temperature of the diesel pilot later in the cycle than when the fuel has a lower heat capacity. In the phasing model, using a fixed ignition temperature, rather than a fixed timing, resulted in excellent reproduction of the experimental pressure curve.

Similarly, the spark-ignited stoichiometric engine (6 cylinder, 280 kW, 600-2400 rpm) also showed different phasing behavior than the spark-ignited lean-burn engine. Here, the modeling results showed that a substantially different scaling factor for the laminar burning velocity (to account for cylinder turbulence) was needed at $\lambda=1$ than at $\lambda=1.55$, to ensure adequate prediction of the experimental pressure history. The net effect was that ethane and propane, as fastest burning fuels as compared to methane, amplified the increase in peak pressure (and thus peak temperature) in this stoichiometric engine as compared to the lean-burn engine. Preliminary comparison of the knocking predictions with the measured Knock-Limited Spark Timing (KLST) shows that using the adapted phasing model resulted in a faithful reproduction of the differences in knock behavior among the different fuel compositions tested.

Regarding the differences in knock behavior, as anticipated by the discussion surrounding Figure 1, above, the results for the ultra-lean burn dual-fuel engine show a substantially different response to the presence of ethane in the fuel as compared to the lean-burn engine; a given fraction of ethane has a lower effect on the knock resistance of the fuel for the diesel-pilot engine. These differences are large enough for commercially available fuels to be considered in any activities towards choosing a method for quantifying the knock properties of the fuel.

Lastly, we note that the results show that a relatively simple method to quantify the impact of fuel composition on the combustion phasing, has sufficient physical reality to predict the measured pressure histories in commercially available engines faithfully. Combination of the pressure history obtained with accurate detailed autoignition chemistry in a 0-D simulation yields an accurate method to quantify the knock resistance of the fuel. These relatively simple models provide useful insight into the physical/chemical origins of (variations in) engine performance.

References

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